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Urban Form Energy Use and Emissions in China: Preliminary Findings and Model Proof of Concept

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Contents

Executive Summary 1

1. Introduction 2

2. Existing Research 3

2.1. Scope of Analysis 3

2.2. Published Data 4

2.3. Urban Form Energy and Emissions Measurement Tools 5

2.4. Lifecycle Assessment Modeling Approaches 6

3. Data, Model Structure, and Results 7

3.1. LuJing Case Study Description 7

3.2. Data Sources 9

3.3. Model Structure 10

3.3.1. Urban Form LCA Model 11

3.3.2. Agent Based Modeling (ABM) 15

3.4. Results 17

3.4.1. Embodied Energy and Emissions 19

3.4.2. Building Operational Energy and Emissions 21

3.4.3. Personal Transportation Energy and Emissions 22

4. Overall Findings 24

5. Policy Linkages 24

6. Conclusions and Further Work 28

Acknowledgments 30

References 31

Appendix 1: Survey Form 34

List of Figures

Figure 1: Artist's Rendering of Jinan LuJing Superblock 8
Figure 2: Structure of LBL Urban Form Assessment Model 11
Figure 3: Structure of Urban Form Building Raw Materials Production LCA Sub-Module 12
Figure 4: Structure of Urban Form Building Material LCA Module 13
Figure 5: Construction Module of Urban Form Building LCA Model 14
Figure 6: Maintenance Module of Urban Form Building LCA Model 14
Figure 7: Demolition Module of Urban Form Building LCA Model 15
Figure 8: Snapshot of LBL Agent-Based Model of LuJing Residential Development 16
Figure 9: LuJing Residential Development Embodied and Operational Energy Use 18
Figure 10: Structure of LuJing Embodied Energy Use 19
Figure 11: Portions of LuJing Buildings-Related Total Lifetime Energy Use by Phase 20
Figure 12: Structure of LuJing Household Consumption-related Embodied Energy 21
Figure 13: Structure of LuJing Buildings' Operational Energy Use 22
Figure 14: LuJing Personal Transportation Energy Use by Mode 23
Figure 15: Annualized lifecycle energy of LuJing compared to Beijing-area case study buildings and the lifecycle zero energy building (LC-ZEB) line 26

List of Tables

Table 1: Select Urban Energy Use and Emissions Tools 5
Table 2: Jinan Per-Capita Income and Expenditures (2006) 9
Table 3: Assumed Fuel Energy Coefficients 10
Table 4: LuJing Embodied and Operational Energy Use and Emissions 18
Table 5: LuJing and China Average Urban Household Vehicle Ownership Rates (2008) 23
Table 6: California State- and City-Level Energy and Environmental Policies 28

Executive Summary

Urbanization is reshaping China's economy, society, and energy system. Between 1990 and 2008 China added more than 300 million new urban residents, bringing the total urbanization rate to 46%. The ongoing population shift is spurring energy demand for new construction, as well as additional residential use with the replacement of rural biomass by urban commercial energy services. This project developed a modeling tool to quantify the full energy consequences of a particular form of urban residential development in order to identify energy- and carbon-efficient modes of neighborhood-level development and help mitigate resource and environmental implications of swelling cities.

LBNL developed an integrated modeling tool that combines process-based lifecycle assessment with agent-based building operational energy use, personal transport, and consumption modeling. The lifecycle assessment approach was used to quantify energy and carbon emissions embodied in building materials production, construction, maintenance, and demolition. To provide more comprehensive analysis, LBNL developed an agent-based model as described below. The model was applied to LuJing, a residential development in Jinan, Shandong Province, to provide a case study and model proof of concept.

This study produced results data that are unique by virtue of their scale, scope and type. Whereas most existing literature focuses on building-, city-, or national-level analysis, this study covers multi-building neighborhood-scale development. Likewise, while most existing studies focus exclusively on building operational energy use, this study also includes embodied energy related to personal consumption and buildings. Within the boundaries of this analysis, food is the single largest category of the building energy footprint, accounting for 23% of the total.

