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Lifecycle Assessment of Beijing-Area Building Energy Use and Emissions: Summary Findings and Policy Applications

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Executive Summary

Buildings are at the locus of three trends driving China's increased energy use and emissions: urbanization, growing personal consumption, and surging heavy industrial production. Migration to cities and urban growth create demand for new building construction. Higher levels of per-capita income and consumption drive building operational energy use with demand for higher intensity lighting, thermal comfort, and plug-load power. Demand for new buildings, infrastructure, and electricity requires heavy industrial production. In order to highlight one key implication of China's ongoing urbanization, rising personal consumption, and booming heavy industrial sector, this study presents a lifecycle assessment (LCA) of the energy use and carbon emissions related to residential and commercial buildings. The purpose of the LCA model is to quantify the impact of a given building and identify policy linkages to mitigate energy demand and emissions growth related to China's new building construction.

Results of the residential and commercial building LCA model case study analysis show that building operations account for on average 80% of energy use and related emissions while building materials comprise almost 20%, with maintenance, construction, and demolition covering the remaining small portions of the total lifetime energy and emissions. Commercial buildings are more material and energy intensive than similarly-sized residential buildings. However, the wide range of energy and material intensity values among the ten Beijing-area buildings used in this study suggests that particular building's lifecycle energy use and emissions are highly situation specific.

The most useful potential policy application of the residential and commercial building LCA models is for comparative analysis beyond the Beijing case studies analyzed in this study. Scenario analysis can be used for benchmarking and identification of policy priorities. The LCA approach allows policy makers to add an embodied energy dimension to new codes uses to incentivize construction of zero energy buildings. Another policy application would be to use the models to help develop bottom-up emissions inventories, in which case it would be important to disaggregate energy use data for more accurate emissions modeling. The LBNL building LCA models developed in this study were limited by incomplete local input data; however they can serve as an indicator of potential policy-linked LCA model development. Depending on the type of LCA model policy integration, it may be useful to incorporate occupancy data for per-capita results. On the question of density and efficiency, it may also be useful to integrate an explicit spatial scaling mechanism for modeling neighborhood and city-level energy use and emissions.

Lifecycle Assessment of Beijing-area Building Energy Use and Emissions
Summary Findings and Policy Applications

Buildings are at the locus of three trends driving China's increased energy use and emissions: urbanization, growing personal consumption, and surging heavy industrial production. Migration to cities and urban growth create demand for new building construction. Higher levels of per-capita income and consumption drive building operational energy use with demand for higher intensity lighting, thermal comfort, and plug-load power. Demand for new buildings, infrastructure, and electricity requires heavy industrial production. In order to quantify the implications of China's ongoing urbanization, rising personal consumption, and booming heavy industrial sector, this study presents a lifecycle assessment (LCA) of the energy use and carbon emissions related to residential and commercial buildings. The purpose of the LCA model is to quantify the impact of a given building and identify policy linkages to mitigate energy demand and emissions growth related to China's new building construction.

1. Introduction

As efficiency has become a higher priority with growing energy demand, policy and academic attention to buildings has focused primarily on operational energy use. Existing studies estimate that building operational energy consumption accounts for approximately 25% of total primary energy use in China.[1] However, buildings also require energy for mining, extracting, processing, manufacturing, and transporting materials, as well as energy for construction, maintenance, and decommissioning. Building and supporting infrastructure construction is a major driver of industry consumption--in 2008 industry accounted for 72% of total Chinese energy use.[2] The magnitude of new building construction is large in China--in 2007, for example, total built floor area reached 58 billion square meters.[3] During the construction boom in 2007 and 2008, more than two billion m^2 of building space were added annually; China's recent construction is estimated to account for half of global construction.[4] Lawrence Berkeley National Laboratory (LBNL) developed an integrated LCA model to capture

[1] The building energy consumption data has been adjusted based on the data estimation that has been performed to support the Lawrence Berkeley National Laboratory (LBNL) China bottom-up end use model. This estimate reflects the energy by end use (e.g., space heating), information not available from official data reported in China's Statistical Yearbooks. For details see Zhou N. and Lin J. "The Reality and Future Scenarios of Commercial Building Energy Consumption in China," *Energy& Buildings,* 2008, 40 (12): 2121-2127.
[2] NBS. 2009. *China Statistical Yearbook 2009.*
[3] Urban building floor area is obtained from the 2008 China Statistical Yearbook. Statistical information is not available for the rural building floor area. This report estimates rural floor area using per capita floor space of houses from Table 9-37, Housing Conditions of Rural Household by Region (2007), and rural population from Table 3-4, Population by Urban and Rural residence and Region in 2008 China Statistical Yearbook (2007).
[4] John E. Fernández, "Resource Consumption of New Urban Construction in China," *Journal of Industrial Ecology* 11, no. 2 (2007): 99-115.

the energy and emissions implications of all aspects of new buildings from material mining through construction, operations, and decommissioning. Over the following four sections, this report describes related existing research, the LBNL building LCA model structure and results, policy linkages of this lifecycle assessment, and conclusions and recommendations for follow-on work. The LBNL model is a first-order approach to gathering local data and applying lifecycle assessment to buildings in the Beijing area--it represents one effort among a range of established, predominantly American and European, LCA models. This report identifies the benefits, limitations, and policy applications of lifecycle assessment modeling for quantifying the energy and emissions impacts of specific residential and commercial buildings.

2. Existing Research

Research into building energy use and emissions can be categorized by its use of top-down or bottom-up approaches. Whereas top-down approaches commonly use econometric analysis to attribute energy use and emissions to a given sector of the economy, bottom-up methods use engineering and statistical analysis to calculate sector information from population and process data.[5] Comparison of published studies shows that top-down input-output analysis of the energy requirements for residential building production generates specific energy use (MJ/m^2) values that are 90% higher than comparable bottom-up process-LCA analysis.[6] The ongoing use of top-down and bottom-up methods has given rise to a range of published estimates when it comes to quantifying the absolute energy use of buildings, as well as the corresponding portions of embodied versus operational energy use. The LCA models featured in this study use bottom-up approaches to calculate the energy and carbon emissions of individual buildings.

While the LCA approach has been used to quantify energy and environmental impacts since at least the 1960's, it was not codified until the 1990's and subsequently in 2006, when the International Organization for Standardization (ISO) published ISO 14040 (*Environmental Management--Life-cycle Assessment--Principles and Framework*) and ISO 14044 (*Requirements and Guidelines*).[7] The ISO 14040 standard outlined four general methodological components of LCA analysis: goal scope and definition, data inventory and analysis, impact assessment, and interpretation of results. Starting with the scope of analysis, this report includes all of the components of a building LCA as well as discussion of potential policy applications in China.

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[5] Lukas G. Swan and V. Ismet Ugursal, "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques," *Renewable and Sustainable Energy Reviews* 13, no. 8 (October 2009): 1819-1835.

[6] Jonas Nässén et al., "Direct and indirect energy use and carbon emissions in the production phase of buildings: An input-output analysis," *Energy* 32, no. 9 (September 2007): 1593-1602.

[7] Elcock D. 2007. "Lifecycle Thinking within the Oil and Gas Exploration and Production Industry," Argonne National Laboratory Report ANL/EVS/R-07/5.

2.1. Scope of Analysis

Within the methodological scope defined by ISO 14040, published building LCA analyses can be divided between studies that focus on building materials and component combinations (BMCC) and studies of the whole process from cradle to grave (WPCG). There are five key differences between BMCC and WPCD building LCA approaches. Whereas BMCC analysis may generate a useful and largely comparable number for understanding the energy or environmental impact, for example, of a window, WPCG analysis is not static--results can range significantly from building to building due to variation of conditions and input variables. Second, the functional units of analysis differ between BMCC and WPCG approaches--it is often energy per mass of material for BMCC while results are usually presented in terms of energy per square meter for WPCG. Likewise, WPCG analysis requires more assumptions about relationships among complex processes that comprise a given building's lifecycle. Fourth, while WPCG analysis is usually predicated on reducing energy and environmental impacts on a policy or development level, BMCC is often used to compare products on a consumer level. Finally, WPCG analysis requires multiple sources of data from designers, engineers, suppliers, and interviews, while BMCC LCAs are often based solely on industrial processes.[8] This study uses multiple Chinese and international data sources to perform WPCG LCA analysis of ten buildings in and around Beijing.

The scope of building LCA analysis also refers to the type of buildings studied, the boundaries of analysis, and the impacts or outputs of the assessment. This study developed separate LCA models for residential and commercial buildings; civil engineering construction, such as stadiums, is not included. By quantifying all the impacts of a given product or activity from cradle to grave, LCA can come to resemble a snake that eats its own tail in the sense that all activities and products are part of a larger system of energy production, use and emissions that fuels the entire economy. In order to have clear and consistent boundaries of analysis, this study starts with all the inputs that go into, for example, producing building materials, but it does not include upstream requirements of energy production, e.g., the energy required to mine the coal used to generate electricity. This study focuses on energy and emissions impacts of production, transportation, use, and decommissioning during each phase of the building's lifespan. Regarding impacts, LCA outputs correspond to each study's desired uses and available data; as such, many LCA studies quantify buildings' global warming potential, energy use, other resource requirements, impact on acidification, eutrophication, ozone depletion, lifecycle cost, human toxicity, etc. Due to data limitations and the absence of similar published studies, this study uses energy and carbon emissions per square meter as its primary output.

[8] Oscar Ortiz, Francesc Castells, and Guido Sonnemann, "Sustainability in the construction industry: A review of recent developments based on LCA," *Construction and Building Materials* 23, no. 1 (January 2009): 28-39.

2.2. Published Data

Data relating to material and energy intensity of buildings in China is gradually becoming available through published case studies and academic articles. However consistent, transparent, and verifiable sources are not publically available for lifecycle inventory or assessment purposes in China.[9] In the United States a similar data gap was filled by academics and private consultancies until the National Renewable Energy Laboratory (NREL) established the U.S. LCI Database Project in 2001.[10] The NREL LCI database contains material and component information that can be used to create complete lifecycle inventories and assessments; although the database is publicly available, it is intended for LCA practitioners and does not include complete assessments for general use.

In China, most building LCA-related data are published in academic articles, reports, and graduate student theses. Case study research provides useful information on specific buildings among various climate zones, though results data are not always complete, comparable, or verifiable. The lack of publically available data in China limits the ability of LCA analysis to be integrated into policy-linked building assessment systems; furthermore, there is an absence of established references or benchmarks against which to judge successfully completed LCA building analyses.[11] This study supplements Chinese data from academic sources with case study data from American building LCA analysis. Key data inputs for this study included the energy intensity of material mining, transport, and production (MJ/kg), material intensity of building production (kg/m^2), operational energy use (MJ/m^2/year), and energy requirements of building decommissioning and demolition (MJ/m^2). Specific data points and sources are discussed in Section 3 below.

2.3. Building Energy and Emissions Measurement Tools

Dozens of building energy and emissions measure tools have been developed in the United States and the European Union, most of which are targeted towards urban planners, property developers, architects, and engineers.[12] Two key types of building tool are building component/material evaluation programs and building operational energy use simulation models. The Building for Environmental and Economic

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[9] The Beijing University of Technology developed a Chinese National Database of materials life cycle assessment (MLCA) that is described at http://www.cnmlca.com/index.htm (Gong XZ et al. 2006); however, data are not publically available through this website. The Tsinghua University Building Energy Research Center has also conducted building lifecycle assessment, though their model and data are also not publically available.

[10] The NREL LCI database is freely available at http://www.nrel.gov/lci/database/default.asp.

