

Article

Empirical Operational Energy Analysis of Downtown High-Rise *vs.* Suburban Low-Rise Lifestyles: A Chicago Case Study

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Abstract: It is widely accepted that the concentration of people living in high-density city centers offers greater operational energy efficiency and lower greenhouse gas emissions than lower-density expanded suburbs. The prevailing assumption is that lower-density suburbs are dominated by larger low-rise buildings that have higher building energy use requirements and greater per-person automobile travel requirements than high-density city centers dominated by medium- and high-rise buildings located in close proximity to a variety of public transit systems. However, very few studies to date have utilized empirical data at an individual household scale to evaluate differences in the operational energy (OE) footprints for both building and transportation energy end-uses between high-rise urban and low-rise suburban households. Therefore, this work collects empirical data on building and transportation OE consumption by individuals and households living in two economically similar groups: existing high-rise residential buildings in downtown Chicago, IL, USA and existing low-rise residential buildings in suburban Oak Park, IL, USA. Data were collected from over 500 households via an online survey. We considered the following components of residential living: (1) building OE (BOE), which includes electricity and/or natural gas use for all building energy end-uses; and (2) transportation OE (TOE), which includes the OE for multiple modes of transportation (*i.e.*, automobile, bus, subway, regional train, *etc.*) based on average travel behavior in each location, as well as the OE for supporting transportation infrastructure. We estimate that downtown high-rise living in this sample of residences in Chicago, IL accounts for approximately 427 GJ of primary OE per household per year, on average, which was 14% lower than the average for suburban low-rise living in the Oak Park, IL homes (499 GJ per household per year). However, on a per-person basis, downtown high-rise living accounts for approximately 246 GJ of primary OE per person per year, which was approximately 61% higher than suburban low-rise living (153 GJ per person per year). In both building types, building OE was the single largest contributor to total OE use. This study accurately captured the energy requirements associated with realistic behaviors and lifestyles of occupants of both low-rise suburban and high-rise urban households, and found that building OE dominates the total OE, which suggests that efforts to reduce building OE should be given high priority in building design and management as well as urban planning.

Keywords: operational energy; high-rise; low-rise; life style; transportation; infrastructure; Chicago

1. Introduction

The United Nations forecasts that 70% of the world's projected 9 billion inhabitants will live in urban areas by the year 2050, up from 51% of 7 billion urbanized inhabitants as of 2010 [1]. The enormity

of this total figure of 2.8 billion people moving into cities over the next 40 years is perhaps more clearly appreciated when converted into an annual rate of 70 million people per year, or nearly 200,000 people per day. The human race will need to build a new or expanded city of more than one million people every week for the next 40 years to cope with this urban growth.

It is widely accepted that the concentration of people in high-density city centers, which are dominated by medium- and high-rise buildings located close to a variety of public transit systems, offers greater energy efficiency and lower greenhouse gas (GHG) emissions than lower-density expanded suburbs, which are dominated by larger low-rise buildings with higher building energy use requirements and greater per-person automobile travel requirements [2–6]. However, a number of recent studies have challenged this notion by attempting to quantify the operational energy (OE) use (and sometimes also the embodied energy [EE] use) of buildings, transportation, and supporting infrastructure. Findings have been mixed: while several recent studies conclude that high-density urban areas are indeed more energy- or carbon-efficient on a life cycle basis [3,7–10], other recent studies suggest otherwise [11–17]. However, very few studies to date have utilized empirical data at an individual household scale to evaluate differences in the OE footprints for both building and transportation energy end-uses between high-rise urban and low-rise suburban households and occupants. Further, very little data is available in the literature on the OE use of high-rise buildings, which limits direct comparisons between high-rise and low-rise buildings [18].

Therefore, this work collects empirical data on OE consumption by individuals and households living in existing high-rise residential buildings in downtown Chicago, IL, USA and in existing low-rise residential buildings in suburban Oak Park, IL, USA. We consider the following components of residential living: (1) building OE (BOE), which includes electricity and/or natural gas use for all building energy end-uses; and (2) transportation OE (TOE), which includes the OE for multiple modes of transportation (*i.e.*, automobile, bus, subway, regional train, *etc.*) based on average travel behavior in each location, as well as the OE for supporting transportation infrastructure. This study focuses on OE for two main reasons. First, several studies have shown that OE for both building and transportation end-uses typically dominates the total life-cycle energy consumption compared to the EE requirements for the acquisition of raw materials, their processing, manufacturing, transportation to site, construction, maintenance, and replacement of materials or systems [3,7,12]. Second, most previous studies have used population-average assumptions for travel patterns and building energy use; however, more empirical data are needed to accurately capture the energy requirements associated with realistic behaviors and lifestyles of occupants of both low-rise suburban and high-rise urban households.

2. Case Studies and Methodology

Households in four existing residential towers spanning two downtown Chicago, IL locations (Chicago Loop and Lakeview) were recruited as the downtown high-rise case studies. The low-rise case study homes included existing single-family detached homes and several duplex/townhomes recruited in suburban Oak Park, IL, USA. Their geographic locations and connected transportation systems are shown in Figure 1. These areas were chosen for convenience, but also reflect two distinct urban and suburban residential areas in a major metropolitan area in the United States.

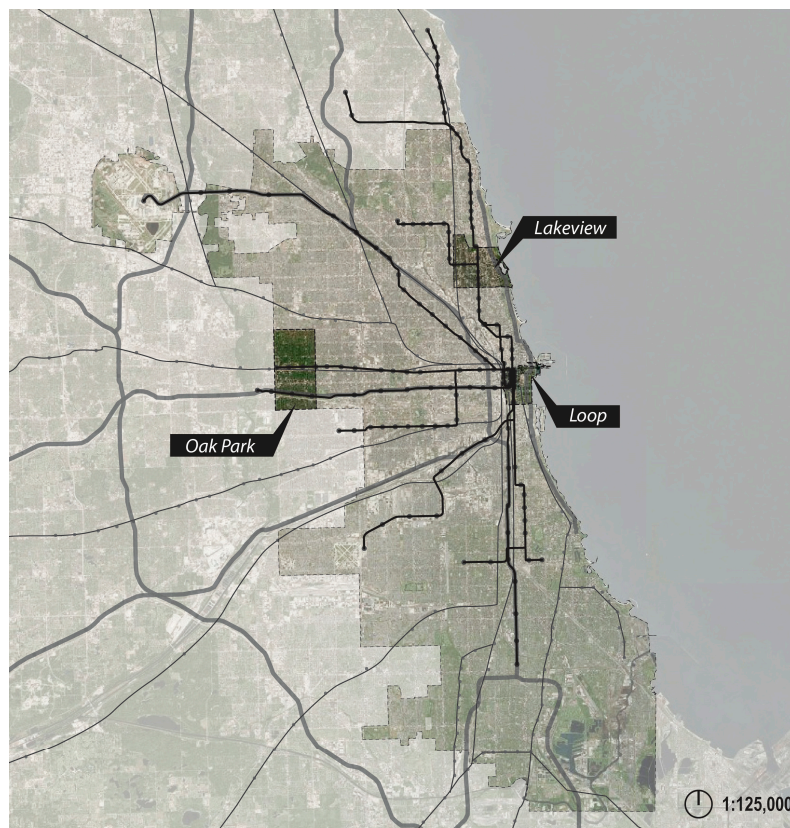


Figure 1. Study case locations relative to central Chicago and its major transportation systems.

2.1. Case Study Set 1: Downtown High-Rise Residential Towers in Chicago, IL, USA

The four downtown residential towers are located in areas of relatively high urban density and are served by numerous forms of public transportation (see Figure 2). These four residential towers were chosen for convenience based on the positive response by their developers, architects, and management companies. However, their locations generally represent two distinct areas of downtown Chicago high-rise residential life. The Aqua Tower and the Legacy at Millennium Park are both located in the downtown Chicago Loop (population density: 7200 people/km²). The 73-story Legacy at Millennium Park is located in the heart of a central business district of the Chicago Loop, facing eastward to Millennium Park and Lake Michigan. The 86-story Aqua Tower is located in Lakeshore East, a master-planned mixed-use urban development comprising apartments, condos, luxury townhomes, shops, and a six-acre park as the neighborhood's centerpiece. The 27-story Commonwealth Plaza (comprising two towers) is located on the edge of the Lakeview and Lincoln Park neighborhoods (Lakeview population density: 12,000 people/km²), approximately 8 km north of the downtown Chicago Loop [19,20]. These are two of the highest density residential neighborhoods in the City of Chicago. These residential towers were also chosen because they included both relatively new and older existing construction: both the Aqua and Legacy towers were recently constructed (2009–2010), while the Commonwealth towers were built in 1956.



Figure 2. The high-rise residential buildings in downtown Chicago (left to right): Aqua Tower, Commonwealth Plaza and the Legacy at Millennium Park, Chicago. Image Source: CTBUH.

2.2. Case Study Set 2: Suburban Low-Rise Residences in Oak Park, IL, USA

The Village of Oak Park, IL was chosen as the representative suburban low-rise residential area for comparison to the downtown high-rise towers. The location was also selected for convenience, in part because of the strong support of our study displayed by the area's leadership. Oak Park (population density: 4262 people/km²) is located approximately 14 km from Chicago's city center [20]. As an inner suburban neighborhood, Oak Park constitutes a relatively dense mix of single-family homes and apartments, with a relatively walkable environment. It is also accessible to much of Chicagoland's public transportation systems, including the Chicago Transit Authority (CTA) green and blue elevated train and subway lines and the regional Metra train lines. Because of this connection to public transit, Oak Park is considered distinctly suburban, rather than exurban like many of Chicago's other surrounding towns (e.g., Aurora or Naperville, IL, USA). Figure 3 shows the different urban layouts of the surrounding communities of the downtown high-rise and suburban low-rise cases in this research.