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, urban form modeling 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 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. The agent based modeling aspect of the model can be useful for understanding how policy incentives can impact individual behavior and the aggregate effects thereof.

The most useful elaboration of the urban form assessment model would be to further generalize it for comparative analysis. Scenario analysis could be used for benchmarking and identification of policy priorities. If the model is 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 model, 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 a more explicit spatial scaling mechanism for modeling neighborhood and city-level energy use and emissions, i.e. to account for scaling effects in public infrastructure and transportation.

Urban Form Energy Use and Emissions in China: Preliminary Findings and Model Proof of Concept

1. Introduction

Urbanization is reshaping China's economy, society, and energy system. Between 1990 and 2008 China added more than 300 million new urban residents, bringing the total urbanization rate to 46%.[1] This population shift has spurred energy demand for construction of new buildings and infrastructure, as well as additional residential use with the replacement of rural biomass by urban commercial energy services.[2] End-use efficiency, population density, and structural characteristics of economic development influence the growth of energy demand and carbon emissions. By 2030 China's urbanization rate is expected to reach 70%, with cities adding more than 400 million new residents between 2010 and 2030.[3] This project developed a modeling tool to quantify the full energy consequences of a particular form of urban residential development in order to identify energy- and carbon-efficient modes of neighborhood-level development and help to mitigate the resource and environmental implications of swelling cities.

In the first phase of this project Lawrence Berkeley National Laboratory (LBNL) used survey data gathered by collaborators at Shandong University, Tsinghua University, MIT, and Beijing Normal University to develop a tool for measuring the energy and carbon implications of a specific urban residential development in Jinan City, Shandong Province. LBNL developed a hybrid modeling tool that combines lifecycle assessment with agent-based modeling. The lifecycle assessment approach was used to quantify the energy and emissions embodied in building materials production, construction, maintenance, and demolition. To broaden the analysis beyond the building, an agent-based model was constructed to describe the energy and carbon implications of building operations (e.g., appliance use and climate control), personal transportation (e.g., commuting to work), and personal consumption (e.g., annual food consumption). Energy use and carbon emissions from these three areas were calculated on the basis of aggregated individual behavior as described by survey results and Jinan Statistical Yearbook data. The resulting hybrid model was populated with case study data from the LuJing superblock residential development in Jinan to provide a proof of concept of the model assumptions and structure.

Over the following four sections, this report describes related existing research, the LBNL urban form assessment model and its results, policy linkages of this assessment, and conclusions and recommendations for further work. The LBNL model is a first-order approach to using local data for lifecycle assessment and agent-based modeling of urban form energy use and emissions--it represents a proof of concept for sub-city-level energy analysis. This report identifies the benefits, limitations, and

[1] National Bureau of Statistics (NBS) 2009. *China Statistical Yearbook 2009*.
[2] Aden N, et al. 2009. *How Can China Lighten Up? Urbanization, Industrialization, and Energy Demand Scenarios*. Lawrence Berkeley National Laboratory Report LBNL-3527E.
[3] Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, *World Population Prospects: The 2008 Revision*, http://esa.un.org/unpp; China Energy Research Institute (ERI), 2009.

policy applications of combined lifecycle assessment and agent-based modeling for quantifying the energy and emissions impacts of neighborhood-level residential developments.

2. Existing Research

This project is differentiated from the vast array of published research by its scale, modeling approach, and China focus--most projects have used simulation data or statistical extrapolation to focus on either building- or city-level energy and emissions assessment in the United States or Europe.

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.[4] 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.[5] 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*).[6] 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.

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

[4] 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.
[5] 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.
[6] Elcock D. 2007. "Lifecycle Thinking within the Oil and Gas Exploration and Production Industry," Argonne National Laboratory Report ANL/EVS/R-07/5.

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.[7] This study uses multiple Chinese and international data sources to perform WPCG LCA analysis of a sample urban residential development in Shandong province.

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 and agent-based models for building and occupant-related energy use. 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, as well as the embodied energy related to personal consumption. This study does not include the public infrastructure required to support residential developments. 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 as its primary output.

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.[8] 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.[9] 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.