[11] Trusty WB, Horst S. 2002. "Integrating LCA Tools in Green Building Rating Systems," available at http://www.athenasmi.ca/publications/docs/LCA_Tool_Integr_Paper.pdf.

[12] For an overview of current building LCA tools see Ignacio Zabalza Bribián, Alfonso Aranda Usón, and Sabina Scarpellini, "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification," *Building and Environment* 44, no. 12 (December 2009): 2510-2520.

Sustainability (BEES) software tool is an example of BMCC LCA (discussed above) that combines environmental and economic cost analysis to assist in building component selection.[13]

EnergyPlus is a building envelope, heating ventilation and air-conditioning (HVAC), water use, and building-scale renewable energy simulation program.[14] The roots of EnergyPlus are in the BLAST (Building Loads Analysis and System Thermodynamics) and DOE-2 energy analysis and thermal load simulation tools. It is not a stand-alone tool; rather its utility is integration of high-resolution building energy simulation with external databases (e.g., local weather patterns) and interfaces. EnergyPlus version 5.0 was released in April 2010 and includes updated modules on natural and mechanical ventilation and on-site wind energy supply, among others. The simulation software can be applied to residential or commercial buildings. In this study EnergyPlus was linked with the operational module of the LBNL commercial building LCA model to demonstrate its feasibility for high-resolution analysis.

2.4. Lifecycle Assessment Modeling Approaches

Lifecycle assessment models can be categorized among three types: economic input-output LCA (I-O LCA), process-based LCA, and hybrid LCA, which combines I/O and process analysis. Economic I-O LCA uses a top-down approach that generates average sector energy use and emissions values not always appropriate for case study research.[15] A well-known example of hybrid LCA in the United States is the Carnegie Mellon EIO LCA.[16] The U.S. EIO LCA is based on the Department of Commerce, Bureau of Economic Analysis input-output table, which describes 491 sectors of the economy in 1997. The model combines aggregate process information with input-output data to calculate an amount of emissions, energy use, and employment per dollar of production in a given sector. EIO-LCA analysis is limited to goods and services as defined by the Department of Commerce--i.e., the user must make additions and assumptions to assess a larger and more complex unit such as a building. Furthermore, the EIO-LCA results cover the impacts of production, but do not include related upstream energy and infrastructure requirements. The UC Berkeley BuiLCA model is an example of hybrid LCA applied to the commercial buildings sector.[17]

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[13] BEES software is freely available at http://www.bfrl.nist.gov/oae/software/bees/.

[14] EnergyPlus software is freely available at http://apps1.eere.energy.gov/buildings/energyplus/.

[15] Yuan Chang, Robert J. Ries, and Yaowu Wang, "The embodied energy and environmental emissions of construction projects in China: An economic input-output LCA model," *Energy Policy* In Press, Corrected Proof (n.d.), http://www.sciencedirect.com/science/article/B6V2W-50FHN08-2/2/a074fb2de9bd9dc5982e0ff16c775024.

[16] Carnegie Mellon EIO LCA data are freely available at http://www.eiolca.net/.

[17] Vieira, PMdS (2007) *Environmental Assessment of Office Buildings*. U.C. Berkeley Doctoral Dissertation in Civil and Environmental Engineering.

Process-based LCA models are often focused on decision-support analysis for product or process evaluation. In the transport sector, the Argonne National Laboratory (ANL) GREET (Greenhouse gas, Regulated Emissions and Energy use in Transport) model provides lifecycle assessment of liquid fuels, both from well to pump and pump to wheels, i.e. fuel production and combustion.[18] The GREET model does not include embodied energy of vehicles or related infrastructure. In the buildings area, the ATHENA model is an example of a private-sector process-based LCA tool. The ATHENA model is described as a corrective compliment to more myopic green building rating systems such as GBTool and earlier versions of LEED (Leadership in Energy & Environmental Design).[19] ATHENA provides a detailed analysis of building embodied energy, solid waste, and emissions; however the proprietary nature of the results limits their transparency and comparability. In China, Tsinghua University has developed a process-based LCA tool for building energy analysis called BELES (Building Environmental Load Evaluation System). The BELES model assesses buildings and their components environmental loads via four indexed endpoint values: resource exhaustion, energy exhaustion, human health damage, and ecological damage.[20]

3. Data, Model Structure, and Results

In the first phase of this project LBNL used case study data gathered by collaborators at the Tsinghua University Building Energy Research Center, the University of California, Berkeley BuiLCA project, and data from other building-LCA publications to develop two separate tools for measuring the energy implications of a given urban residential or commercial building.[21] Tsinghua provided data on six residential buildings and four commercial office buildings in the Beijing area, as described in Table 1 below. Table 1 also shows summary modeling results of total energy use and emissions for each of the buildings.

Table 1: Summary of Beijing Case Study Building Data

Building	Built Area m^2	Vintage (construction year)	Lifespan years	Total Lifetime Energy GJ	Total Lifetime Emissions tonnes CO_2
Residential #1	30,000	2001	30	900,000	70,000
Residential #2	8,000	2000	30	240,000	19,000

[18] The GREET model is freely available at http://www.transportation.anl.gov/modeling_simulation/GREET/.
[19] Trusty WB, Horst S. 2002. "Integrating LCA Tools in Green Building Rating Systems," available at http://www.athenasmi.ca/publications/docs/LCA_Tool_Integr_Paper.pdf.
[20] Gu, D. et al. 2007. "A Lifecycle Assessment Method for Buildings," *Proceedings: Building Simulation* 2007:1595-1600.
[21] Key data sources include Tsinghua University (2009), Gu et al. (2007), and Vieira (2007).

Residential #3	7,000	1999	30	280,000	22,000
Residential #4	13,000	2001	30	470,000	37,000
Residential #5	30,000	1998	30	940,000	73,000
Residential #6	16,000	2002	30	460,000	36,000
Commercial #1	42,000	1998	30	1,500,000	120,000
Commercial #2	142,000	2000	30	4,900,000	380,000
Commercial #3	30,000	2001	30	1,000,000	82,000
Commercial #4	10,000	2001	30	340,000	26,000

Source: Tsinghua University, 2009; LBNL China Building LCA Model.

The data for the residential and commercial LCA models was generated by case studies performed in Beijing and Berkeley, California, as well as information from academic literature. Where local Chinese data were not available the model used international proxy values, for example for the material, energy, and transport intensity of carpet tile. The case studies provide an empirical, bottom-up information source for calculating building energy use and resultant carbon emissions. However as discussed below, the data-intensiveness of lifecycle assessment modeling leads to a tradeoff between comprehensiveness and feasibility or comparability.

3.1. Model Structure

LBNL developed an integrated modeling tool that combines process-based lifecycle assessment with spreadsheet-based building operational energy use modeling.[22] The lifecycle assessment approach was used to quantify energy and carbon emissions embodied in building materials production, construction, maintenance, and demolition. To provide higher-resolution analysis, LBNL developed an EnergyPlus simulation module in parallel with the operational energy use module to separately characterize the operational energy use. EnergyPlus is a simulation tool that quantifies operational energy impact of building design choices.[23] The parallel EnergyPlus module was populated with case study data from Beijing-area developments and supplemental international information to provide a preliminary structure for further elaborating and enhancing the commercial building LCA model; input and output data were separately administered in the LBNL commercial building operational energy use and EnergyPlus operational energy use modules. Beyond operational energy use, the residential and

[22] The LBNL building LCA tool is integrated in the sense that it includes multiple tools and modeling approaches; however, it does not include economic input-output analysis.

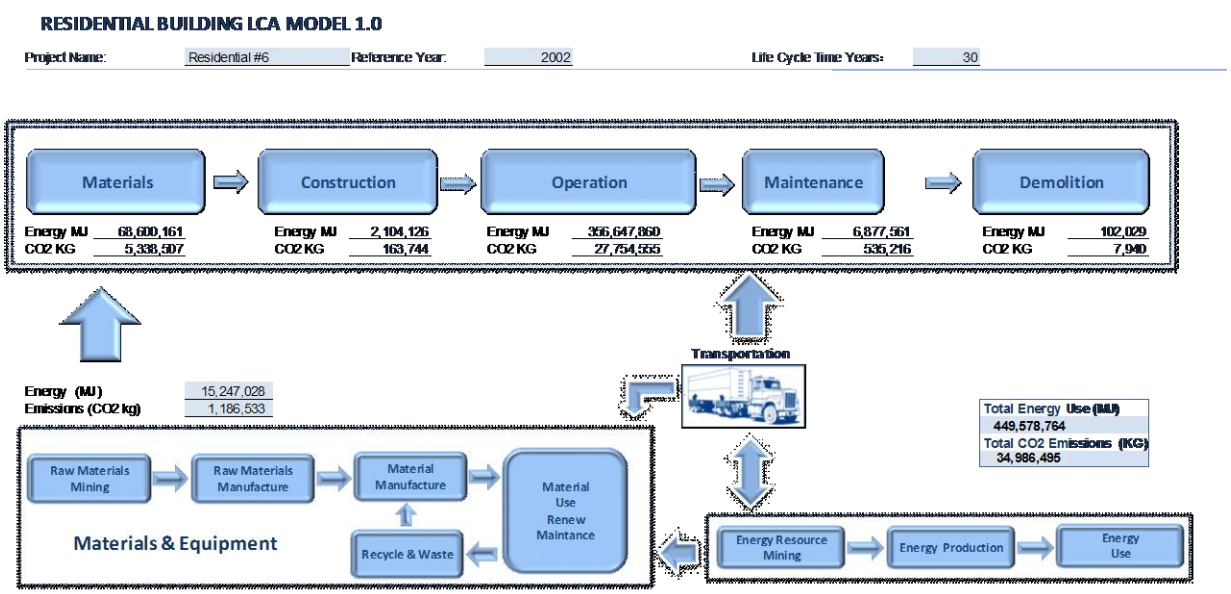
[23] EnergyPlus was developed by the U.S. Department of Energy and is freely distributed online at http://apps1.eere.energy.gov/buildings/energyplus/.

commercial building LCA models are based on spreadsheet-based lifecycle assessment modules covering each stage and component within the buildings expected lifespan.

3.2. Residential Building LCA Model

The residential building LCA model is comprised of six sections, as shown in Figure 1 below. The first two modules cover the production of materials and equipment from the mining of raw materials through manufacturing to the transport of materials and equipment to the building site. The third module covers the energy use and emissions related to actual construction of the building, for example covering the diesel fuel used by earth-moving equipment. Operation of the occupied building is the fourth and largest module of the model, in terms of energy use and related carbon dioxide emissions. Building maintenance and equipment replacement comprises the fifth module, and demolition and recycling are the final module. The materials, maintenance, and demolition phases of the model explicitly model transport as well as direct embodied energy of the building components. The embodied energy of energy, e.g., the energy required to mine coal and manufacture electricity generation, transmission, and distribution equipment are not included in the scope of this analysis. The outputs for each module are the total energy use in megajoules and the energy-related carbon dioxide emissions in kg CO_2. The total energy use and related CO_2 emissions for each building are calculated as the sum of these six components, as discussed following Table 2 below.

Figure 1: Structure of LBL Residential Building LCA Model



The model is structured to display results for the lifetime of a single building; the user chooses whether to use case study data from an actual measured Beijing-area building or input new data from another building. Policy makers may find the existing data

useful for setting building construction and equipment standards and identifying policy priorities, while specialists and designers can use the test building function to evaluate a new actual or hypothetical case.[24] The model input choice is displayed in the yellow boxes in Figure 2 below. In the case of new building data input, the model provides average default values to supplement missing or unavailable information such as the number of days per year of air conditioner use, etc.