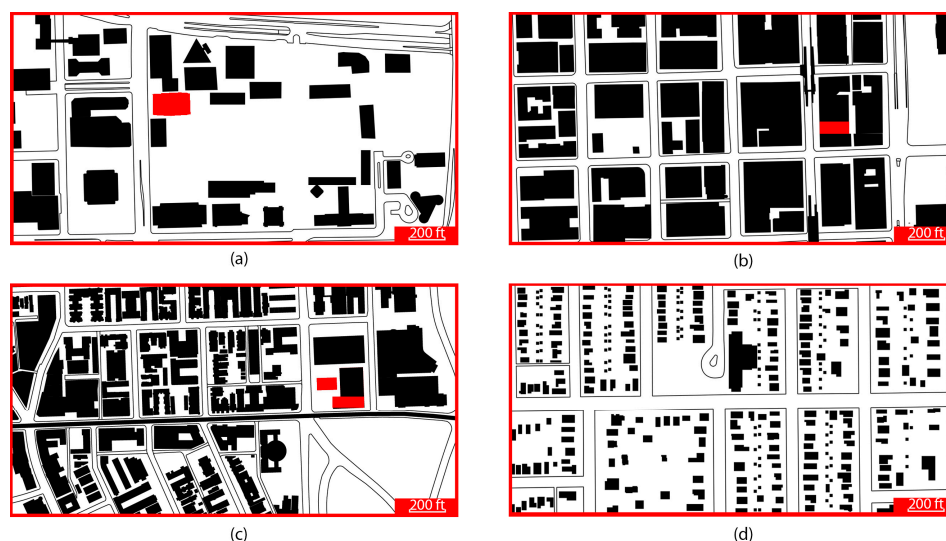


Figure 3. The surrounding community layouts (shown in red) of the downtown high-rise cases and a typical community's layout of the suburban low-rise buildings in this research. (a) Aqua Tower (downtown high-rise case); (b) Legacy at Millennium Park (downtown high-rise case); (c) Commonwealth Plaza (downtown high-rise case); (d) Oak Park (suburban low-rise cases).

2.3. Data Collection

Operational building energy data and personal and household travel characteristics were collected via a comprehensive online survey created using SurveyGizmo. The research approach and the questionnaire were reviewed and approved by the Illinois Institute of Technology Institutional Review Board (IRB) via an expedited procedure. The study launched in Oak Park in February 2014, and in the Legacy at Millennium Park, Commonwealth Plaza, and Aqua Tower in March, May, and June 2014, respectively. The survey remained open for approximately three months in each case. Participants were recruited by a combination of activities, including promoting on the websites of the buildings and their respective community groups, emailing solicitations to residents, advertising in the building and/or community newsletters, posting flyers in the buildings, mailing letters to targeted households, and giving presentations at social and community events. Although it took approximately 45 min to complete the survey, over 1500 individuals were contacted directly, resulting in over 500 responses. The information from the online questionnaires completed by residents included:

- Demographics: each household member's age, gender, race, employment status, *etc.*
- Household information: annual income, ownership status, time of residence, age of residential buildings, *etc.*
- Residential building and unit information, including:
 - Downtown residential towers: unit type, room #, ground floor area (GFA), floor #, *etc.*
 - Oak Park: building type, completion (year), structural and exterior wall material, floor #, GFA, heating & cooling system, outdoor feature, parking facility, *etc.*
- Owned vehicle/bicycle information: type, year, and distances traveled for various uses
- Travel behavior during a typical week: under each type of destination location (*i.e.*, work, school, shopping, restaurant/entertainment, family/friends)
 - The collected data included frequency, travel time, modes of travel (*i.e.*, walking, bicycling, automobile, bus, local CTA train, and regional Metra train), and distances traveled via each mode of travel
- Monthly utility usage: electric, gas, and water usage data for a 12-month period (participants could choose to upload their actual utility bills or fill out the actual usage for energy consumption from those bills)

2.4. Data Analysis

2.4.1. Building Operational Energy (BOE)

The amount of annual BOE was gathered from participants' utility bills (*i.e.*, electric, gas, and, for the high-rise towers, chilled water [21–23] bills) collected from individual households in both downtown and Oak Park residences. The individual households in all locations were asked to either submit a copy of the most recent 12 months of utility bills, including electric and/or gas bills, or to enter the same data directly into the online survey. In addition, the management personnel at the downtown residential towers were asked to provide the most recent 12 months of utility bills, including electric, gas, and chilled water bills (if applicable), for the entire building. The whole-building bills for different residential towers covered different operational categories and serving areas. For example, the whole-building bills in the Legacy Building covered usage for all public areas and spaces outside individual units, plus usage of heated and chilled water within individual units. The whole-building bills in the Aqua Tower and Commonwealth Plaza covered usage in public areas as well as usage for cooking, heating, and heated and chilled water within individual units.

Because of differences in survey launch and completion times, the collected utility data did not fall in the exact same 12-month period for all households. Further, some of the collected utility data

did not cover a full 12-month period. For example, the electricity usage data provided by Home A may have covered only 10 months from March 2013 to December 2013, while the natural gas usage data provided by Home B covered 11 months from May 2013 to April 2014. Therefore, two approaches were taken to provide a comparable 12-month dataset for as many homes as possible. First, the 12-month period of April 2013 to March 2014 was chosen as the common analysis period for annual BOE use because it was the period of time that contained the largest number of overlapping utility bill responses. Second, any missing data on monthly energy use for individual homes during any remaining months in this 12-month period were estimated by simple and/or multiple linear regression models between monthly energy use, monthly cooling degree days (CDD), and/or monthly heating degree days (HDD). The regressions were constructed using only the months for which there were utility bill data. The approach was considered appropriate because heating and cooling end-uses account for nearly half of the annual energy use in a typical U.S. home, making space conditioning the largest energy expense for most homes [24]. Only those buildings/households that provided at least eight months of energy usage data across all the applicable energy source types (*i.e.*, electric, gas, and chilled water where applicable) were included for the regression analysis.

For the cases that used electricity for cooling and gas for heating, a linear regression model was used to predict the missing electricity usage associated with CDD, and another linear regression model was used to predict the missing gas usage associated with HDD. For the downtown residential towers that use chilled water provided and delivered by the city's district chilled water system for cooling, a linear regression model was used to predict the missing chilled water usage associated only with CDD. For the cases that used electricity for both cooling and heating, a multiple linear regression model was used to predict the missing electric usage associated with both CDD and HDD.

Site energy use data (*i.e.*, the energy consumed directly at the buildings) were then converted into source (*i.e.*, primary) energy use for the analysis herein. Source energy is the sum of the energy consumed at a facility and the energy required to extract, convert, and transport that useful energy to the facility [25] (p. 3). The various site energy metrics from the collected utility bills (*i.e.*, "kWh" for electricity bills, "therm" for gas bills, and "ton-hour" for chilled water bills) were converted to source energy (MJ) using Equations (1)–(3):

$$\text{Electric : } 1 \text{ MJ}_{\text{source}} = 1 \text{ kWh}_{\text{site}} \times 3.6 \text{ MJ/kWh} \times 3.167 \text{ MJ}_{\text{source}}/\text{MJ}_{\text{site}} \quad (1)$$

$$\text{Natural Gas : } 1 \text{ MJ}_{\text{source}} = 1 \text{ therm}_{\text{site}} \times 105.5 \text{ MJ/therm} \times 1.084 \text{ MJ}_{\text{source}}/\text{MJ}_{\text{site}} \quad (2)$$

$$\text{Chilled Water : } 1 \text{ MJ}_{\text{source}} = (1 \text{ ton-hour}_{\text{site}} \times 12.66 \text{ MJ/ton-hour} \times 3.167 \text{ MJ}_{\text{source}}/\text{MJ}_{\text{site}})/6.1 \quad (3)$$

In Equation (1), 3.6 converts from kWh to MJ and 3.167 converts site energy to source energy for grid electricity in Chicago [26,27]. In Equation (2), 105.5 converts therms to MJ and 1.084 converts site energy to source energy for natural gas in Chicago [26,27]. In Equation (3), 12.66 converts ton-hours to MJ; 3.167 converts site energy to source energy for electricity in Chicago [22,26,27]; and 6.1 is the estimated coefficient of performance (COP) for the electric motor driven centrifugal chillers used by Thermal Chicago's downtown chilled water loop [28]. Unfortunately, the exact COP of the chillers was not available; a conservative estimate of 6.1 was used, as it is the COP for a baseline centrifugal chiller according to ASHRAE 90.1-2007 [29].

2.4.2. Transportation Operational Energy (TOE)

Next, TOE requirements for transportation and supporting infrastructure were quantified on both a per-household and a per-person basis across both urban and suburban scenarios. These data were based on actual travel data collected through the survey combined with data on vehicle fuel economy from FuelEconomy.gov [30] for personal vehicle use, as well as the transportation LCA database (tLCAdb) for public transit use and supporting infrastructure for all modes of travel [31–33]. The modes of transport included automobile, bus, CTA train (Chicago's combination of local subway

and elevated rail trains), and Metra (the Chicago area's regional rail system). As Table 1 shows, the OE categories include vehicle operation, roadway/station lighting, station escalator operation, station train control, and others.

Table 1. Categories of operational energy analysis for transportation systems.

OE Components	Automobile	Bus	CTA Train/Metra
Vehicle	Overall operation	Propulsion Idling	Propulsion Idling Station Lighting; Station Parking Lighting; Station Escalators operation; Station Train Control
Infrastructure	Roadway Lighting	Roadway Lighting	

The online survey gathered information on the number, make/model, and year of automobiles owned by each household, as well as the annual vehicle miles traveled (VMT) by automobile. The average annual automobile OE per household in each study case was then calculated using Equation (4):

$$\text{Avg.OE} = \frac{\sum_{i=1}^n \left(\frac{VMT_i}{MPG_i} \right)}{n} \times 0.133 \frac{\text{GJ}_{\text{site}}}{\text{gallon}} \times 1.05 \frac{\text{GJ}_{\text{source}}}{\text{GJ}_{\text{site}}} \quad (4)$$

In Equation (4), n is the total number of households that reported their travel behavior in each study case; VMT_i is the annual miles traveled by automobile by Household i ; MPG_i is the average estimated fuel economy (miles per gallon) [30,34] of all of the automobiles reported by household i ; 0.133 converts gallons of gasoline to gigajoules (GJ) based on the average energy density of the fuel [26,35]; and 1.05 converts gasoline from secondary energy to primary energy.

It should be noted that not all the survey takers who reported their detailed travel behavior provided the complete vehicle information (*i.e.*, number, make/model, and/or year). In the absence of these data, assumptions were made based on each location to estimate the likely fuel economy of vehicles in each missing household. The average year of automobiles owned by the households in the Aqua Tower, Commonwealth Plaza, Legacy Building, and Oak Park was reported as 2008, 2006, 2010, and 2005, respectively. Also, larger vehicles (*e.g.*, vans, minivans, and pickup trucks) accounted for a larger portion of vehicles in the Oak Park households than did smaller vehicles (*e.g.*, sedans, hatchbacks, convertibles, and coupes). The opposite was true for vehicle owners in the downtown high-rise households (see Appendix A for more detailed data). Therefore, in the absence of information on vehicle make/model (and thus fuel economy), the most popular vehicles of the most appropriate type were assumed to be owned in each location. A 2008, 2006, and 2010 Toyota Camry, which was the best-selling passenger car in the corresponding years in the United States [36], was assumed as the vehicle type for those in high-rise households who did not report the complete vehicle information, while a 2005 Chevrolet TrailBlazer, which was the best-selling SUV in the United States in the same year [37], was assumed as the vehicle type for those Oak Park households who did not report complete vehicle information [30,38].