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[7] 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.

[8] 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.

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

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.[10] 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).

Beyond building energy use, there is a wide range of published data relating to transportation energy use and emissions, consumption-related energy use and emissions, and city-level energy use in China. The transformation of transportation systems in China has spurred a bevy of academic publications; this study incorporates recent data from academic sources--e.g., Cherry (2009).[11] The energy and carbon emissions impacts of household energy use have also been analyzed in China based on published National Bureau of Statistics data.[12] Likewise, top-down analysis has been used to perform comparative assessment of energy use and emissions in Chinese cities.[13]

2.3. Urban Form Energy and Emissions Measurement Tools

Given the lack of national-level energy and environmental initiatives during the early 2000's, a number of US states and cities implemented their own policies. A range of tools was developed to support these sub-national policies, including the four tools listed in Table 1 below. Whereas the WRI and UrbEmis tools are freely distributed online, the ICLEI and ITE tools are only available by subscription or purchase.

Table 1: Select Urban Energy Use and Emissions Tools

Tool Name	Scope	Purpose
WRI/WBCSD GHG Protocol	National-level sectoral modeling tool using IPCC coefficients and assumptions	Development of sector GHG emissions inventories
ICLEI CACP Tool	Community or government-agency level assessment	Tool for community or government agency emissions inventory and forecast analysis
UrbEmis Environmental Management Software	California air districts, urban areas	Estimate air emissions related to land use and transportation
ITE Trip Generation Manual	US national-level data on transportation and land use	Simulate transportation behavior and land use based on US historical

[10] 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 (accessed October 10, 2010).
[11] Cherry CR, et al. 2009. "Comparative environmental impacts of electric bikes in China," *Transportation Research Part D: Transport and Environment* 14, no. 5 (July 2009): 281-290.
[12] Feng ZH, et al. 2010. "The impact of household consumption on energy use and CO2 emissions in China," *Energy* In Press, 2010.
[13] Dhakal S. 2009. "Urban energy use and carbon emissions from cities in China and policy implications," *Energy Policy* 37, no. 11 (November 2009): 4208-4219.

		data

The International Council for Local Environmental Initiatives (ICLEI) was founded in 1990; in 2003 the International Council for Local Environmental Initiatives was renamed 'ICLEI—Local Governments for Sustainability'.[14]

URBEMIS stands for "Urban Emissions Model." It was developed for the Air Resources Board of the California Environmental Protection Agency in 2007. The model estimates air pollution emissions in tons per year for various land uses, area sources, construction projects, and project operations. Mitigation measures can also be specified to analyze the effects of mitigation on project emissions.[15]

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.[16] 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 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.[17] On the urban form level the World Bank's Energy Sector Management Assistance Program (ESMAP) has been working on developing an integrated urban model for responding to climate change in cities.[18]

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.[19] A well-known example of economic input-output LCA in the United States is the Carnegie Mellon EIO LCA.[20] 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

[14] ICLEI. 2010. " Chronology of Efforts of ICLEI on Local Climate Action," http://www.iclei.org/fileadmin/user_upload/documents/Global/Progams/CCP/Introduction/ICLEI_Climate_Chronology.pdf (accessed October 10, 2010).
[15] "Urbemis 2007 Program," http://www.arb.ca.gov/planning/urbemis/urbemis2007/urbemis2007.htm (accessed October 23, 2010).
[16] 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.
[17] BEES software is freely available at http://www.bfrl.nist.gov/oae/software/bees/.
[18] World Bank (ESMAP). 2009. " Energy Efficient Cities Initiative: Tools & Assessments," available at http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1256566800920/boydell.pdf.
[19] 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.
[20] Carnegie Mellon EIO LCA data are freely available at http://www.eiolca.net/.

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.[21]

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.[22] 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).[23] 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.[24]

3. Data, Model Structure, and Results

The LBNL urban form assessment tool is designed to calculate emissions inventory and energy footprint information as well as provide cross-sectional information for understanding the relationship between urban form, energy use, economic development, and socio-demographic patterns. The independent variables are urban form typology, household income, behavior, building characteristics, personal transportation, and household size. The dependent variables of the model are energy use and emissions per capita and per square meter.