Figure 2: User Data Input Module of Residential Building LCA Model

RESIDENTIAL BUILDING Description

Project Name:	Residential #6	Location	Beijing
Construction Year:	2,002	Life Cycle Time Years	30
Construction Area (M2)	16,195	Residential Building Application	Family
Climate Zone	*Summer Hot Winter Cold*	Residential Building Structure	High-rise house (<20)
Building Type	Residential	Construction Technology	Frame Construction
Family Number	210	Building Height (M)	> 25 Meters
Windows Areas Ratio (%)	0		
Heating Type	Centralized Coal-Fired Boilers	Fans	1
Heating Days / Yr	120	Electricity Stove %	0
Air Conditionor Type	Split Air Conditioner	Microwave Stove	1
Average AC Days / Yr	60	Electricity Rice Pot	1
Family AC Ownership Rate (%)	152%	Electricity Room Heater	0
Elevator Number	2	Electricity Water Heater %	90%
Design Elevator Power (KW/per Unit)	16	Gas Stove %	100%
Elevator Load Rate (%)	15%	Gas Water Heater %	100%
Family AVG Lighting (W)	116		
Lighting Load Rate (%)	5%		
Hot Water Supply Type	*(data not available)*		
Per Family Hot Water (KG/Day)	*(data not available)*		
Water Consumption (Tons/Day)	*(data not available)*	Data Source:	Use Test Building Data / Load Building Data
Gray Water Treatment (Tons/Day)	*(data not available)*		
AVG Desktops Per Family	1	Load Building Data:	
Refrigerator Per Family	1	Residential Building Selection:	Residential #6
Washing Machine Per Family	1		
TV Per Family	1		

This project calculated the lifecycle energy use and emissions of ten buildings in the Beijing "hot summer, cold winter" climate zone according to survey data on heating and air conditioning usage days. Whereas the residential building LCA model calculates heating and cooling energy use and emissions from heating degree days, the commercial building LCA model uses climate zone inputs to calculate heating energy use from intensity assumptions. The commercial model is structured to adjust heating days per year by provincial location and related climate zone; commercial heating degree day assumptions may not be over-ridden and the resulting operational energy use data are independent of equipment data or technology assumptions. The water categories in Figure 2 are included for the purpose of further analysis; however, building-specific water-usage data were not available for this study. Once the user has specified model inputs, the first module calculates the energy and carbon requirements of building materials production.

[24] While the LBNL building LCA tool data are not yet detailed or accurate enough to serve as the basis for a building rating tool, its structure and methodology present a policy-linked approach for evaluating building energy and emissions performance.

Figure 3: Structure of Residential Building Raw Materials Production LCA Sub-Module

RESIDENTIAL BUILDING Materials

Project Name: Residential #6 Construction Year: 2,002 Construction Area (M2) 16,195

Raw Materials

Main Materials	Amount(KG)	Raw Materials	Raw Materials Amount (KG)	Manufacture Energy (MJ)	Transportation (MJ)
Cement	388680	Limestone	505,284.00	15,158.52	272.8534
Cement		Sandstone	31,094.40	932.83	16.7910
Cement		Gypsum	19,434.00	583.02	10.4944
Cement		Cement clay	77,736.00	2,332.08	41.9774
Cement		Water	3,886.80	116.60	2.0989
Steel	1213005.5	Water	53773746.82	1613212.405	29037.82328
Steel		Manganese ore	41242.187	1237.26561	22.27078098
Steel		Limestone	272926.2375	8187.787125	147.3801683
Steel		Magnesium limestone	194000.88	5822.4264	104.8036752
Steel		Fluorite	2426.011	72.78033	1.31004594
Steel		Iron-ore	1361288.127	40838.64381	729.6955886
Aluminum	46317.7	Water	759,610.28	22,788.31	410.1896
Aluminum		Aluminum-ore	11,069.93	332.10	5.9778
Aluminum		Limestone	185.27	5.56	0.1000
Aluminum		Salt	741.08	22.23	0.4002
Clay Standard Brick	393538.5	Clay	983,846.25	29,515	531.2770
Clay Standard Brick		Soot	4328.9235	129.867705	2.33761869
Aeroconcrete	552249.5	Limestone	191,244,001.85	5,737,320	103271.7610
Aeroconcrete		Sandstone	2,385,717.84	71,572	1288.2876
Aeroconcrete		Gypsum	3,700,071.65	111,002	1998.0387
Aeroconcrete		Cement clay	5,964,294.60	178,929	3220.7191
Aeroconcrete		Water	34,626,043.65	1,038,781	18698.0636
Aeroconcrete		Freestone	198,809,820.00	5,964,295	107357.3028
Aeroconcrete		Manganese ore	6,626.99	199	3.5786
Aeroconcrete		Magnesium limestone	26,507.98	795	14.3143
Aeroconcrete		Iron-ore	184,451.33	5,534	99.6037
Aeroconcrete		Soot	1,889,245.54	56,677	1020.1926
Glass	69800.45	Water	37762.04345	1132.861304	20.39150346
Glass		Siliceous raw material	44113.8844	1323.416532	23.82149758
Glass		Sandstone	44113.8844	1323.416532	23.82149758
Glass		Magnesium limestone	10470.0675	314.102025	5.65383645
Glass		Limestone	3490.0225	104.700675	1.88461215
Glass		Mirabilite	698.0045	20.940135	0.37692243
Glass		Tin-ore	2.3732153	0.071196459	0.001281536
Glass		Salt	9981.46435	299.4439305	5.389990749
Ceramics	506903.5	Water	118,311.28	3,549.34	63.89
Ceramics		Clay pits	387,882.56	11,636.48	209.46
Ceramics		Pyrophyllite	98,136.52	2,944.10	52.99
Ceramics		Kaolin	22,202.37	666.07	11.99
Ceramics		Feldspar	18,704.74	561.14	10.10
Ceramics		Lead frit	5,981.46	179.44	3.23
Ceramics		Sodium fluosilicate	304.14	9.12	0.16
Ceramics		Pencil stone	105,942.83	3,178.28	57.21
Ceramics		calcium carbonate	105,942.83	3,178.28	57.21
Copper	3239	Water	1307584.3	39227.529	706.095522
Copper		Copper ore	25672.314	770.16942	13.86304956
Copper		Limestone	4664.16	139.9248	2.5186464
Copper		Quartz	2332.08	69.9624	1.2593232
Copper		Cast iron Ball	566.825	17.00475	0.3060855
Copper		Sulphuric acid	22025.2	660.756	11.893608
Copper		Magnesite brick	174.906	5.24718	0.09444924
Copper		Coke	1033.241	30.99723	0.55795014
			Energy Consumption MJ	14977434.06	269593.8132
			Total Energy MJ		15247027.88
			CO2 Emission KG	1165553.098	20979.95576
			Total CO2 Emission		1186533.054

Source: Tsinghua University, 2009; LBNL China Building LCA Model.

Prior to their manufacture into construction inputs, the primary resources for building materials needed to be mined and transported. Figure 3 shows a snapshot of the residential buildings raw materials production module for residential building #6. This module captures the extraction, production, and transport energy requirements of key raw material inputs. The cement portion of the module, for example, quantifies the energy required for producing the water, limestone, sandstone, gypsum, and clay typically used for cement production.

Figure 4: Structure of Residential Building Materials LCA Module

RESIDENTIAL BUILDING Materials

Project Name: Residential #6 | Construction Year: 2002 | Construction Area (M2): 16,195 | Building Type: Family

Main Materials Manufacture / Transportation Energy Consumption

Index	Main Materials Names	Manufacture (MJ)	Transportation (MJ)
1	Section Steel	773,716	19,617
2	Steel Bar	26,822,159	680,050
3	Aluminum	12,326,066	99,430
4	Cement	2,044,457	95,337
5	Glass	1,399,499	8,467
6	Structure Ceramics	10,407,393	75,651
7	Clay Brick	767,625	86,624
8	Concrete	735,212	518,138
9	Wood	0	114,745
10	Copper	311,592	3,069
11	Sanitary Ceramics	4,859	5,344
		55,276,127	1,698,058

Manufacture (MJ)	65,291,852
Transportation (MJ)	3,308,309
Total (MJ)	68,600,161

Manu CO2 (KG)	5,081,052
Trans CO2 (KG)	257,455
Total CO2 Emi (KG)	5,338,507

Aux Materials Manufacture / Transportation Energy Consumption

Index	Main Materials Names	Manufacture (MJ)	Transportation (MJ)
1	Acrylic Rubber - Waterproofing	952,752	1,048,027
2	Carpet Tile	24,131	26,544
3	Fireproofing	7,407,431	8,148,174
4	Curtain Wall	636,787	700,466
5	Epoxy Grout	24,131	26,544
6	Fire Retardant	1,706,953	187,765
7	Glass Fiber	34,350	1,247
8	Gypsum board	6,034,957	768,339
9	Insulation - Expanded Polystyrene	15,372,294	161,043
10	Iron	13,280	14,608
11	Paint	2,078,920	25,297
12	Plaster	370,380	407,418
13	Plywood	501,980	29,216
14	Polyethylene Sealant	1,690,758	21,377
15	Polypropylene - Piping	1,134	1,247
16	PVC-Waterstop	136,848	150,533
17	Reinforcing Steel	2,424,359	299,640
18	Resilient Flooring	332,969	366,266
19	Wood-Doors,Frames	10,851	11,936
20	Wood-Flooring	2,429	2,672
		5,471,707	1,290,304

Equipments Manufacture / Transportation Energy Consumption

Index	Main Equipments Names	Manufacture (MJ)	Transportation (MJ)
1	Kitchen equipment	33,000	2,400
2	Assembly and connection materials	9,600	330
3	Accessories for pipes	48,000	2,700
4	Boilers and furnaces	96,000	5,800
5	Engine equipment	87,000	4,050
6	Material moving/handling machinery	120,000	9,750
7	Stereo System	18,954	4,015
8	Household electric appliances	400,000	93,500
9	Cable communicating equipment	480,000	58,200
10	Power generating equipment	195,000	8,100
11	On-off controllers	320,000	22,400
12	Lighting ballasts and equipment	154,000	16,800
13	Light bulbs	25,000	4,060
14	Metal wired products	184,000	20,000
15	Chillers	231,000	18,900
16	Pumps and compressors	62,000	4,100
17	Room Air Conditioner	1,029,624	7,342
18	Fan Coil	810,840	18,000
19	Elevator	240,000	19,500
		4,544,018	319,946

Each of the six Beijing residential building case studies included data on material, manufacturing, and transport intensities of eleven key building materials and nineteen categories of equipment. These were supplemented with twenty categories of auxiliary building materials data from the U.C. Berkeley BuiLCA modeling project.[25] BuiLCA data were collected from a new classroom building constructed on the U.C. Berkeley campus in 2009--these inputs could be improved in future research through collection

[25] Vieira, PMdS (2007) *Environmental Assessment of Office Buildings*. U.C. Berkeley Doctoral Dissertation in Civil and Environmental Engineering.

of local Chinese residential building data. The categories of equipment data, such as "kitchen equipment" and "stereo system" were provided by collaborators at Tsinghua University. Mass amounts of equipment, such as room air conditioners and stereos, were estimated on the basis of statistical appliance ownership data for Beijing urban households in 2008.[26] Ownership data and survey information from Tsinghua were combined with manufacturing and transport energy intensity assumptions to calculate total energy and emissions requirements of building materials.