Last, the annual vehicle OE per passenger miles traveled (PMT) via public transportation, including bus and light/heavy rail transit, and the annual transportation infrastructure OE per PMT, including automobile, bus, and light/heavy rail transit, were estimated using the transportation LCA database (tLCAdb) [31–33,39]. The resulting vehicle OE usage for bus, CTA train, and Metra train in Chicago were estimated to be 3.21, 1.04, and 1.02 MJ/PMT, respectively, and the resulting transportation infrastructure OE usage for automobile, bus, CTA train, and Metra train in Chicago was estimated to be 0.04, 0.002, 0.057, and 0.246 MJ/PMT, respectively. Total annual TOE was then estimated by multiplying these values by the annualized passenger miles traveled by each mode of transport reported in the online survey.

3. Results

A large number of survey responses were received in both the high-rise and low-rise scenarios, as shown in Table 2. Individuals from nearly 1000 households were contacted in the downtown high-rise towers, resulting in 249 fully or partially completed surveys (response rate of 25%). Over 560 low-rise households in Oak Park were initially contacted, resulting in 273 fully or partially completed surveys (response rate of 48%). A similar number of both high-rise and low-rise households completed the survey, providing a robust dataset of over 500 responses for analysis, split approximately evenly between high-rise and low-rise households.

Table 2. Questionnaire response summary.

Response Summary	Aqua	Commonwealth	Legacy	Downtown High-Rise	Suburban Low-Rise
				Towers	Oak Park
No. of completed responses ¹	40	31	41	112	123
No. of partially completed responses	29	32	76	137	150
No. of responses	69	63	117	249	273
No. of households contacted directly	264 ²	375	357	996	565 ³
Response rate	26.1%	16.8%	32.8%	25%	48.3%

Notes: ¹ Considering the fact that not all questions were compulsory and the questionnaire was very time-consuming (approximate 45 min to complete), a ‘Completed’ questionnaire was defined as one where at least 60% of the questions were answered. A ‘Partially Completed’ questionnaire was defined as one where less than 60% of the questions were answered; ² The Aqua Tower features 18 floors of hotel space (334 rooms), 30 floors of apartments (474 units), and 25 stories of condominiums (264 units). Due to legal issues raised by the building owner and management, only condo residents (264) were able to participate in the survey; ³ This was the number of households the research team reached out to via local events, presentations, local authorities, schools, personal connections, *etc.*

Table 3 outlines the basic characteristics of the two case study sets using data collected from the partially and fully completed surveys, as well as several other public data sources. In general, Oak Park residents were younger than downtown high-rise residents, and also had larger household sizes. Most of the low-rise Oak Park homes were older (built before 1950), while two of the downtown towers (Aqua and Legacy) were recently constructed (2009–2010) and one tower (Commonwealth) was built in 1956. In terms of neighborhood statistics, downtown Chicago residences indeed had a higher population density and greater accessibility to public transportation than Oak Park residences. Oak Park residences had a larger average ground floor area (GFA) than the downtown high-rise cases on a per-household basis, but a smaller average GFA than the Aqua Tower or Legacy Building on a per-person basis.

Table 3. Basic characteristics of the two case study sets.

Characteristics	Downtown High-Rise			Total Towers	Suburban Low-Rise
	Aqua Tower	Legacy	Commonwealth Plaza		Oak Park
	Household ¹				
Avg. Resident Age (y)	48.5	54.6	47.8	51.1	31.8
Avg. HH Size	1.8	1.9	2.0	1.9	3.3
Avg. GFA/HH (m ²)	132.0	181.1	128.2	147.1	226.4
Avg. GFA/person (m ²)	73.3	95.3	64.1	77.4	68.6
Car Ownership/HH	1.4	1.2	1	1.2	1.8
Car Ownership/person	0.8	0.6	0.5	0.6	0.5

Table 3. Cont.

Characteristics	Downtown High-Rise			Total Towers	Suburban Low-Rise
	Aqua Tower	Legacy Building ²	Commonwealth Plaza		Oak Park
Completion Year	2010	2009	1956	N/A	71.9% built before 1950 24.7% built 1950–1999 3.4% built after 2000
Height	250 m	262 m	77 m	N/A	Typically 10 m or lower
# of Floors	86	73	27	N/A	Typically 1–3
# of Units	738	357	375	N/A	Typically 1 per abode
Structural Material	Concrete	Concrete	Steel/Concrete	N/A	Wood Frame or Stone or Brick
# of Available Parking Spaces	1271	449	293	N/A	N/A
# of Available Parking Spaces/Unit	1.7	1.3	0.8	1.4	N/A
Neighborhood ³	Loop		Lakeview	N/A	Oak Park
Neighborhood Population	22,655		64,631	N/A	51,781
Neighborhood Density	7200/km ²		12,000/km ²	N/A	4262/km ²
Distance to Chicago Loop	Walkable		6 km (average)	N/A	11–16 km (average)
Public Transport System in Reasonable Walking Distance	All CTA Lines, All Metra Lines & Multiple Bus Lines		CTA Red, Purple and Brown Lines, Metra UP-N Line & Multiple Bus Lines	N/A	Green & Blue CTA lines, Metra UP-West Line & Pace Buses

Notes: ¹ Data source: the survey completed by the households across all the cases; ² Data source: Building management companies, CTBUH Skyscraper Center [19] & U.S. Census Bureau [20]; ³ Data source: U.S. Census Bureau [20] & Chicago Metropolitan Agency for Planning (CMAP) [40].

3.1. Building Operational Energy (BOE)

3.1.1. Building Operational Energy (BOE) Analysis of Suburban Low-Rise Residential Buildings

The total annual BOE for Oak Park households was calculated based on their individual utility bills, which consisted of two parts: BOE via electricity use (BOE_e) and BOE via natural gas use (BOE_g). Site energy use for these two end-uses was converted to source energy use using Equations (1) and (2). Table 4 summarizes the combination of these two annual building BOE measures from April 2013 to March 2014 for the Oak Park households, normalized for floor area, per household, and per person. Appendix B provides full details on annual BOE for each home.

Table 4. Descriptive statistics of the estimated annual operational energy of Oak Park homes ($N = 64$).

Summary Statistic	BOE _e MJ/m ² /y	BOE _g MJ/m ² /y	Total BOE MJ/m ² /y	Total BOE GJ/HH/y	Total BOE GJ/person/y
Minimum	76.9	0.0	626.0	55.2	27.6
Maximum	1760.2	2257.3	4017.5	1306.3	579.9
Mean	661.0	1077.0	1737.9	393.2	120.7
Std Dev	368.6	415.8	624.8	214.9	84.7

The average annual BOE (on a source energy basis) of the Oak Park low-rise residential buildings ($N = 64$) was estimated to be 1738 MJ/m²/year (standard deviation = 624.8 MJ/m²/year), which included an average of 661 MJ/m²/year for electricity (BOE_e) and 1077 MJ/m²/year for natural gas (BOE_g). On a per-household and per-person basis, the Oak Park low-rise residences consumed approximately 393 GJ/HH/year (standard deviation = 214.9 GJ/HH/year) and 121 GJ/person/year (standard deviation = 84.6 GJ/person/year), respectively. There was a wide distribution in total BOE, ranging from a minimum of 626 MJ/m²/year to a maximum of 4018 MJ/m²/year.

3.1.2. Building Operational Energy (BOE) Analysis of Downtown High-Rise Residential Buildings

Unlike the Oak Park low-rise homes, which all had individual utility bills, the total BOE for the Chicago downtown high-rise residences consisted of two parts: the BOE via electricity use [41]

paid by the individual units (BOE_i) and the BOE via electricity, gas, and/or chilled water paid by the building management (BOE_b). The Aqua Tower was unfortunately excluded from the BOE analysis because the energy usage data received from its building management was too limited to be used to conduct a reasonable BOE analysis. The Aqua Tower is a mixed-use building including condominiums, apartments, and hotel spaces, with all of the amenities accessible to all permanent and temporary residents. Unfortunately, their whole-building bills reflected usage for the entire building, and could not be broken down into the three space types and thus permanent condominium residents could not be assigned individual unit energy use.

Both source energy and site energy use were examined since the energy sources used for cooling and heating were very different in the Commonwealth Plaza and Legacy Building. The Commonwealth Plaza uses gas heating and electric cooling, but the Legacy Building uses electricity for both heating and cooling (the gas bills of the Legacy Building are only for ranges and fireplaces in the lobby). Appendix C provides detailed BOE_b data for both high-rise buildings. The total annual source BOE use paid for by the building management (Source BOE_b) from April 2013 to March 2014 for the Commonwealth Plaza is estimated to be $1569 \text{ MJ/m}^2/\text{year}$, which is about 74.6% of the Legacy at $2105 \text{ MJ/m}^2/\text{year}$. However, the result is opposite when considering site energy alone. The total annual site BOE use paid for by the building management (Site BOE_b) of the Commonwealth Plaza is estimated to be $1160 \text{ MJ/m}^2/\text{year}$, which is about 23% more than the Legacy at $943 \text{ MJ/m}^2/\text{year}$. This large discrepancy is due to source-to-site conversion efficiencies for electricity generation.

Table 5 summarizes the total annual BOE estimated for downtown high-rise households (on the basis of both site and source energy), calculated as a sum of BOE_b and BOE_i . Appendix D provides detailed annual BOE data for each home in Commonwealth Plaza (C#) and the Legacy Building (L#) from April 2013 to March 2014. The average annual source OE for the downtown high-rise residential buildings ($N = 42$) was estimated to be $2520 \text{ MJ/m}^2/\text{year}$ (standard deviation = $615.2 \text{ MJ/m}^2/\text{year}$). On a per-household and per-person basis, the downtown high-rise residential buildings were estimated to consume 388 GJ/HH/year (standard deviation = 283.8 GJ/HH/year) and $226 \text{ GJ/person/year}$ (standard deviation = $152.4 \text{ GJ/person/year}$).

Table 5. Descriptive statistics of the estimated total annual operational energy of downtown high-rise homes ($N = 42$).