This module quantifies the energy and emissions of the building materials production and transportation--it builds on the primary resource extraction values covered in the previous module (Figure 3). The materials section uses mass and intensity information of various construction inputs and equipment to calculate their related energy use, which is then aggregated at the module level. Total building materials energy use and emissions are calculated by aggregating manufacturing and transport energy use from the "Main Materials," "Auxiliary Materials," and "Equipment" subtotals (Figure 4).

Table 2: Assumed Fuel Energy Coefficients

	Primary Energy Content
Electricity	10.22 MJ/kWh
Coal	29.27 MJ/kg (standard coal)
Diesel	42.65 MJ/kg
Natural Gas	38.93 MJ/m^3

All forms of energy use are aggregated into a common unit of primary-equivalent megajoules throughout the model to provide comparability and enhance analytical flow. Table 2 shows the fuel energy coefficients used in this study; they are consistent with China national fuel energy content values published by the National Bureau of Statistics.[27] Carbon emissions resulting from energy use are calculated with the assumption of 10% non-fossil energy (e.g., hydropower or nuclear), 70% coal, 5% natural gas, and 15% oil. The megajoule equivalent of a kilowatt hour of electricity was calculated annually with the heat rate frozen at 349 grams coal per kWh. Carbon intensity and electricity heat rates are fixed over the lifetime of each building.

[26] National Bureau of Statistics. 2009. *China Energy Statistical Yearbook 2009*. Beijing:NBS.
[27] *Ibid.*

Table 3: Average Residential Building Material Intensity Values

Material	Material Intensity kg/m^2	Production Intensity MJ/kg	Transport Intensity MJ/kg
Section Steel	14	23	0.58
Steel Bar	39	23	0.58
Aluminum	2.0	270	2.1
Cement	160	5.3	0.25
Glass	3.6	20	0.12
Fire Retardant*	11	10	1.1
Insulation - Expanded Polystyrene*	9.0	110	1.1
Paint*	1.4	90	1.1
Wood	3.4	-	2.7
Copper	0.20	96	0.95

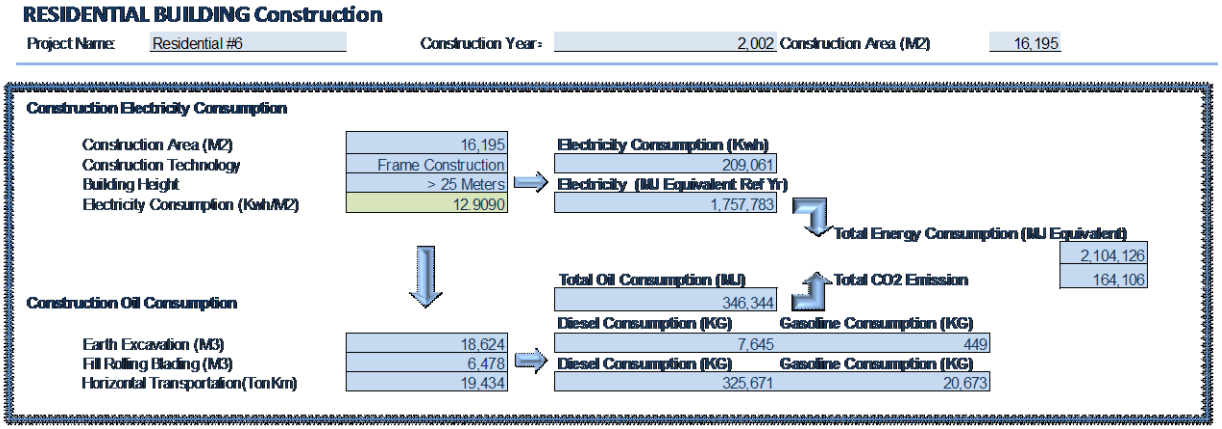
* Based on supplemental data from Vieira (2007).

Table 3 shows average intensity values for the six Beijing-area residential building case studies. Each building has unique characteristics that make for a wide range of material use, material manufacturing, and material transport intensity values. Steel bar material intensity, for example, varied from 14 kg per square meter in residential building #3 to 73 kg per square meter in building #6.[28] Likewise with production intensity, other published sources range from 3.6 megajoules of energy per kg of cement produced (Kofoworola, 2009) to 7.8 MJ/kg (Chen, 2001).[29] Transport intensity also varies widely depending on the proximity of the building to the material production facilities or the source of the material in the case of wood. The range of these values underscores the highly approximate nature of using lifecycle assessment to capture as large and complex of a system as total building energy use.

[28] The LBNL 2050 LEAP energy end-use model includes an average steel content of Chinese building construction of 37 kg per square meter in 2005.

[29] Total cement production intensity varies by technology and fuels. The LBNL 2050 LEAP energy end-use model includes average Chinese cement production intensity of 3.3 MJ/kg for rotary kilns and 4 MJ/kg for shaft kilns in 2005.

Figure 5: Construction Module of Residential Building LCA Model



The construction module is divided between electricity use and oil consumption for powering equipment and transporting materials on-site. The amount of energy use is calculated on the basis of the building area, construction technology, and building height. Electricity and fuel intensity of construction varies by building construction technology based on case study data provided by Tsinghua. Figure 5 shows that Residential Building #6 was made using frame construction, which requires an average 12.9 kWh per square meter. International building LCA tools such as ATHENA perform more detailed analysis of construction energy that includes building construction type, e.g., conventional reinforced concrete with curtain wall exterior cladding system as opposed to glass. As with building material use and production energy intensity, there is likely to be variation of construction energy use per square meter--this is an area that would benefit from further empirical research.

Figure 6: Operations Module of Residential LCA Model

BUILDING Operation

Project Name:	Residential #6	Construction Year:	2002	Construction Area (M2)	16,195

Building Type	Residential			
Heating Type	Centralized Coal-Fired Boilers	Total Consumption (MJ Equivalent) /Yr	Life Consumption (MJ)	Life Total CO2 (KG)
Heating Days / Yr	120	11,888,262	356647860	27754555
Life Cycle Time Years:	30	Per Yr Consumption MJ /M2	Life (MJ/M2)	Life CO2(KG/M2)
		734	22022	1714

Heating Operation Energy Consumption

Electricity Consumption		Electricity Consumption (Kwh)		Total Energy MJ
Construction Area (M2)	16,195	0		0
Heating Type	Centralized Coal-Fired Boilers	Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Electricity Consumption (Kwh/M2)	0	0	0	0
Fuel Consumption				Total Energy MJ
Construction Area (M2)	16,195			3460488
Heating Type	Centralized Coal-Fired Boilers	Fuel Consumption (MJ)	Transportation (MJ)	Total CO2 KG
Fuel Consumption (MJ/M2)	214	3460467	21	269297

Air Conditioner Energy Consumption

Family Number	210	Electricity Consumption (Kwh)		Total Energy MJ
Climate Type	Summer Hot Winter Cold	229824		3445805
Residential Building Application	Family	Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Air Conditionor Type	Split Air Conditioner	3227013	218791	268155
Average AC Days / Yr	60			
Family AC Ownership Rate (%)	152%			

Elevator Energy Consumption

Commerical Building Structure:	High-rise house (<20)	Electricity Consumption (Kwh)		Total Energy MJ
Elevator Number	2	1752		26268
Design Elevator Power (KW/per Unit)	16	Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Elevator Load Rate (%)	15.00%	24600	1668	2044

Lighting Energy Consumption

Family Number	210	Electricity Consumption (Kwh)		Total Energy MJ
Design Lighting Per Family(W)	116	10640		159530
Lighting Hours (Avg Per day)	1	Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Lighting Load Rate (%)	5.00%	149400	10129	12415

Electricity Equipment Energy Use

Family Number	210			
AVG Desktops Per Family	1	Electricity Consumption (Kwh)		Total Energy MJ
Refrigerator Per Family	1	240475		3392872
Washing Machine Per Family	1	Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
TV Per Family	1	3376567	16304	264035
Fans	1			
Electric Stove	0			
Microwave Oven	1			
Electric Rice Pot	1			
Electric Room Heater	0			

Gas Stove Cooking

				Total Energy MJ
Family Number	210			1403300
Gas Stove %	100%	Fuel Consumption (MJ)	Transportation (MJ)	Total CO2 KG
Gas Water Heater %	100%	1314198	89103	109206

The operations module is focused on six areas of building energy end-use: heating, air conditioning, elevators, lighting, residential equipment, and stove cooking. Figure 6 shows the structure of each of these sub-modules. The residential equipment sub-module is comprised of nine end uses: computer, refrigerator, washing machine, TV, fan, electric stove, microwave oven, electric rice cooker, and electric space heater. The lighting energy consumption sub-module shows use as a portion of total capacity--i.e.,

average usage is equivalent to turning all of the lights in the household on for one hour per day. Given the prevalence of chargeable devices such as mobile phones and digital media players, the plug-load category of operational energy use is likely to grow. In most building types this sub-module accounts for the largest portion of operational energy use. One lacuna in the operations module is explicit modeling of public area energy use beyond elevators--e.g., water pumping, common area lighting, security, and access controls. Lifecycle operational energy use assumes constant annual consumption over the lifetime of the building.

Figure 7: Maintenance Module of Residential Building LCA Model

BUILDING Maintenance

Project Name: Residential #6 | Construction Year: 2002 | Construction Area (M2): 16,195

Maintenance Clean Energy Consumption

Index	Maintence Items	Family Process (MJ)	Family Transportation (MJ)
1	Clean Floors	360	108
2	Clean Windows	840	504
3	Clean HVAC	600	720
4	Clean Ceramics	360	288
5	Repaint Walls	4,157,840	1,663,136
6	Maintence Roof	330	198
		4,159,970	1,664,846

Replace Equipments Manufacture / Transportation Energy Consumption

Index	Main Equipments Names	Process (MJ)	Transportation (MJ)
1	Kitchen equipment	6,600	480
2	Accessories for pipes	19,200	1,080
3	Boilers and furnaces	24,000	1,450
4	Engines	29,000	1,350
5	Material moving/handling machinery	9,600	780
6	Stereo System	18,954	4,015
7	Household electric appliances	32,000	7,480
8	Cable communicating equipment	48,000	5,820
9	Power generating equipment	6,500	270
10	On-off controllers	8,000	560
11	Electric lighting Fixtures	7,700	840
12	Light bulbs	225,000	36,540
13	Metal wired products	4,600	500
14	Chillers	7,700	630
15	Pumps and compressors	6,200	410
16	Room Air Conditioner	514,812	3,671
17	Fan Coil	13,514	300
18	Elevator	4,800	390
		986,180	66,566

Process (MJ)	5,146,149
Transportation (MJ)	1,731,411
Total (MJ)	6,877,561

Process CO2 (KG)	400,476
Transportation CO2 (KG)	134,739
Total CO2 (KG)	535,216

The maintenance module is divided into maintenance/cleaning and equipment replacement portions. The first portion is comprised of six key tasks, the most energy-intensive of which is repainting due to large wall areas and energy-intensiveness of paint production. Equipment replacement is broken down among eighteen categories, as shown in Figure 7 above. The data in Figure 7 show energy requirements for maintenance of Residential building #6 over its assumed 30-year lifespan. As with the building materials module, this section quantifies the embodied energy and transport requirements of the building equipment based on equipment-specific survey data and estimates developed in Beijing and Berkeley, California.[30]

[30] Data are contained in Tsinghua (2009), Gu et al. (2007), and Vieira (2007).

Results of the maintenance module are highly sensitive to equipment lifespan assumptions. Increasing the average useful lifespan of incandescent and fluorescent light bulbs, for example, from three to six years would reduce their lifetime energy use by more than 130 GJ. Increased maintenance to reduce turnover rates and manufacturing of higher quality equipment with longer useful lifetimes both have potential to reduce building energy use.

Figure 8: Demolition Module of Residential Building LCA Model

BUILDING Demolition

Project Name: Residential #6 | Construction Year: 2,002 | Construction Area (M2): 16,195

Building Demolition Consumption

Construction Area (M2)	16,195
Building Demolition	19,434
Blading	34,010
Crane Transportation	48,585

Energy Consumption (MJ)	102,029
Total CO2 Emission KG	7,940

Recycling Materials

Index	Main Materials Names	Recycle Rate (%)	Amount (KG)	Manufacture (MJ)	Transportation (MJ)	Recycle Energy (MJ)
1	Section Steel	70.00%	23,807	541,601	13,732	555,333
2	Steel Bar	70.00%	825,297	18,775,511	476,035	19,251,546
3	Aluminum	95.00%	44,002	11,709,763	94,459	11,804,222
4	Glass	80.00%	55,840	1,119,599	6,773	1,126,373
5	Copper	95.00%	3,077	314,475	5,539	320,013
					Total Energy (MJ)	33,057,487
					Embodied CO2 (KG)	2,572,554

The final module in the residential building LCA model covers demolition and decommissioning. Energy use for building deconstruction is calculated on the basis of construction area, with intensity of destruction, blading, and crane use assumed to be equal among all buildings. While an aggregate average approach is useful for first-round analysis, it does not capture the non-linear effects of building size and structure type, or the potential for disproportionately large environmental impacts. One study, for example, found that building decommissioning can account for up to 8% of total lifecycle emissions of some pollutants.[31]

Beyond accounting for the range of decommissioning impacts, another difficult aspect of demolition modeling is how to credit the embodied energy of materials recycling.[32] This study assumed 70% of steel was recycled, 95% of aluminum and copper, and 80% of glass, with the energy credit going to the next building constructed with these materials--i.e., the recycling energy was not credited back to the original building. The scale of potential savings for use of recycled materials is suggested by a study of

[31] Junnila, S.; Horvath, A.; Guggemos, A. (2006) "Life-cycle Assessment of Office Buildings in Europe and the U.S." *J. Infrastructure Syst*, *12* (1), 10–17.

[32] Santos Vieira, P, et al. (2008) "Assessing the End-of-Life Impacts of Buildings," *Environ. Sci. Technol.* 2008 (42):4663-4669.

residential house construction in Sweden, which found that total lifecycle energy use, including feedstock energy, for a house with maximum recycled material content was only 60% the level of a comparable house with all new materials.[33] The Thormark (2000) study clearly credited all of the recycling to the new recipient building. Regarding the discussion of equipment maintenance and replacement above, an important area of further research is to determine whether recycled materials have a shorter useful lifetime than new materials, and whether there is an optimal level or type of material recycling in buildings.

3.3. Residential Model Results

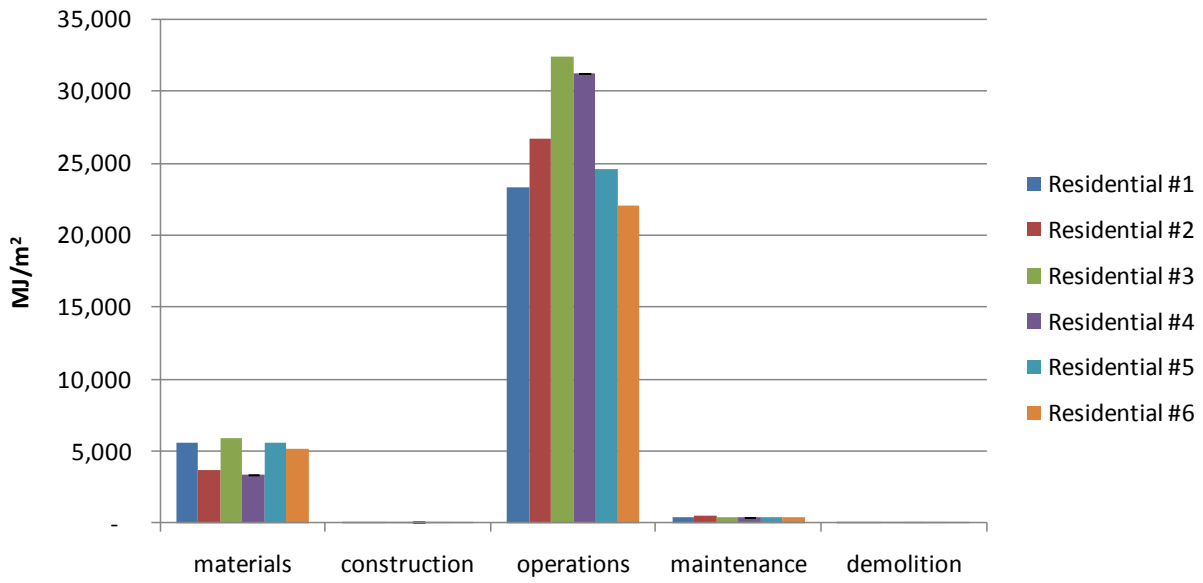
The residential model results show that operational energy use is the largest portion of the lifecycle followed by the embodied production and transport energy of materials. Figure 9 illustrates the unit-area lifecycle energy use of the six case study buildings. Operational energy use per square meter varied by more than 30% between the six Beijing-area residential case study buildings. Materials energy use per square meter varied by 44% among the six Beijing-area residential case study buildings, with Building #3 nearly doubling Building #4. The anomalies of Building #4's unit energy use reveal a key gap in building LCA analysis: the human element. Building #4's materials energy use is the lowest and its operational energy is the highest because it has a high occupant density. Aside from occupancy rates, the LCA approach also excludes detailed impacts of behavior-related personal consumption.

LBNL residential building LCA model results are consistent with other published analysis of residential energy use in China. Research conducted in 2004 found that China's average annual residential building operational energy use was 17.2 GJ per household in 1997.[34] The average annual operational energy use of the Beijing-area residential case study buildings in this study was 900 MJ per square meter. Multiplied by the average household size of 73 square meters, the average annual residential operational energy use was 65 GJ per household--a feasible amount given China's high growth after 1997 and Beijing's place among the country's most economically developed regions.

[33] Thormark C. 2000. "Environmental analysis of a building with reused building materials," *International Journal of Low Energy and Sustainable Buildings*, Vol. 1, 2000.

[34] Zhang QY. 2004. "Residential energy consumption in China and its comparison with Japan, Canada, and USA," *Energy and Buildings* 36, no. 12 (December 2004): 1217-1225.

Figure 9: Unit Lifecycle Energy Use among Beijing Case Study Residential Buildings

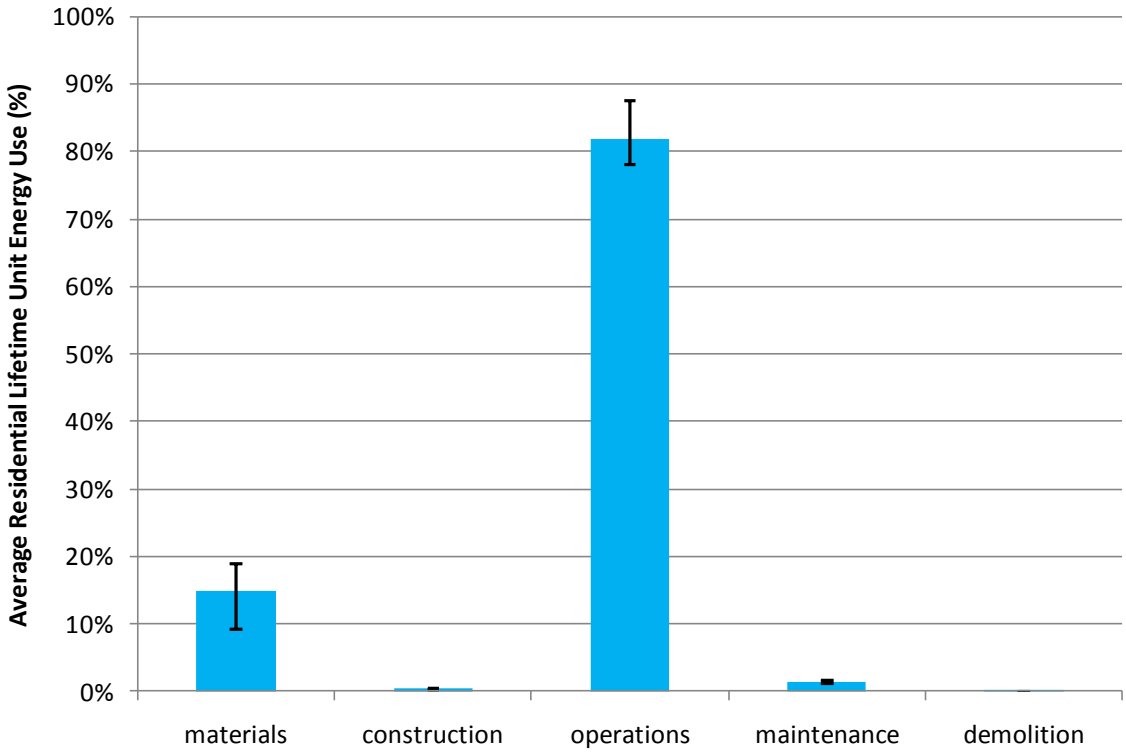


Note: operations energy use is linearly extrapolated over the expected lifetime of the building.

The results shown in Figure 10 underscore the importance of operations in building energy use insofar as they are based on an expected thirty-year lifespan. If residential buildings were used for more than thirty years the operations area of Figure 10 would expand beyond 82% of total unit lifetime energy use.[35] These findings reinforce the policy emphasis on operations for reducing building energy use and emissions. Residential building demolition and construction unit lifetime energy use amount to 6 and 126 MJ per square meter; however, demolition is displayed as zero percent in Figure 10 because it accounts for less than 0.05% of total lifetime unit energy use. Carbon emissions results directly mirror the energy results; the average residential building emissions were 2.5 tonnes carbon dioxide per square meter over the modeled lifetime. The error bars in Figure 10 illustrate the range of values among the six building case studies. The operational portion of total energy varied between 78% and 88% and the materials portion ranged from 9% to 19% of total, underscoring the site-specificity of each building LCA analysis.

[35] Assuming that marginal growth of operational energy use is greater than embodied energy requirements of building refurbishment, equipment replacement, and maintenance.