Summary Statistic	Site BOE $\text{MJ/m}^2/\text{y}$	Source BOE $\text{MJ/m}^2/\text{y}$	Site BOE GJ/HH/y	Source BOE GJ/HH/y	Site BOE GJ/person/y	Source BOE GJ/person/y
Commonwealth Plaza ($N = 20$)						
Minimum	1218.8	1756.5	66.6	113.3	28.7	44.0
Maximum	1440.2	2457.6	356.4	581.6	211.9	319.2
Mean	1289.9	1981.8	155.6	238.4	97.5	148.5
Std Dev	61.5	194.8	71.9	112.8	48.8	72.2
Legacy Building ($N = 22$)						
Minimum	1050.7	2445.0	106.0	255.7	53.0	127.9
Maximum	1577.3	4112.8	788.2	1,838.7	394.1	919.4
Mean	1228.6	3008.5	215.9	524.9	122.0	296.1
Std Dev	133.5	422.8	138.9	323.7	74.2	172.5
Downtown Tower Average ($N = 42$)						
Minimum	1050.7	1756.5	66.6	113.3	28.7	44.0
Maximum	1577.3	4112.8	788.2	1838.7	394.1	919.4
Mean	1257.8	2519.6	187.2	388.4	110.3	225.8
Std Dev	108.8	615.2	114.9	283.8	63.8	152.4

Figures 4 and 5 show the distributions of both source and site annual energy use for the Commonwealth Plaza ($N = 20$) and Legacy Building ($N = 22$). Compared to the older Commonwealth Plaza (built in 1956), the newer Legacy Building (built in 2010) is widely assumed to be more energy efficient based on its many energy-saving features such as a high-performance curtain wall and having

a connection to the city's district chilled water system [42,43]. However, the Legacy Building was estimated to consume 1229 MJ/m²/year (standard deviation = 133.5 MJ/m²/year) on a site BOE basis, on average, which is only slightly less than the average site energy use in the much older Commonwealth Plaza (1290 MJ/m²/year, standard deviation = 61.5 MJ/m²/year). This result might indicate that the BOE saved by the energy saving features in the Legacy Building is offset by the energy consumed by its greater amenities (*i.e.*, indoor pool, whirlpool spa, fitness center, *etc.*). Moreover, when comparing the source BOE use, the Commonwealth Plaza is predicted to consume 1982 MJ/m²/year (standard deviation = 194.8 MJ/m²/year), on average, which is approximately 34% less than the newer Legacy Building at 3001 MJ/m²/year (standard deviation = 422.8 MJ/m²/year). This heightened discrepancy is clearly due to the use of electric heating in the Legacy instead of natural gas heating in the Commonwealth Plaza.

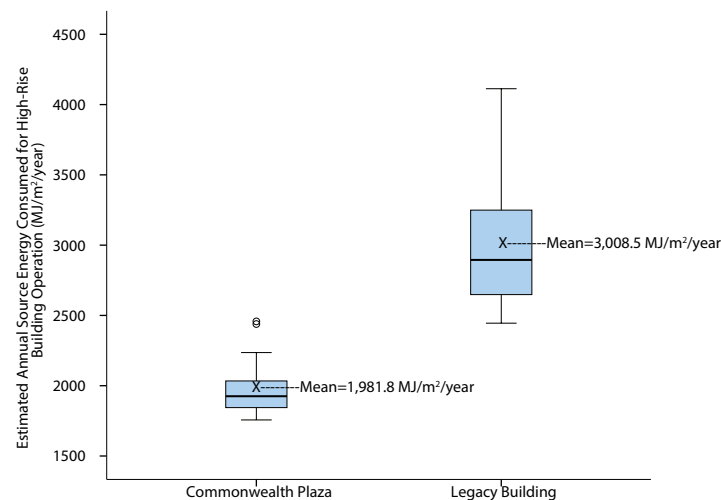


Figure 4. Annual source energy consumed for building operation of the high-rise Commonwealth Plaza and Legacy buildings (MJ/m²/year).

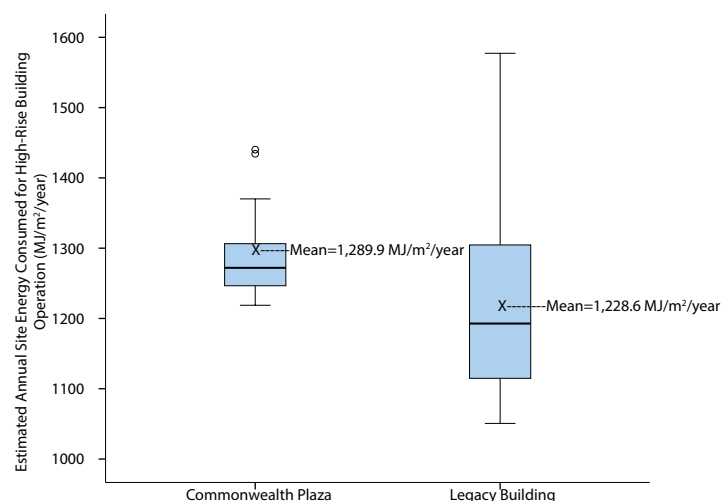


Figure 5. Annual site energy consumed for building operation of the high-rise Commonwealth Plaza and Legacy buildings (MJ/m²/year).

3.1.3. Building Operational Energy (BOE) Comparison of High-Rise *vs.* Low-Rise Residential Buildings

As shown in Tables 4 and 5, the downtown residential towers are predicted to consume 2520 MJ/m²/year source BOE, on average, which is approximately 45% greater than the suburban

low-rise residential buildings (with an average of 1738 MJ/m²/year). However, these differences are smaller when averaged on a per-household basis because the Oak Park residences are much larger than the high-rise units (Table 2). The downtown residential towers are estimated to consume 388 GJ/HH/year in source BOE, which is actually slightly less than the suburban low-rise residences at 393 GJ/HH/year. However, on a per-person basis, the high-rise units are estimated to consume 226 GJ/person/year in source OE, which is ~87% greater than the suburban low-rise residential buildings at 121 GJ/person/year.

Figures 6–8 graphically compare the distribution of BOE in downtown high-rise ($N = 42$) and suburban low-rise ($N = 64$) homes, presented on a floor area, per-household, and per-person basis, respectively. Full data for the detailed annual BOE by each home are provided in Appendixs A and C. Differences in annual source BOE between the downtown high-rise and the suburban low-rise home groups were statistically significant on both a floor area and a per-person basis ($p < 0.0001$ according to nonparametric Mann–Whitney U tests) (see Table 6). However, differences in annual source BOE on a per-household basis were not statistically significant ($p = 0.552$).

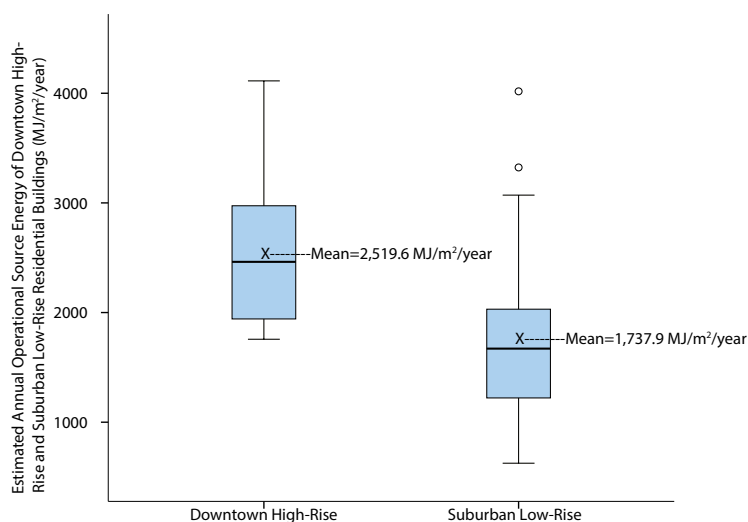


Figure 6. Annual source operational energy use of downtown high-rise residences in Chicago, IL and suburban low-rise residences in Oak Park, IL on a floor area basis (MJ/m²/year).

These data demonstrate that households in this sample of downtown high-rise residential buildings in Chicago, IL actually consume more annual building OE (on a source energy basis) than low-rise residences in suburban Oak Park, IL, both on a floor area and per-person basis. However, the annual building source OE use is comparable on a per-household basis (*i.e.*, Oak Park low-rise residences consume only ~1.2% more source BOE per household than the downtown high-rise residences, on average). It should be noted that these findings are limited to the specific building types and household demographics surveyed here. For example, super-tall and luxury residential buildings such as the Legacy Building likely require more BOE for elevators, pumps, fans, on-site management services, and other amenities than a conventional high-rise building. Also, the fact that fewer people live in a relatively larger size unit in downtown high-rise cases resulted in greater BOE use on a per-person basis (*i.e.*, the average GFA per person in the Legacy Building is 1.4 times larger than in Oak Park, as shown in Table 2). However, a larger household (HH) size in the Oak Park homes resulted in less OE consumption on a per-person basis (*i.e.*, the average HH size in Oak Park is 3.3 in this study, but only 2.4 across the entire Oak Park neighborhood [40]). In addition, 37.8% of the household members in the Oak Park residences in this study were children under 18 (compared to only 5.5% in the downtown residences), who might not require as much BOE as a typical adult does. These factors are explored in more detail in the next section. Given these limitations, annual OE use

on both a per-household and a per-person basis were chosen for the final BOE comparisons after taking into account the energy use associated not only with buildings but also with transportation and supporting transportation infrastructure.

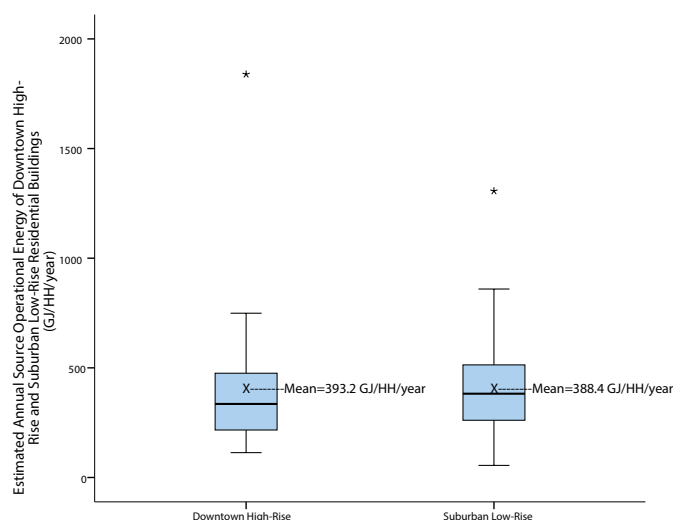


Figure 7. Annual source operational energy use of downtown high-rise residences in Chicago, IL and suburban low-rise residences in Oak Park, IL on a per-household basis (GJ/HH/year).

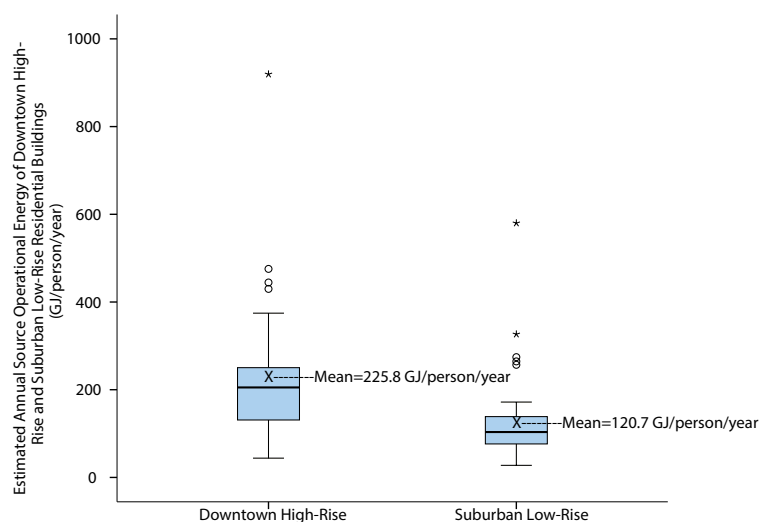


Figure 8. Annual source operational energy use of downtown high-rise residences in Chicago, IL and suburban low-rise residences in Oak Park, IL on a per-person basis (GJ/person/year).

Table 6. Mann–Whitney U test statistics for the downtown high-rise and suburban low-rise homes.

Test Statistics	Source BOE MJ/m ² /y	Source BOE GJ/HH/y	Source BOE GJ/person/y
Mann–Whitney U	432	1252	576
Wilcoxon W	2512	2155	2656
Z	−5.891	−0.594	−4.961
Asymp. Sig. (2-tailed)	0.000	0.552	0.000

3.1.4. Building Operational Energy (BOE) Correlation Analysis

It is important to analyze correlations between BOE and several characteristics of the households and residential buildings surveyed herein. Four variables were evaluated for their influence on the variability in BOE, including the age of residential buildings (ARB, in years), annual HH income, HH size, and GFA/HH (in m²). Linear correlations were first conducted between BOE and each

of these variables, treating high-rise and low-rise scenarios separately. Annual HH income was grouped into 12 different income ranges in the survey, and thus was coded in the correlation analysis as 1 for “Under \$50,000”, 2 for “\$50,000–\$59,999”, 3 for “\$60,000–\$69,999”, 4 for “\$70,000–\$79,999”, 5 for “\$80,000–\$89,999”, 6 for “\$90,000–\$99,999”, 7 for “\$100,000–\$124,999”, 8 for “\$125,000–\$149,999”, 9 for “\$150,000–\$199,999”, 10 for “\$200,000–\$249,999”, 11 for “\$250,000–\$299,999”, and 12 for “\$300,000 and over.” ARB was excluded in the downtown high-rise scenarios because there were only two different ages of residential towers (*i.e.*, the ages of Legacy Building and Commonwealth Plaza were 7 and 60, respectively).

BOE per HH was not significantly correlated with annual HH income ($R^2 = 0.10$) or HH size ($R^2 = 0.02$) in the downtown high-rise cases ($N = 42$), but was strongly correlated with GFA/HH ($R^2 = 0.90$). Similarly, BOE per person was not significantly correlated with annual HH income ($R^2 = 0.03$) or HH size ($R^2 = 0.10$) in the downtown high-rise cases ($N = 42$), but was correlated with GFA/HH ($R^2 = 0.66$). Comparably, BOE per HH was not significantly correlated with ARB ($R^2 = 0.15$) or HH size ($R^2 = 0.13$) in the suburban low-rise cases ($N = 64$), and was only weakly correlated with annual HH income ($R^2 = 0.30$). BOE per HH was moderately correlated with GFA/HH ($R^2 = 0.53$) in the low-rise cases. Finally, BOE per person was not significantly correlated with ARB ($R^2 = 0.10$), annual HH income ($R^2 = 0.01$), HH size ($R^2 = 0.15$), or GFA/HH ($R^2 = 0.26$) in the suburban low-rise cases ($N = 64$). Further, annual HH income was similar across the two home types; the median income bracket was “\$150,000–\$199,999” in both locations ($p = 0.80$ according to nonparametric Mann-Whitney U tests). These correlations clearly demonstrate that the most significant predictor of variability in BOE in both high-rise and low-rise cases is the size of the units or homes (*i.e.*, GFA/HH). Annual HH income, HH size, and ARB only minimally impacted the BOE results. Therefore, it is not necessary to correct for any of these factors in subsequent analyses.

3.2. Transportation Operational Energy (TOE)

3.2.1. Travel Behavior Analysis

A comprehensive travel survey was included in the online survey to collect data on the type and number of automobiles owned and operated by each household, as well as their typical weekly travel behavior via all modes of transport for various destinations, including work, school, shopping, restaurant/entertainment, family/friends, and “other” (for the respondent to specify if applicable). These values were then extrapolated for a one-year period. The modes of travel include walking, bicycling, automobile, bus, local CTA train (*i.e.*, the City of Chicago’s combination of elevated rail and underground subway mass transit system), regional Metra train (similar to Amtrak), and others (if applicable). Table 7 summarizes the average annual distances traveled by all modes of transport to all destinations for both downtown and suburban homes, presented on both s per-household and s per-person basis.

Automobile travel was found to be the most widely used mode of transport in both study locations, and interestingly, it shared more than half of the total annual distance traveled by residents of both urban (64.7%) and suburban (57.1%) living scenarios. Regional Metra train travel was the second most widely used mode of transport for suburban low-rise residents (27.8% share), but was the least widely used mode of transport for downtown high-rise residents (only 2.1% share). For the other public modes of transport, downtown high-rise residents relied on CTA trains slightly more than buses (CTA train shares were 7.1% *vs.* bus shares of 6.8%), while suburban low-rise residents shared a similar usage rate of CTA trains (7.7%) but had a very small usage rate of buses (1.3%) [44].

Table 7. Average annual distances traveled by all the modes of transport, per household and per person, to all the destinations in the downtown high-rise and suburban low-rise scenarios.

Mode of Transport	Downtown High-Rise			Suburban Low-Rise		
	km/HH/y	km/person/y	Percent of Total	km/HH/y	km/person/y	Percent of Total
Walking	2293	1206	15.5%	1914	579	5.3%
Bicycle	416	219	2.8%	253	77	0.7%
Automobile	9595	2050	64.7%	20,645	6256	57.1%
Bus	1010	531	6.8%	486	147	1.3%
CTA train	1059	557	7.1%	2786	843	7.7%
Metra train	307	162	2.1%	10,070	3051	27.8%
Other	149	78	1.0%	43	13	0.1%
Total	14,829	7803	100%	36,197	10,966	100%

3.2.2. Transportation Operational Energy (TOE)

Table 8 shows the average annual source OE estimated for all modes of transport in both downtown and suburban locations. Automobile transport was the single largest transport use in both locations, accounting for over 90% of transportation OE in both cases. It was estimated to be 94.3 GJ per household per year in the low-rise Oak Park cases, which was approximately 2.8 times greater than in the Chicago downtown high-rises (33.3 GJ/HH/y). On a per-person basis, the average annual source OE for automobile transport in Oak Park was calculated to be 28.6 GJ/person/y, which was approximately 1.6 times greater than in the Chicago downtown high-rises (18.4 GJ/person/y). Transportation OE for regional Metra train travel was higher for the suburban low-rise residences (on both a per-household and a per-person basis), and was similar for local CTA train transit in both locations, although the total energy use of these modes was quite low overall. The average annual source OE for all modes of transportation was estimated to be 103.5 GJ/HH/year on a per-household basis in Oak Park, which was approximately 2.7 times greater than the Chicago downtown high-rise residences at 37.9 GJ/HH/year. Similarly, the average annual source OE for all modes of transportation was estimated to be 31.4 GJ/person/year in Oak Park, which was approximately 1.6 times greater than in the downtown Chicago high-rise residences at 19.9 GJ/person/year. Clearly, residents in the suburban low-rise cases studies herein used much more operational TOE than residents in the downtown high-rise cases, primarily because of greater per-person and per-household automobile travel, which is consistent with most previous literature [3,7,12].

Table 8. Average annual operational energy of automobile, bus, CTA train and Metra train transport across both urban high-rise and suburban low-rise scenarios on both a per-household and a per-person basis.

Mode of Transport	Downtown High-Rise			Suburban Low-Rise		
	GJ/HH/y	GJ/person/y	Percent	GJ/HH/y	GJ/person/y	Percent
Auto	34.9	18.4	92.3%	94.3	28.6	91.1%
Bus	2.0	1.0	5.4%	1.0	0.3	0.9%
CTA Train (local)	0.7	0.4	1.8%	1.8	0.6	1.8%
Metra Train (regional)	0.2	0.1	0.5%	6.4	2.0	6.2%
Total	37.9	19.9	100.0%	103.5	31.4	100.0%

Table 9 summarizes the average annual source OE requirements of the supporting transportation infrastructure (*i.e.*, for automobile, bus, local CTA train, and regional Metra train travel) estimated for downtown high-rise and suburban low-rise residences on both a per-household and a per-person basis. Data are taken directly from tLCAdB.

Table 9. Estimates of operational energy of the supporting infrastructure for automobile, bus, CTA train, and Metra train travel from tLCadb.

Mode of Transport	Downtown High-Rise			Suburban Low-Rise		
	GJ/HH/y	GJ/person/y	Percent	GJ/HH/y	GJ/person/y	Percent
Auto	0.24	0.13	72.7%	0.52	0.16	24.0%
Bus	0.00	0.00	0.0%	0.00	0.00	0.0%
CTA Train	0.04	0.02	12.1%	0.10	0.03	4.6%
Metra Train	0.05	0.02	15.2%	1.55	0.47	71.4%
Total	0.33	0.17	100%	2.17	0.66	100%

The average annual OE for the transportation infrastructure in Oak Park was estimated to be 2.2 GJ/HH/year on a per-household basis, which was approximately 6.6 times greater than in the Chicago downtown high-rise residences (~0.33 GJ/HH/year). Similarly, on a per-person basis, average annual OE for transportation infrastructure was estimated to be 0.66 GJ/person/year in Oak Park, which was approximately 3.9 times greater than in the downtown Chicago high-rise residences at 0.17 GJ/person/year. In the urban high-rise homes, infrastructure OE for automobile transport was the largest contributor to the total transportation infrastructure OE (share of 72.7%), followed by infrastructure OE for Metra train (15.2%) and CTA train (12.1%) travel. In suburban low-rise homes, infrastructure OE for Metra train was the largest contributor to the total transportation infrastructure OE (share 71.4%), followed by infrastructure OE for automobile travel (at 24%).