Figure 10: Average Portions of Residential Building Unit Lifetime Energy Use by Phase

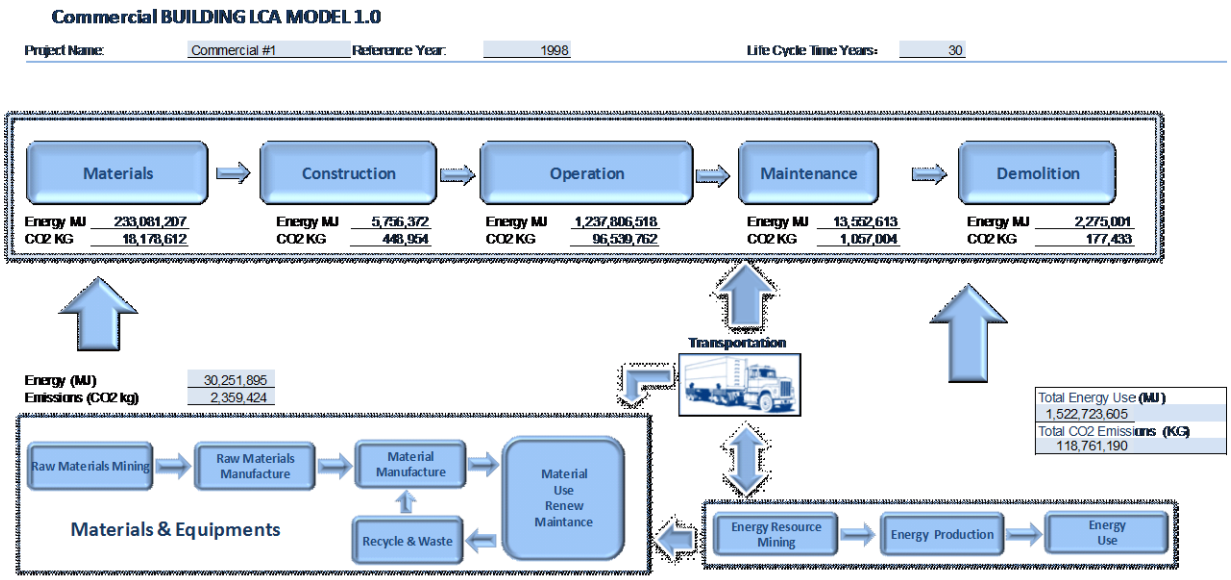


Note: error bars illustrate the variation among the six residential building case studies.

3.4. Commercial Building LCA Model

The commercial building LCA model is structured similarly to the residential model; key differences are that material, equipment, and energy-use intensities are higher and the EnergyPlus modeling tool is established in parallel with the operations module. Figure 11 shows the six modules of the commercial building LCA tool, as described in residential model above. Total energy use and related carbon dioxide emissions are calculated as a sum of each module.

Figure 11: Structure of Commercial Building LCA Model



The commercial building LCA model's structure, including its ability to model existing case studies or a newly-inputted test building, is identical to the residential LCA model. However, commercial-building material intensity values are on average 50% higher than residential buildings. Table 4 shows average intensity values for the four Beijing-area commercial building case studies. The material manufacturing and material transport intensity values are identical to those in the residential model.

Table 4: Average Commercial Building Material Intensity Values

Material	Material Intensity kg/m^2	Production Intensity MJ/kg	Transport Intensity MJ/kg
Section Steel	1.5	23	0.58
Steel Bar	73	23	0.58
Aluminum	4.9	270	2.1
Cement	260	5.3	0.25
Glass	8.1	20	0.12
Gypsum board*	43	8.6	1.1
Acrylic Rubber - Waterproofing*	59	10	1.1
Paint*	1.4	90	1.1
Wood	1.3	-	2.7
Copper	0.39	96	0.95

* Based on supplemental data from Vieira (2007).

The category of "commercial buildings" includes a wide range of structures from hotels, to hospitals, to government office buildings and shopping malls. The commercial building data for this study covered four office buildings in and around Beijing. Although they are all office buildings, each building has unique characteristics that

make for a range of material use values, separately from the varied material manufacturing and transport intensity values mentioned in the residential building section above. Aluminum use intensity, for example, varied from 2 kg to 9kg per square meter and glass use ranged from 1 to 12 kg per square meter among the four commercial case study buildings. The range of these values underscores the contingent site-specificity of building lifecycle assessment.

Figure 12: Structure of Commercial Building Materials LCA Module

BUILDING Materials

Project Name: Commercial #1 | Construction Year: 1998 | Construction Area (M2): 42,365 | Building Type: Office

Main Materials Manufacture / Transportation Energy Consumption

Index	Main Materials Names	Manufacture (MJ)	Transportation (MJ)
1	Section Steel	1,448,115	36,716
2	Steel Bar	70,550,435	1,788,738
3	Aluminum	54,989,783	443,585
4	Cement	57,938,374	2,701,767
5	Glass	6,871,794	41,573
6	Structure Ceramics	10,406,983	75,648
7	Clay Brick	533,208	60,171
8	Concrete	1,364,897	961,906
9	Wood	0	152,969
10	Copper	1,579,261	15,556
11	Sanitary Ceramics	13,769	15,145
		204,103,589	6,263,072

Aux Materials Manufacture / Transportation Energy Consumption

Index	Main Materials Names	Manufacture (MJ)	Transportation (MJ)
1	Acrylic Rubber - Waterproofing	2,492,333	2,741,566
2	Carpet Tile	63,124	69,436
3	Fireproofing	19,377,327	21,315,060
4	Curtain Wall	1,665,792	1,832,371
5	Epoxy Grout	63,124	69,436
6	Fire Retardant	446,527	491,180
7	Glass Fiber	89,856	3,262
8	Gypsum board	15,787,029	2,009,923
9	Insulation - Expanded Polystyrene	40,212,858	421,278
10	Iron	34,739	38,213
11	Paint	5,438,310	66,174
12	Plaster	968,888	1,065,776
13	Plywood	1,313,146	76,426
14	Polyethylene Sealant	4,422,906	55,922
15	Polypropylene - Piping	2,966	3,262
16	PVC-Waterstop	357,984	393,783
17	Reinforcing Steel	6,341,956	783,837
18	Resilient Flooring	871,024	958,127
19	Wood-Doors,Frames	28,385	31,223
20	Wood-Flooring	6,355	6,990
		14,313,608	3,375,347

Equipments Manufacture / Transportation Energy Consumption

Index	Main Equipments Names	Manufacture (MJ)	Transportation (MJ)
1	Kitchen equipment	33,083	2,406
2	Assembly and connection materials	9,624	331
3	Accessories for pipes	48,120	2,707
4	Boilers and furnaces	96,240	5,815
5	Engines	87,218	4,060
6	Material moving/handling machinery	120,300	9,774
7	Stereo System	0	0
8	Household electric appliances	401,000	93,734
9	Cable communicating equipment	481,200	58,346
10	Power generating equipment	195,488	8,120
11	On-off controllers	320,800	22,456
12	Lighting ballasts and equipment	154,385	16,842
13	Light bulbs	25,063	4,070
14	Metal wired products	184,460	20,050
15	Chillers	231,578	18,947
16	Pumps and compressors	62,155	4,110
17	Room Air Conditioners	1,139,054	8,122
18	Fan Coil	812,867	18,045
19	Elevator	300,600	24,424
		4,703,233	322,358

Manufacture (MJ)	223,120,430
Transportation (MJ)	9,960,777
Total (MJ)	233,081,207

Manu CO2 (KG)	17,401,745
Trans CO2 (KG)	776,867
Total CO2 Emi (KG)	18,178,612

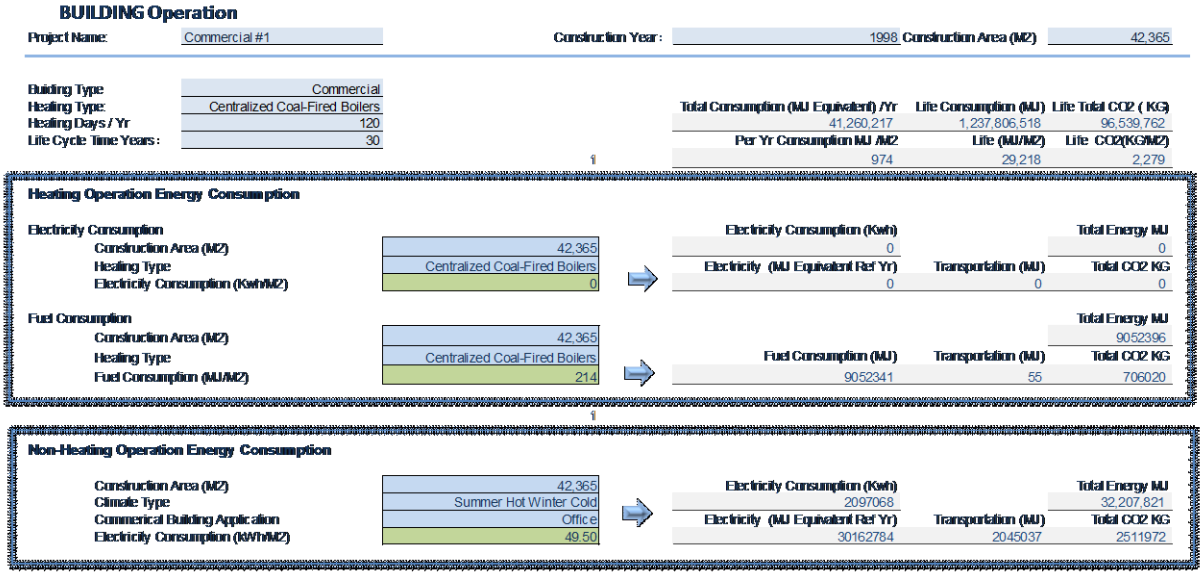
Each of the four Beijing commercial building case studies included data on material, manufacturing, and transport intensities of eleven key building materials and nineteen categories of equipment. This module quantifies the energy and emissions of the building materials production and transportation--it does not include primary resource extraction which is covered in a separate module (Figure 3). The materials section uses mass and intensity information of various construction inputs and equipment to calculate their related energy use, which is then aggregated at the module level. Total building materials energy use and emissions are calculated by aggregating manufacturing and transport energy use from the "Main Materials," "Auxiliary Materials," and "Equipment" subtotals (Figure 12). Auxiliary materials data from the U.C. Berkeley BuiLCA model were integrated into the commercial building LCA model on a material intensity basis--i.e., assuming the same usage of paint and epoxy grout per square meter. According the case study modeling results, overall unit energy (MJ/m^2) of commercial building materials is on average 20% higher than residential buildings.

The operations module of the commercial building model is comprised of two sections: an EnergyPlus simulation-based module and a simplified assessment tool based on Beijing case-study building data. Figure 13 shows the three modules of the simplified module, which is the default source of operations energy use and emissions data in the commercial building LCA model. The simplified module focuses on electricity and fuel use for heating and an aggregated, non-heating (cooling, lighting, and miscellaneous load) operational energy use category based on intensity information that varies by climate zone and commercial building type--i.e., office versus hotel, etc.[36] All of the commercial case studies in the study were office buildings and therefore exhibited more clustering that otherwise would have been the case. The average annual operational energy use of the Beijing case study commercial (office) buildings was 950 MJ per square meter--a feasible amount given the LEAP 2050 energy end-use model average commercial building operational intensity of 610 MJ/m^2 in 2008.[37]

[36] Intensity information is sourced from Tsinghua (2009) and Gu et al. (2007).

[37] The LEAP 2050 intensity value is an average value for all commercial buildings throughout China. An earlier iteration of the LEAP 2050 model is described in Appendix One of Aden N, et al. 2009. *How Can China Lighten Up? Urbanization, Industrialization, and Energy Demand Scenarios* Lawrence Berkeley National Laboratory Report LBNL-3527E.

Figure 13: Supplementary Operations Module of Commercial Building LCA Model



BUILDING Operation

Project Name:	Commercial #1	Construction Year :	1998	Construction Area (M2)	42,365

Building Type	Commercial			
Heating Type	Centralized Coal-Fired Boilers	Total Consumption (MJ Equivalent) /Yr	Life Consumption (MJ)	Life Total CO2 (KG)
Heating Days / Yr	120	41,260,217	1,237,806,518	96,539,762
Life Cycle Time Years :	30	Per Yr Consumption MJ /M2	Life (MJ/M2)	Life CO2(KG/M2)
		974	29,218	2,279

Heating Operation Energy Consumption

Electricity Consumption			Electricity Consumption (Kwh)		Total Energy MJ
Construction Area (M2)	42,365		0		0
Heating Type	Centralized Coal-Fired Boilers		Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Electricity Consumption (Kwh/M2)	0		0	0	0
Fuel Consumption					Total Energy MJ
Construction Area (M2)	42,365				9052396
Heating Type	Centralized Coal-Fired Boilers		Fuel Consumption (MJ)	Transportation (MJ)	Total CO2 KG
Fuel Consumption (MJ/M2)	214		9052341	55	706020

Non-Heating Operation Energy Consumption

Construction Area (M2)	42,365		Electricity Consumption (Kwh)		Total Energy MJ
Climate Type	Summer Hot Winter Cold		2097068		32,207,821
Commerical Building Application	Office		Electricity (MJ Equivalent Ref Yr)	Transportation (MJ)	Total CO2 KG
Electricity Consumption (kWh/M2)	49.50		30162784	2045037	2511972

In order to provide a more detailed analysis, an EnergyPlus operational module was established to run in coordination with the LBNL commercial building LCA model. EnergyPlus provides high-resolution modeling of the interaction between climate, design, and building energy use. The EnergyPlus modeling tool was set up to provide potential integration with future iterations of the commercial building LCA model. However the full capability of EnergyPlus was not utilized in this project due to data constraints and the results were not included in the final results. Figure 14 shows the structure of the EnergyPlus-linked operations module. Primary and final energy use are calculated based on U.S. values, in contrast with the China-specific values in the residential building LCA model. As with the residential building LCA model, EnergyPlus uses local climate data to model heating and cooling degree days and their energy impact.

Figure 14: Operations Module of LBL Commercial Building LCA Model

BUILDING Operation

Project Name:	Commercial #1	Construction Year:	1,998	Construction Area (M2)	42,365

Building Type:	Commercial
Heating Type:	Centralized Coal-Fired Boilers
Heating Days / Yr	120
Life Cycle Time Years:	30

Total Consumption (MJ Equivalent) /Yr	Life Consumption (MJ)	Life Total CO2 (KG)
56,833,071	1704992135	132976788
Total Consumption (MJ) /M2	**Life Consumption (MJ/M2)**	**Life Total CO2 (KG/M2)**
1342	40245	3139

Energy Plus Analysis

EnergyPlus Simulation General Information

Program Version:EnergyPlus 4.0.0.024, 12/7/2009 11:15 AM
Environment: Beijing Beijing CHN CTYW WMO#=545110
Simulation Timestamp: 2009-12-07 11:20:45

Annual Building Utility Performance Summary

Site and Source Energy

	Total Energy [GJ]	Per Total Building Area [MJ/m2]	Per Conditioned Building Area [MJ/m2]
Total Site Energy	20,616	445	445
Net Site Energy	20,616	445	445
Total Source Energy	62,139	1,342	1,342
Net Source Energy	62,139	1,342	1,342

End Uses

	Electricity [GJ]	Natural Gas [GJ]	Other Fuel [GJ]	District Cooling [GJ]	District Heating [GJ]	Water [m3]
Heating	0	4,181	0	0	0	0
Cooling	1,963	0	0	0	0	0
Interior Lighting	5,137	0	0	0	0	0
Exterior Lighting	39	0	0	0	0	0
Interior Equipment	6,688	0	0	0	0	0
Exterior Equipment	0	0	0	0	0	0
Fans	968	0	0	0	0	0
Pumps	801	0	0	0	0	0
Heat Rejection	551	0	0	0	0	12,580
Humidification	0	0	0	0	0	0
Heat Recovery	0	0	0	0	0	0
Water Systems	0	287	0	0	0	1,504
Refrigeration	0	0	0	0	0	0
Generators	0	0	0	0	0	0
	16,148	4,468	0	0	0	14,084

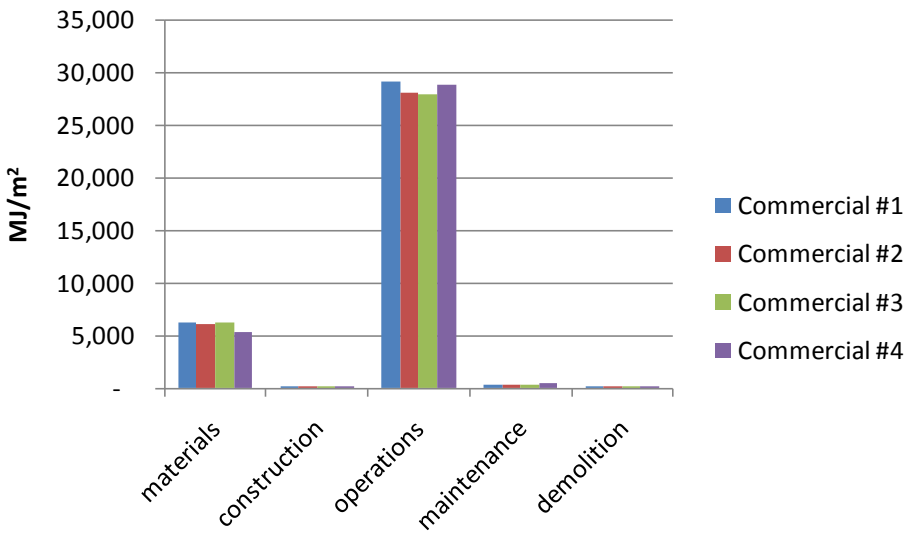
In its high detail and design sophistication, EnergyPlus underscores the specificity of each building's energy consumption and emissions dynamics. The design impact on energy use can be well captured in EnergyPlus, for example by incorporating the heating and lighting benefits of a given area of south-facing windows. Version 5.0 of EnergyPlus can also simulate the impact of water usage and on-site renewable energy generation. By incorporating onsite energy generation, the newest version of EnergyPlus is oriented toward model-based evaluation of zero operational energy buildings.

3.5. Commercial Model Results

The commercial building LCA model results are similar to the residential model insofar as operational energy use is the largest portion of unit lifetime energy use. The average lifetime commercial operational energy use among the four Beijing-area case studies was 29 GJ per square meter--5% higher than residential unit operational energy use. The carbon dioxide emissions results for the commercial building LCA analysis directly mirror the energy results because they are based on weighted average carbon

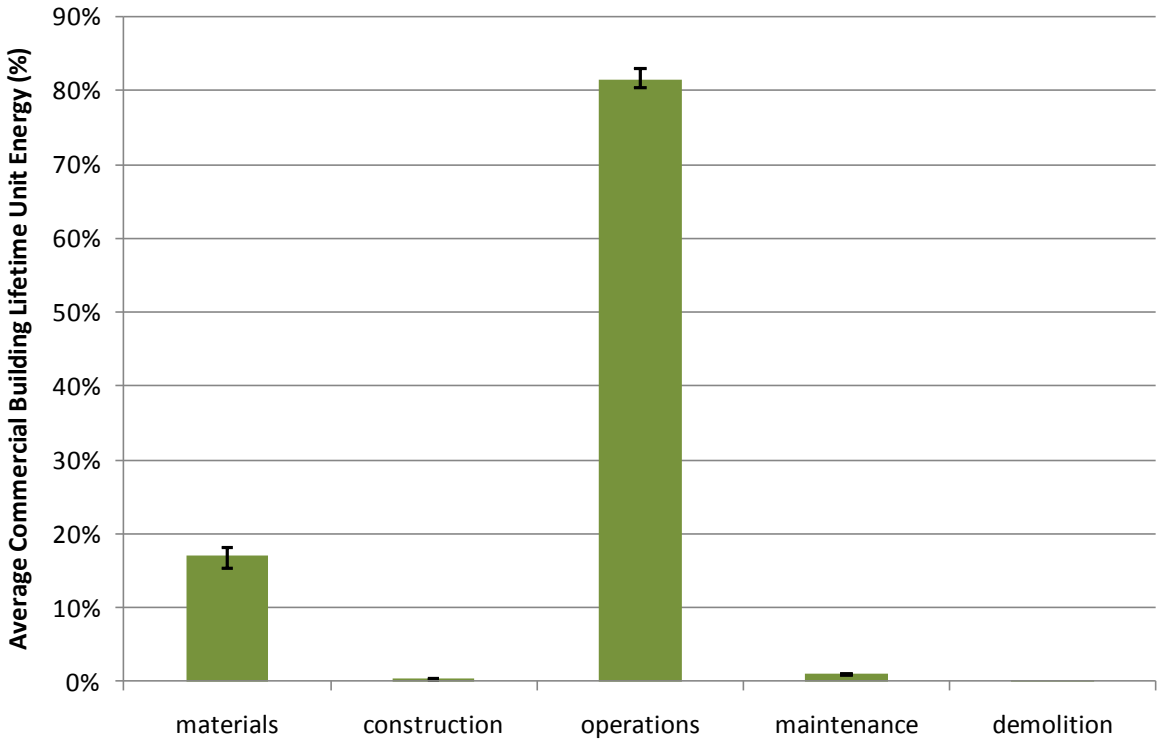
intensiveness of overall energy use. The average lifetime CO_2 emissions per square meter in the commercial buildings was 2.7 tonnes--7% higher than residential buildings.

Figure 15: Commercial Building Lifecycle Energy Consumption



The commercial LCA modeling results indicate that commercial buildings are more materials and operations intensive than residential buildings and less construction- and maintenance-intensive. This finding is reflected in the unbalanced distribution of commercial lifetime unit energy use. Figure 16 shows that operational energy use comprised an average 81% of total lifetime energy use while materials comprised an average 17%. Construction, maintenance, and demolition used 123 MJ/m^2, 345 MJ/m^2, and 54MJ/m^2 respectively; however, their portion of total lifecycle energy is insignificantly small, as illustrated in Figure 16. The implication of this result is that operations should be the first priority of policies aiming to reduce commercial building energy use and emissions.

Figure 16: Average Commercial Building Unit Lifetime Energy Use



The results of the residential and commercial building LCA analyses are confirmed by earlier research. In his article on urban construction in China, Fernandez (2007) found that "Commercial and residential buildings normally consume 80% of their life-cycle energy during this long use phase. The remaining 20% is partly accounted for in the embodied energy of materials of construction (approximately 12% to 18%) and energy in demolition (approximately 2% to 8%) or other end-of-life processes."[38] Other international assessments have provided varied results. A study of single-story office buildings in the U.K. found that embodied energy comprised 67% of operational energy, compared to an average 23% for commercial buildings in this study.[39] This is not, however inconsistent as most of the United Kingdom's climate is much cooler than China and building materials requirements are therefore likely to be higher. Likewise, a study of commercial buildings in Hong Kong found that office building materials and components comprised an average 33% of the total lifecycle impacts.[40] Whereas the LBNL building LCA model focuses on total energy use and emissions, the Hong Kong

[38] Fernández JE. 2007. "Resource Consumption of New Urban Construction in China," *Journal of Industrial Ecology* 11, no. 2 (2007): 99-115.

[39] Y. G. Yohanis and B. Norton, "Life-cycle operational and embodied energy for a generic single-storey office building in the UK," *Energy* 27, no. 1 (January 2002): 77-92.

[40] Chau CK et al. 2007. "Environmental impacts of building materials and building services components for commercial buildings in Hong Kong," *Journal of Cleaner Production* 15, no. 18 (December 2007): 1840-1851.

study quantified total lifecycle environmental impacts including human health, ecosystem quality, and resource depletion, each of which are likely to be disproportionately impacted by materials-related energy use. Absolute annual and lifetime energy use per square meter provides a more concrete basis of comparison; however, absolute China building lifetime energy intensity values are not widely available.