3.3. Comparison of Total Operational Energy for Buildings and Transportation

Finally, the OE data for building, transportation, and supporting transportation infrastructure were combined to make a direct comparison of the total annual source energy requirements associated with typical residential life in both the downtown high-rise and suburban low-rise residences. Data are again presented on a per-household and a per-person basis (e.g., GJ/HH/year and GJ/person/year). As Table 10 and Figure 9 show, the average household in the downtown Chicago high-rise residences was estimated to account for approximately 427 GJ/HH/year in total source OE use, while those in Oak Park low-rise residences were estimated to account for approximately 499 GJ/HH/year, on average. Thus, the average source energy footprint of downtown high-rise residences was approximately 14% lower than suburban low-rise residences on a per-household basis. However, this direction of this difference was opposite when compared on a per-person basis: the average source OE use of those living in downtown Chicago high-rises was estimated to be approximately 246 GJ/person/year compared to only 153 GJ/person/year in Oak Park low-rise residences. Therefore, on a per-person basis, the average source energy footprint was approximately 61% higher for those living in the downtown high-rise residential buildings.

Table 10. Annual source operational energy use associated with residential life (including buildings, transportation, and transportation infrastructure) in the Chicago downtown high-rise and Oak Park low-rise residences.

OE Categories	Downtown High-Rise			Suburban Low-Rise		
	GJ/HH/y	GJ/person/y	Percent	GJ/HH/y	GJ/person/y	Percent
Building	388.4	225.8	91.0%	393.2	120.7	78.8%
Transportation	37.9	19.9	8.9%	103.5	31.4	20.8%
Transportation Infrastructure	0.3	0.2	0.1%	2.2	0.7	0.4%
Total	426.6	245.9	100%	498.9	152.8	100%

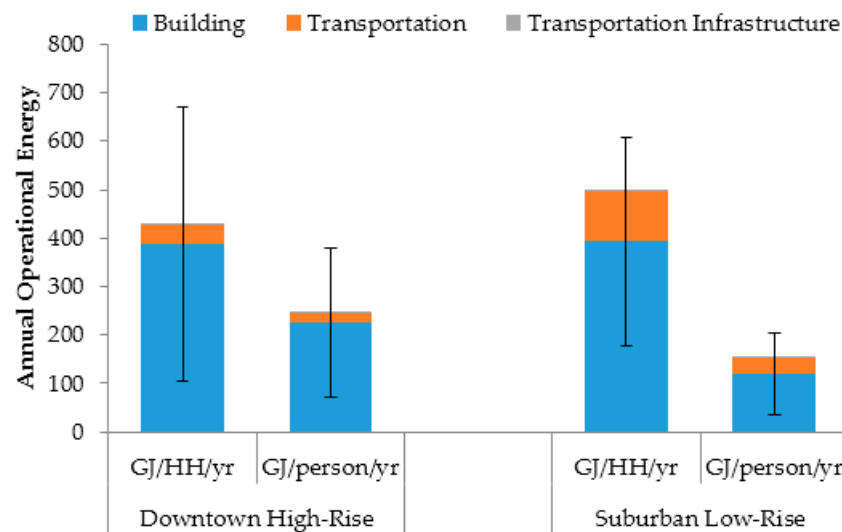


Figure 9. Average (standard deviation) operational source energy use associated with residential life (including buildings, transportation, and transportation infrastructure) in the Chicago downtown high-rise and Oak Park low-rise residences.

4. Discussion

4.1. Comparison to Previous Studies

The findings herein suggest that, when accounting for operational energy (OE) use by buildings, transportation, and transportation infrastructure across these two types of residential case studies, downtown high-rise living was estimated to account for approximately 14% less source OE use than suburban low-rise living on a per-household basis, on average, but approximately 61% more than suburban low-rise living on a per-person basis. This result is in conflict with some early studies such as Norman *et al.* [3], Perkins *et al.* [7], and Stephan *et al.* [10], in which OE for urban high density living was found to be 55%, 24%, and 27% lower than in suburban low density living on a per-person basis, respectively. However, these results are generally in line with other studies such as Fuller *et al.* and Du *et al.* [11,12]. Fuller *et al.* [11] found that city-center living consumed approximately 33% more than inner-suburban low-density living. Similarly, Du *et al.* [12] found that downtown high-rise living (using only public data sources and data from the existing literature) consumed approximately 34% more than suburban low-rise living. Table 11 summarizes the OE results in these previous studies in more detail.

Table 11. Annual operational energy comparison across previous studies.

Previous Studies	Location	Urban Pattern	Building Type	HH Size	Energy Input	GFA/Person (m ²)	BOE		TOE		Total OE	
							GJ/HH	GJ/person	GJ/HH	GJ/person	GJ/HH	GJ/person
Urban high-density scenarios												
Norman <i>et al.</i> (2006) [3]	Toronto, Canada	City center	15-story high-rise	1.8	Unknown	42.8	49.5	27.5	14.2	7.9	63.7	35.4
Perkins <i>et al.</i> (2009) [7]	Adelaide Australia	City center	6–8-story mid-rise	1.6	Site	17.5	32	20	13	8	45	28
Fuller <i>et al.</i> (2011) [11] ¹	Melbourne, Australia	City center	20-story high-rise	2.1	Source	47.6	37.8	18	4.2	2	42	20
Stephan <i>et al.</i> (2013) [10] ²	Brussels, Belgium	City center	10-story high-rise	2	Source	40	50	25	28.8	14.4	78.8	39.4
Du <i>et al.</i> (2015) [12]	Chicago, USA	City center	10-story high-rise	1.6	Source	66	180.6	112.9	24.8	15.5	205.4	128.4
This study	Chicago, USA	City center	27–86-story high-rise	1.9	Source	77.4	388.4	225.8	38.2	20.1	426.6	245.9
Suburban low-density scenarios												
Norman <i>et al.</i> (2006) [3]	Toronto, Canada	Outer suburb	Single-family	3	Unknown	80.5	149.4	49.8	86.4	28.8	235.8	78.6
Perkins <i>et al.</i> (2009) [7]	Adelaide Australia	Inner suburb	2-story terrace	2	Site	113.5	27	14	46	23	73	37
Perkins <i>et al.</i> (2009) [7]	Adelaide Australia	Outer suburb	Single-family	2.5	Site	204	36	13	132	48	168	61
Fuller <i>et al.</i> (2011) [11] ¹	Melbourne, Australia	Inner suburb	Mid-rise	1.6	Source	40	14.4	9	9.6	6	24	15
Fuller <i>et al.</i> (2011) [11] ¹	Melbourne, Australia	Outer suburb	Single-family	2.5	Source	95.2	46.25	18.5	102.5	41	148.8	59.5
Stephan <i>et al.</i> (2013) [10] ²	Brussels, Belgium	Outer suburb	Single-family	4	Source	82.5	118.1	29.5	98	24.5	216.1	54
Du <i>et al.</i> (2015) [12]	Chicago, USA	Outer suburb	Single-family	3.2	Source	66	242.9	75.9	64.6	20.2	307.5	96.1
This study	Chicago, USA	Inner suburb	Single-family	3.3	Source	68.6	393.2	120.7	105.7	32.1	498.9	152.8

Notes: ¹ Transportation in the studies by Fuller *et al.* [11] only considered the travel requirements for work; ² The TOE value listed in Stephan *et al.*'s study [10] in this table was the total transportation energy including both OE and EE. Due to limited information in Stephan *et al.*'s paper [10], the total transportation energy cannot be broken down into OE and EE specifically.

BOE was estimated to be the single largest contributor of the total OE in both the downtown high-rise and suburban low-rise cases. BOE accounted for approximately 91% of the total OE in the downtown high-rise cases, and approximately 79% of the total OE in the suburban low-rise cases. Specifically, the average BOE in downtown high-rise cases was found to be 2.6 GJ/m²/year, 388.4 GJ/HH/year, and 225.8 GJ/person/year. The average BOE in downtown high-rise cases was found to be 1.7 GJ/m²/year, 393.2 GJ/HH/year, and 120.7 GJ/person/year (see Tables 4 and 5). Interestingly, BOE, which has been widely confirmed as one of the largest contributors of the total OE associated with residential life, did not account for as large of a contribution in the studies by Norman *et al.*, Perkins *et al.* and Stephan *et al.* [3,7,10], largely due to higher BOE estimates in this study. For example, the ratio of annual BOE to total OE on a per-person basis was 78% in urban cases and 63% in suburban cases in Norman *et al.* [3], 71% in urban cases and 38% in inner suburban cases in Perkins *et al.* and 63% in urban cases and 55% in inner suburban cases in Stephan *et al.* [10]. Specifically, Perkins *et al.* [7] used site energy instead of source energy, which could significantly lower their BOE value as well as the share of the total OE since electricity has a high primary energy conversion factor (typically ~3). Further, our estimates of BOE as a fraction of total OE are similar to those reported in Fuller *et al.* and Du *et al.* [11,12].

Reasons for these discrepancies likely include: (i) this study used empirical data that capture actual variations in human behaviors and lifestyles in buildings rather than modeled estimates of population averages; (ii) this study used data from existing buildings rather than new, energy-efficient buildings (which others have focused on); and (iii) BOE varies greatly with climate zone, envelope materials and thermal properties, vintage, equipment, occupancy, and many other parameters that may have differed in our sample of buildings. For example, Norman *et al.* and Fuller *et al.* [11] used country-wide average data for the specific cases in Toronto and Melbourne. Stephan *et al.* used relatively simple heat transfer models and regional averages for the determination of BOE. Du *et al.* [12] used modeled energy use of prototypical code-compliant residential buildings of recent construction in Chicago.

Discrepancies may also arise due to differences in the downtown housing cases chosen in this study. Specifically, the scale and function of the downtown housing cases in other studies were relatively small and simple, respectively. For example, the downtown housing case used in Norman *et al.* [3] was a single 15-story condo building in Toronto; Perkins *et al.* [7] used 6–8-story apartment buildings as downtown housing cases in Adelaide; Stephan *et al.* [10] used a 10-story apartment building in the city of Brussels; and Du *et al.* [12] used a prototypical code-compliant 10-story apartment building in Chicago. Thus, none of the prior cases are directly comparable to either the 27-story Commonwealth Plaza or the 73-story Legacy Building, both of which also have larger requirements for pumps, fans, lighting, *etc.*, and also have a large number of common amenities. This study reveals a more realistic picture of operational energy consumption of tall residential buildings.

Based on the data collected on the residents' actual travel behaviors (in terms of travel distances and modes), TOE in this study was found to be greater than the values in all other previous urban high-density studies, and also greater than most other previous suburban low-rise studies. Specifically, automobile OE was found to be the single largest transport use, accounting for over 90% of transportation OE in both locations. The high parking space availability and car ownership in the four downtown residential towers in this study might have encouraged residents to own and drive automobiles (see Table 3). The average number of available parking spaces per unit in the downtown residential towers was 1.4, and the average car ownership per person in the downtown high-rise survey takers was 0.6, which was actually higher than the Oak Park low-rise survey takers. Differences may also be attributable in part to methodological differences between this study and others. For example, none of the other studies listed above conducted a detailed survey to investigate owned vehicle information (*i.e.*, vehicle type, year, and distances traveled for various uses), or actual weekly travel behavior based on multiple major destinations (work, school, shopping, restaurant/entertainment,

family/friends). The collected data on travel behavior, including frequency, travel time, and modes of travel (*i.e.*, walking, bicycling, automobile, bus, local short-distance train, and long-distance commuter train) again allow for a more realistic assessment of TOE in these case study households.

4.2. Research Limitations

There are also a number of limitations to this study that should be noted. The four residential towers in this study, especially the Aqua Tower and the Legacy Building, are much taller than an average high-rise building. Specifically, both the Aqua Tower (262-m tall, 86-story) and the Legacy Building (250-m tall, 73-story) can nearly be categorized as “super-tall” buildings, which would likely consume more operational energy for elevators, water system, pumps, and fans than typical medium- or high-rise buildings. Moreover, both the Aqua Tower and the Legacy Building are luxury residential buildings that offer numerous high-quality on-site management service and amenities, which most certainly require more operational energy than the average residential tower. Additionally, these towers may be unique in that they resulted in a larger GFA/person than the low-rise cases (*e.g.*, 77 m² per person for Chicago high-rise cases compared to 69 m² per person for Oak Park low-rise cases), which further resulted in greater operational energy consumption on a per-person basis in this study. For these combined reasons, the urban high-rise cases may not realistically represent typical high-rise residential buildings in downtown Chicago, although there are certainly many others similar to them.

For these reasons and others, this research could be extended in several ways. First, the embodied energy of these case study buildings and transportation infrastructure (*i.e.*, roads, parking, bus/train stations, train tracks, *etc.*) was not quantified, which limited the analysis to operational energy rather than total life-cycle energy use. Some studies show that EE could be as important as OE from a life-cycle perspective [10,11,45]. Future work should also investigate these same measures across more building types, spanning from low-rise residential to super-tall high-rise structures, and across more residential locations. Moreover, energy consumption that is influenced by direct and indirect impacts resulting from interactions between individual buildings and surrounding urban settings could be considered and analyzed in future work [46]. Further, future research should also quantify the energy implications of more components of urban and suburban infrastructure, such as water, sewage, communications, and power supply and distribution. Lastly, other life-cycle environmental impact categories such as greenhouse gas (GHG) emissions and global warming potential (GWP) could also be quantified and compared between the urban high-rise and suburban low-rise lifestyles.

5. Conclusions

Overall, the empirical evidence in this paper provides a reasonably complete understanding of the operational energy use for buildings, transportation, and transportation infrastructure for both downtown high-rise and suburban low-rise living based on actual case studies in and around Chicago, IL. Data collected from over 500 households suggests that downtown high-rise living in this sample of urban residences in Chicago, IL accounts for approximately 427 GJ of source energy per household per year, on average, which was 14% lower than the average for suburban low-rise living in the Oak Park, IL homes. However, on a per-person basis, downtown high-rise living accounted for approximately 246 GJ per person per year, which was approximately 61% higher than suburban low-rise living. Results from this work can be used to better inform city planning on ways to prioritize energy-saving strategies in residential construction.

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Abbreviations

The following abbreviations are used in this manuscript:

BOE	building operational energy
BOE _b	building operational energy paid by the building management
BOE _c	building operational energy via chilled water
BOE _e	building operational energy via electric
BOE _g	building operational energy via gas
BOE _i	building operational energy paid by the individual units
CDD	cooling degree days
CMAP	Chicago Metropolitan Agency for Planning
COP	coefficient of performance
CTA	Chicago Transit Authority
D	duplex
DOE	Department of Energy
EE	embodied energy
GFA	gross floor area
GHG	greenhouse gas
GJ	gigajoule
HDD	heating degree days
HH	household
LR	low-rise
LCA	life-cycle assessment
MJ	megajoule
MPG	miles per gallon
OE	operational energy
PMT	passenger miles traveled
SD	standard deviation
SF	single family
TH	townhouse
TOE	transportation operational energy
VMT	vehicle miles traveled
# of Pred. Mo.	the number of months predicted

Appendix A. Vehicle Type Investigation of the Chicago Downtown and Oak Park Households

Vehicle Type	Aqua		Commonwealth		Legacy		Downtown High-Rise		Suburban Low-Rise	
							4 Towers (Avg.)		Oak Park	
	CT	%	CT	%	CT	%	CT	%	CT	%
Sedan	23	29.5%	22	46.8%	25	29.1%	70	33.2%	84	25.0%
SUV	25	32.1%	8	17.1%	28	32.6%	61	28.9%	79	23.5%
Van/minivan	2	2.6%	0	0.0%	5	5.8%	7	3.3%	43	12.8%
Hatchback	7	1.3%	4	8.5%	3	3.5%	8	3.8%	22	6.5%
Wagon	0	0.0%	1	2.1%	3	3.5%	4	1.9%	20	5.9%
Pickup truck	0	0.0%	0	0.0%	0	0.0%	0	0.0%	17	5.0%
Crossover	0	0.0%	1	2.1%	4	4.7%	5	2.4%	16	4.8%
Convertible	8	10.3%	3	6.4%	3	3.5%	14	6.6%	15	4.5%
Hybrid	4	5.1%	7	14.9%	5	5.8%	16	7.6%	13	3.9%
Coupe	7	9.0%	0	0.0%	1	1.2%	8	3.8%	12	3.6%
Luxury	4	5.1%	0	0.0%	8	9.3%	12	5.7%	5	1.5%
Electric	1	1.3%	1	2.1%	1	1.2%	3	1.4%	2	0.6%
Motorcycle	2	2.6%	0	0.0%	0	0.0%	2	0.9%	2	0.6%
Other	1	1.3%	0	0.0%	0	0.0%	1	0.5%	6	1.8%
Total	78	100%	47	100%	86	100%	221	100%	336	100%

Appendix B. Estimated Annual Operational Energy Consumption of the Oak Park Low-Rise Residential Buildings (N = 64)

H#	Bldg Type	GFA (m ²)	HH Size	BOE _e (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _e)	BOE _g (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _g)	Total BOE (MJ/m ² /year)	Total BOE (GJ/HH/year)	Total BOE (GJ/person/year)
1	SF	164.4	3	239.8	2	0.259	929.1	2	0.985	1168.9	192.2	64.1
2	SF	111.5	3	874.4	1	0.528	1818.3	0	N/A	2692.7	300.2	100.1
3	SF	92.9	3	322.6	2	0.029	699.7	2	0.967	1022.2	95.0	31.7
4	SF	139.4	3	929.7	2	0.284	938	2	0.995	1867.7	260.3	86.8
5	D	457	1	88.8	1	0.05	1180.1	3	0.979	1268.9	579.9	579.9
6	SF	130.1	3	310	0	N/A	1319.6	1	0.931	1629.6	211.9	70.6
7	SF	148.6	4	1137	1	0.001	2186.4	5	0.944	3323.4	494.0	123.5
8	SF	111.5	1	461.1	0	N/A	445.8	2	0.489	906.9	101.1	101.1
9	SF	140.2	5	1368.6	0	N/A	733.2	1	0.972	2101.9	294.7	58.9
10	SF	418.1	5	487.1	2	0.108	1171.4	2	0.7	1658.5	693.3	138.7

H#	Bldg Type	GFA (m ²)	HH Size	BOE _e (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _e)	BOE _g (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _g)	Total BOE (MJ/m ² /year)	Total BOE (GJ/HH/year)	Total BOE (GJ/person/year)
11	SF	418.1	5	618.6	1	0.573	708.6	3	0.963	1327.2	554.8	111
12	SF	334.4	4	416.5	2	0.533	924.3	2	0.756	1340.8	448.4	112.1
13	SF	223	6	799.7	1	0.08	1255.5	1	0.729	2055.3	458.2	76.4
14	SF	223	4	532.5	1	0.117	1206.7	1	0.958	1739.2	387.8	96.9
15	TH	172.8	3	470.8	1	0.251	477.4	2	0.958	948.2	163.8	54.6
16	TH	195.1	5	1505.5	1	0.72	0	0	N/A	1505.5	293.7	58.7
17	SF	325.2	3	360.8	2	0.082	796.7	2	0.768	1157.5	376.4	125.5
18	TH	232.3	1	188	2	0.038	951.3	1	0.698	1139.3	264.6	264.6
19	SF	325.2	4	1760.2	1	0.319	2257.3	2	0.141	4017.5	1306.3	326.6
20	SF	234.9	3	506.1	1	0.057	1234.1	2	0.898	1740.2	408.7	136.2
21	LR	116.1	2	657.4	1	0.611	996.2	1	0.968	1653.6	192.0	96
22	SF	148.6	3	478.1	1	0.005	1309	1	0.98	1787.2	265.6	88.5
23	SF	557.4	5	624	1	0.231	918.1	2	0.712	1542.1	859.5	171.9
24	SF	260.1	5	1316.4	0	N/A	1272.9	1	0.969	2589.2	673.5	134.7
25	SF	176.5	3	958.6	1	0.191	1944.5	2	0.985	2903.2	512.4	170.8
26	TH	185.8	2	761.3	1	0.128	942.6	2	0.799	1703.8	316.6	158.3
27	SF	353	6	680.3	1	0.018	1320.2	1	0.75	2000.6	706.2	117.7
28	SF	130.1	4	875.4	1	0.03	1130.2	2	0.908	2005.7	260.9	65.2
29	SF	325.2	5	471.3	0	N/A	750	1	0.978	1221.3	397.1	79.4
30	SF	325.2	3	691.9	0	N/A	1839.1	1	0.994	2531	822.9	274.3
31	SF	269.4	4	297.7	1	0.116	897.7	1	0.977	1195.4	322.1	80.5
32	TH	223	3	307.4	1	0.415	546.7	1	0.962	854.1	190.4	63.5
33	SF	232.3	5	703.5	0	N/A	1010	2	0.965	1713.6	398.0	79.6
34	SF	278.7	4	614.8	1	0.004	1415.8	1	0.966	2030.6	565.9	141.5
35	SF	390.2	4	444	1	0.065	726.7	1	0.796	1170.6	456.8	114.2
36	LR	88.3	2	626	0	N/A	0	0	N/A	626	55.2	27.6
37	SF	260.1	4	654.7	1	0.226	917.2	1	0.74	1571.9	408.9	102.2
38	SF	157.9	2	636	0	N/A	849.8	0	N/A	1485.8	234.7	117.3
39	SF	167.2	2	1553.6	1	0.025	1517.4	1	0.98	3071	513.5	256.8
40	SF	195.1	5	667.8	1	0.132	1017	3	0.618	1684.8	328.7	65.7
41	SF	185.8	2	409.2	0	N/A	1274.4	1	0.989	1683.6	312.8	156.4
42	SF	250.8	6	1567	0	N/A	941	2	0.976	2507.9	629.1	104.8
43	SF	176.5	4	939.9	1	0.034	1232.6	1	0.968	2172.5	383.5	95.9
44	SF	278.7	5	908.9	0	N/A	1005.1	2	0.986	1914	533.4	106.7
45	SF	157.3	4	305.5	3	0.528	947.8	3	0.874	1253.3	197.1	49.3
46	SF	171.9	4	430.8	0	N/A	1061.8	0	N/A	1492.6	256.5	64.1
47	SF	167.2	6	973.3	1	0.123	825.3	1	0.93	1798.6	300.8	50.1
48	SF	241.5	4	659.7	0	N/A	1532.9	1	0.968	2192.6	529.6	132.4
49	SF	371.6	2	407.3	0	N/A	1104.6	1	0.948	1511.9	561.8	280.9
50	SF	275.6	2	76.9	0	N/A	809.8	1	0.688	886.7	244.4	122.2