4. Policy Linkages

While lifecycle analysis presents the most comprehensive method for calculating building-related energy use and emissions, its data-intensiveness and contingent topology-specificity may limit the suitability of LCA for wide-scale policy usage. The most propitious policy applications of LCA are for building standards, performance evaluation and certification, and for calculating carbon emissions inventories. The LCA approach developed in this project can be used to identify best practices in all phases of the building lifetime that could then provide benchmarking assessment capability. Likewise, the LCA approach can be useful for standardizing and certifying the lifetime impact of building equipment and appliances. However, topologically-specific dynamics of building energy use limit the generalize-ability of building LCA findings to similar structures within a given climate zone; national-level standards need to account for local climate variation. Within building energy-related policies, the LCA approach developed here could also be used to conduct sensitivity analysis on the impact of building lifetime duration, materials recycling rate, materials manufacturing efficiency, and occupant density on total and per square meter building energy use and emissions, though these findings may also be highly situation-dependent.

Urbanization and economic growth are driving the expansion of building energy use and emissions in China. Within the building sector, multiple studies have found that efficiency improvements are the most cost-effective and timely method for mitigating demand growth and extending service provision.[41] Improvements of building operational energy efficiency often come at the cost of increased embodied energy. A 2010 study of a "low energy" residential building in Italy, for example, found that while the winter heat requirement was reduced by a ratio of 10:1 compared to a conventional building, the overall lifecycle impacts were only reduced by 2:1.[42] Building lifecycle assessment has also been used for comparative research in other countries. One key finding is that high energy embodiment of renewable and high efficiency operational energy technologies can outweigh their benefits over the lifetime of the building.[43]

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[41] Li J. 2008. "Towards a low-carbon future in China's building sector--A review of energy and climate models forecast," Energy Policy 36, no. 5 (May 2008): 1736-1747.

[42] Blengini GA and Di Carlo T. 2010. "The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings," *Energy and Buildings* 42, no. 6 (June 2010): 869-880.

[43] T. Ramesh, Ravi Prakash, and K.K. Shukla, "Life cycle energy analysis of buildings: An overview," *Energy and Buildings* 42, no. 10 (October 2010): 1592-1600.

Additional research has found that passive energy efficiency technologies have lower lifetime energy use than self-sufficient (i.e., zero commercial operational energy use) technologies.[44] As government policies begin to target the construction of so-called zero-energy buildings (ZEB), the LCA approach can help clarify the relationships between embodied and operational energy in different building types. In this way, building LCA modeling can help to inform building construction and equipment codes and renewable energy technology incentive policies.

Figure 17 shows a plot of annual energy use versus annualized embodied energy for each of the residential and commercial buildings covered in this study.[45] Annual energy use (AEU) is comprised of the unit operational energy use (MJ/m^2) while annualized embodied energy (AEE) is the sum of the materials, construction, maintenance, and demolition components of the total lifecycle unit energy use (MJ/m^2) divided by the assumed building lifespan. Annualized life cycle energy (ALCE) expresses the total primary energy use per year of a given building over its expected lifespan. ALCE captures both the embodied and operational aspects of building energy consumption. Building LCA modeling thereby adds a new dimension to the policy focus on zero-energy buildings: both operational and embodied energy are included in ALCE, as shown in the following equation.

$$ALCE = AEU + AEE$$

The Hernandez and Kenny (2010) approach gives rise to a new concept of lifecycle zero energy buildings (LC-ZEB) illustrated in the following equation.

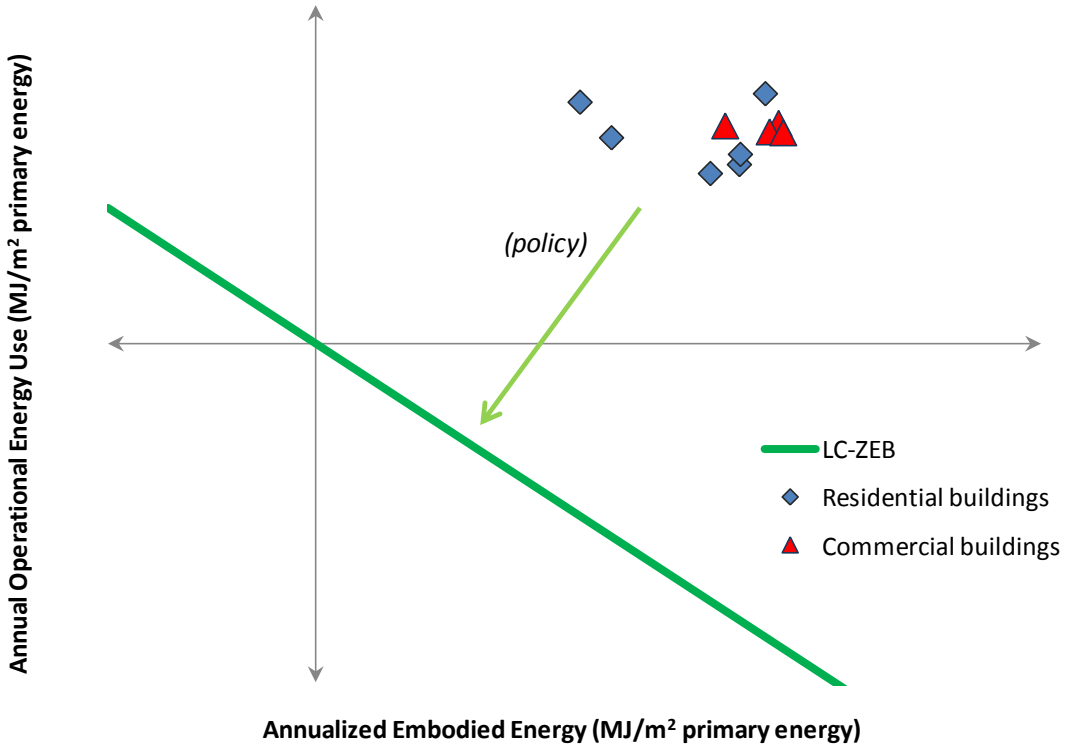
$$ALCE = AEU + AEE = 0$$

By using a lifecycle assessment approach, buildings with positive operational or embodied energy could still be considered "zero energy" as long as the sum of their annualized energy use is zero. The LC-ZEB approach helps to resolve the potential tradeoffs between operational and embodied energy efficiency. The diagonal arrow in Figure 17 illustrates the potential effect of LCA-based policy moving building performance toward an idealized LC-ZEB line.

[44] I. Sartori and A.G. Hestnes, "Energy use in the life cycle of conventional and low-energy buildings: A review article," *Energy and Buildings* 39, no. 3 (March 2007): 249-257.

[45] The concept for this figure and related analysis was originally published in Hernandez P and Kenny P. 2010. "From net energy to zero energy buildings: Defining life cycle zero energy buildings (LC-ZEB)," *Energy and Buildings* 42, no. 6 (June 2010): 815-821.

Figure 17: Annualized lifecycle energy of Beijing-area case study buildings and the lifecycle zero energy building (LC-ZEB) line



Aside from building-level efficiency performance, the 30-year average lifespan of Chinese buildings is detrimental to China achieving its national energy efficiency targets due to ongoing demand for industrial production of building materials. In April of 2010, the Vice-Minister of the Ministry of Housing and Urban-Rural Development (MOHURD), Qiu Baoxing, noted that "Chinese buildings can only stand for between 25 and 30 years. In contrast, the average life expectancy of a building in Britain is 132 years and they last around 74 years in the United States."[46] Tighter enforcement of construction standards will help to address this situation; another potential policy approach to extending the average useful lifetime of residential buildings in China is to expand the secondary (so-called "second hand") real estate market in China through tax and fiscal incentives. On a policy level, the LCA approach can be useful for quantifying the energy and environmental benefits of longer average building lifespans.

In addition to prospective analysis for standards and certification, building LCA can also be useful in calculating or verifying ex post facto, bottom-up carbon emissions inventories. Emissions inventories provide a benchmark for evaluating future outcomes and scenarios as well as an empirical basis for valuing low-carbon

[46] Qian YF. 2010. "'Most homes' to be demolished in 20 years," *China Daily*, August 7, 2010. Beijing: China Daily. (http://www.chinadaily.com.cn/china/2010-08/07/content_11113982.htm)

technologies. By highlighting the embodied energy and emissions of building materials, the LCA approach can also be used to identify the most intensive aspects of industrial production and the supply chain.

5. Conclusions and Further Work

The residential and commercial building models developed in this project show the costs and benefits of applying lifecycle assessment methods to buildings. Among the shortcomings, the aggregations and assumptions inherent in LCA undermine its accuracy and long-term validity. For example, while the aggregation of all energy use into megajoules facilitates comparisons and lifecycle continuity, it also simplifies and distorts the carbon implications of different building situations. Likewise, the assumption of frozen operational energy use over the entire building lifespan ignores the trend of increasing plug loads, changing end-use efficiency, and demographic shifts. Nonetheless, the LCA models developed here can be useful for quantifying dynamics of building energy use and emissions, and for facilitating overall efficiency improvements.

Each of the six modules of the LBNL building LCA model has areas of potential improvement. The raw materials sub-module is limited by the exclusion of building site-specific data on the energy and resource requirements of mining, extraction, processing, and transportation. A more comprehensive LCA would also include the energy requirements of energy provision. The materials module is contingent on accurate local mass data that was not available for all materials for case study buildings covered in this project. Rather than grafting selected American commercial building material data onto the Chinese case study buildings, as this study did, local data should be used throughout any future, improved LCA assessment. The construction module was a first-order approach based on construction area, building height, and construction technology--a more detailed, site-specific assessment should be use in future, improved LCA analysis. Lack of building-specific appliance and equipment ownership and usage data limited the fidelity of the operations module. The operations module is further complicated by changing plug loads and efficiencies over the lifetime of the building--an issue that was avoided in this study by freezing current operational energy use over the expected lifespan. The maintenance module is sensitive to equipment stocks and replacement rates--these data should be further localized and improved through survey research in future LCA analysis. Finally, the demolition module assumed constant intensity across all building types for lack of site-specific data for a process that has yet to occur. Aside from its gross simplicity, the demolition module did not fully resolve the issue of energy and emissions credits for recycled materials. The LBNL building LCA models were a first-order effort at using the lifecycle assessment approach to facilitate building energy efficiency policy making in China--their results should not be considered for enduring data so much as an indicator of potential work to come.

Increased emphasis on sustainability necessitates a lifecycle approach to fully understand the relationship between embodied and operational energy use in buildings. However, the wide range of required data and diversity of stakeholders throughout a building's lifecycle challenge the semantic integrity of a single model, especially given the wide variation of building components and topologies. The LBNL building LCA model described here focused on total energy use and emissions output to inform energy efficiency policy making. A related area that would benefit from further research is the development of lifecycle building performance assessment (LBPA) tools geared toward actors more directly involved than policy makers.[47]

The most useful elaboration of the residential and commercial building LCA models would be to further generalize them for comparative analysis. Scenario analysis could be used for benchmarking and identification of policy priorities. If the models are to be used for inventories, it is important to disaggregate the energy use data for more accurate emissions modeling. Depending on the policy integration of the models, it may be useful to incorporate occupancy data for per-capita results. On the question of density and efficiency, it may also be useful to integrate an explicit spatial scaling mechanism for modeling neighborhood and city-level energy use and emissions.

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