H#	Bldg Type	GFA (m ²)	HH Size	BOE _e (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _e)	BOE _g (MJ/m ² /year)	# of Pred. Mo. (BOE _e)	R ² (BOE _g)	Total BOE (MJ/m ² /year)	Total BOE (GJ/HH/year)	Total BOE (GJ/person/year)
51	SF	82.7	3	653.9	1	0.211	1810.5	1	0.81	2464.4	203.8	67.9
52	SF	260.1	4	418	0	N/A	1105.6	0	N/A	1523.6	396.3	99.1
53	SF	334.4	4	381.1	1	0.011	1320.7	0	N/A	1701.8	569.1	142.3
54	SF	255.5	4	352.7	0	N/A	828	1	0.926	1180.7	301.7	75.4
55	TH	102.2	4	500.7	4	0.842	891.1	4	0.359	1391.7	142.2	35.6
56	SF	152.4	2	578.3	1	0.162	1377.1	3	0.991	1955.4	297.9	149
57	SF	511	4	535.4	4	0.346	1028.5	4	0.824	1564	799.1	199.8
58	SF	241.5	5	721.4	1	0.277	1076.2	2	0.842	1797.5	434.2	86.8
59	SF	195.1	4	815.2	0	N/A	892	0	N/A	1707.2	333.1	83.3
60	SF	311.8	4	354.1	3	0.166	938.4	4	0.728	1292.4	402.9	100.7
61	SF	195.1	3	402.7	1	0.003	986.5	0	N/A	1389.3	271.0	90.3
62	SF	148.6	2	591.3	0	N/A	1354.8	0	N/A	1946.1	289.3	144.6
63	SF	92.9	2	1406.9	0	N/A	1213.1	1	0.697	2620	243.4	121.7
64	SF	125.8	4	513.1	2	0.289	813.5	1	0.917	1326.6	166.9	41.7

Appendix C. Estimated Annual Operational Energy Consumption Paid by the bUilding Management for the Chicago Downtown Residential Towers

Measure	Commonwealth	Legacy
GFA(m ²)	54396	70153
Site BOE _e (MJ/m ² /year)	149.9	585.5
Source BOE _e (MJ/m ² /year)	474.6	1854.2
# of Pred. Mo. (BOE _e)	1	0
R ² (BOE _e)	0.440	N/A
Site BOE _g (MJ/m ² /year)	1009.8	114.6
Source BOE _g (MJ/m ² /year)	1094.6	124.2
# of Pred. Mo. (BOE _g)	1	1
R ² (BOE _g)	0.986	0.950
Site BOE _c (MJ/m ² /year)	0	243.1
Source BOE _c (MJ/m ² /year)	0	126.2
# of Pred. Mo. (BOE _c)	0	0
R ² (BOE _c)	N/A	N/A
Total Site BOE _b (MJ/m ² /year)	1159.7	943.2
Total Source BOE _b (MJ/m ² /year)	1569.2	2104.6

Appendix D. Estimated Annual Total Operational Energy Consumption in the Chicago Downtown Residential Towers ($N = 42$)

H #	GFA (m ²)	HH Size	Site BOE _i (MJ/m ² /year)	Source BOE _i (MJ/m ² /year)	# of Pred. Mo. (BOE _i)	R ² (BOE _i)	Total Site BOE (MJ/m ² /year)	Total Source BOE (MJ/m ² /year)	Total Site BOE (GJ/HH/year)	Total Source BOE (GJ/HH/year)	Total Site BOE (GJ/person/year)	Total Source BOE (GJ/person/year)
C1	111.48	1	148.1	469.2	1	0.280	1307.8	2038.4	145.8	227.2	145.8	227.2
C2	157.93	4	87.6	277.5	1	0.630	1247.3	1846.7	197.0	291.7	49.2	72.9
C3	102.19	2	280.5	888.3	0	N/A	1440.2	2457.6	147.2	251.1	73.6	125.6
C4	134.705	2	106.9	338.4	1	0.328	1266.5	1907.6	170.6	257.0	85.3	128.5
C5	104.6983	2	163.0	516.2	0	N/A	1322.6	2085.4	138.5	218.3	69.2	109.2
C6	111.48	1	80.1	253.7	4	0.476	1239.8	1822.9	138.2	203.2	138.2	203.2
C7	69.675	1	122.2	387.1	1	0.189	1281.9	1956.3	89.3	136.3	89.3	136.3
C8	78.965	1	89.7	284.0	1	0.060	1249.3	1853.2	98.7	146.3	98.7	146.3
C9	107.4853	2	81.9	259.4	4	0.342	1241.6	1828.6	133.5	196.6	66.7	98.3
C10	106.835	1	98.1	310.8	2	0.189	1257.8	1880.0	134.4	200.8	134.4	200.8
C11	92.9	3	59.1	187.3	4	0.404	1218.8	1756.5	113.2	163.2	37.7	54.4
C12	102.19	2	145.4	460.4	2	0.393	1305.0	2029.6	133.4	207.4	66.7	103.7
C13	260.12	4	210.5	666.5	0	N/A	1370.1	2235.8	356.4	581.6	89.1	145.4
C14	167.22	1	107.2	339.6	2	0.378	1266.9	1908.9	211.9	319.2	211.9	319.2
C15	65.03	1	140.4	444.6	2	0.009	1300.0	2013.8	84.5	131.0	84.5	131.0
C16	111.48	1	117.6	372.4	3	0.013	1277.2	1941.6	142.4	216.5	142.4	216.5
C17	111.48	5	127.6	404.0	1	0.096	1287.2	1973.2	143.5	220.0	28.7	44.0
C18	46.45	2	274.6	869.6	3	0.027	1434.3	2438.9	66.6	113.3	33.3	56.6
C19	260.12	2	78.7	249.2	3	0.164	1238.3	1818.4	322.1	473.0	161.1	236.5
C20	116.125	1	86.1	272.8	0	N/A	1245.8	1842.0	144.7	213.9	144.7	213.9
L21	185.8	2	157.1	497.5	0	N/A	1100.3	2602.2	204.4	483.5	102.2	241.7
L22	90.6	2	226.9	718.7	4	0.936	1170.1	2823.3	106.0	255.7	53.0	127.9
L23	185.4	2	499.0	1580.4	0	N/A	1442.2	3685.0	267.4	683.3	133.7	341.7
L24	139.4	2	224.5	711.1	0	N/A	1167.7	2815.8	162.7	392.4	81.4	196.2
L25	102.2	2	382.5	1211.3	0	N/A	1325.7	3315.9	135.5	338.9	67.7	169.4
L26	226.3	2	340.3	1077.8	0	N/A	1283.5	3182.5	290.5	720.2	145.2	360.1
L27	745.2	2	114.5	362.7	0	N/A	1057.7	2467.3	788.2	1838.7	394.1	919.4
L28	185.8	3	419.7	1329.3	5	0.870	1362.9	3433.9	253.2	638.0	84.4	212.7
L29	167.2	1	147.2	466.3	1	0.723	1090.4	2571.0	182.3	429.9	182.3	429.9
L30	139.4	2	107.5	340.4	1	0.555	1050.7	2445.0	146.4	340.7	73.2	170.4
L31	185.8	1	143.5	454.4	2	0.607	1086.7	2559.1	201.9	475.5	201.9	475.5
L32	131.9	2	634.1	2008.1	1	0.843	1577.3	4112.8	208.1	542.5	104.0	271.3
L33	274.1	2	198.7	629.2	1	0.377	1141.8	2733.8	312.9	749.2	156.5	374.6
L34	185.8	2	186.2	589.6	0	N/A	1129.4	2694.3	209.8	500.6	104.9	250.3
L35	139.4	2	274.5	869.3	0	N/A	1217.7	2973.9	169.7	414.4	84.8	207.2
L36	92.9	2	228.2	722.7	2	0.640	1171.4	2827.3	108.8	262.7	54.4	131.3
L37	115.4	1	270.9	858.0	5	0.838	1214.1	2962.6	140.1	341.8	140.1	341.8
L38	139.4	2	290.0	918.3	1	0.737	1233.1	3022.9	171.8	421.2	85.9	210.6
L39	139.4	2	428.3	1356.4	2	0.758	1371.5	3461.1	191.1	482.3	95.6	241.1
L40	110.2	2	286.3	906.6	0	N/A	1229.4	3011.2	135.5	331.8	67.7	165.9
L41	139.4	1	342.6	1085.1	2	0.879	1285.8	3189.8	179.2	444.5	179.2	444.5
L42	139.4	2	376.3	1191.8	2	0.907	1319.5	3296.4	183.9	459.4	91.9	229.7

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