3.1. LuJing Case Study Description

Jinan is the capital of Shandong Province in Northeastern China, located about 400 km south of Beijing. As with other areas of Northeastern China, the climate is defined by hot summers and cold winters. The total population of Jinan is approximately 6 million residents. In 2007, Jinan GDP was calculated at 256

[21] Vieira, PMdS (2007) *Environmental Assessment of Office Buildings*. U.C. Berkeley Doctoral Dissertation in Civil and Environmental Engineering.
[22] The GREET model is freely available at http://www.transportation.anl.gov/modeling_simulation/GREET/.
[23] 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.
[24] Gu, D. et al. 2007. "A Lifecycle Assessment Method for Buildings," *Proceedings: Building Simulation* 2007:1595-1600.

billion RMB or 42,000 RMB GDP per capita--more than double the 2007 national average per-capita GDP of 20,000 RMB.[25]

The LuJing residential development was built in 2002. The development includes 540 units among more than a dozen buildings with a total construction area of 63,000 m^2. This analysis is based on background information on the LuJing development as well as survey responses from 230 households. This study assumes that the 230 household responses are representative of the entire LuJing residential development; aggregate LuJing results are linearly scaled up from survey-based analysis.

Figure 1: Artist's Rendering of Jinan LuJing Superblock

Source: http://www.jndxzy.com/xmjc_2.asp?id=458; accessed 10.8.2010.

The LuJing residential development is situated on a bus rapid transit line near the center of Jinan. According to survey responses, average annual per-capita income in this development is approximately double the Jinan 2006 average of 17,000 RMB.[26] The average household size among LuJing residents (3.23 versus 2.88 for all Jinan residents) suggests that many families live in the development. Rather

[25] National Bureau of Statistics. 2009. *China Statistical Yearbook 2009*. Beijing: China National Statistics Press.
[26] National Bureau of Statistics. 2007. *Jinan Statistical Yearbook 2007*. Jinan: NBS.

than representing the average Jinan residential situation, the LuJing development illustrates a relatively luxurious lifestyle to which many urban residents apparently aspire.

3.2. Data Sources

This study relied on a range of published and unpublished data sources from China and the United States. The residential survey data were collected by graduate students from Shandong University and MIT in 2009.[27] Per-capita income and expenditure data from the 2007 Jinan Statistical Yearbook were combined with survey income data to disaggregate residential consumption types. Table 2 below shows the breakdown of personal expenditure by income category among average Jinan residents in 2006. The personal consumption portion of this study focused on the five categories listed in Table 2, i.e., food, clothing, household appliances and services, healthcare, and housing services (e.g., mortgage and insurance). Matrix data from China's 2005 National Input-Output tables were used to calculate the embedded energy use in personal consumption and household expenditures. Assumptions and approximations were necessary to link the expenditure and input-output data. All clothing was assumed to be textiles, the energy intensity of household appliances was assumed to be equivalent to "other manufacturing industry," the energy intensity of healthcare was assumed to be equivalent to the "sales, hotel, and restaurant" sector, and housing expenditure energy intensity was equated with "finance and insurance" sector. The building LCA component of the model was supported by case study data from Beijing and California.[28] Beijing is in the same climate zone as Jinan and therefore likely to share heating and cooling characteristics; however, this project did not review city building codes and enforcement in both cities--i.e., there may be differences. Building maintenance energy use for HVAC, window cleaning, and roof maintenance, for example, was estimated for China's situation based on California data.[29] Energy conversion factors are from national-level data published by China's National Bureau of Statistics.

Table 2: Jinan Per-Capita Income and Expenditures (2006)

relative income	income category	expenditure on food	expenditure on clothing	expenditure on HH appliances & services	expenditure on healthcare	expenditure on housing
% total population	RMB/person/year	%	%	%	%	%
<5% (lowest income)	4,618	37%	5%	3%	6%	13%
(60-80%)	20,264	20%	7%	3%	4%	6%
80-90%	26,944	20%	9%	6%	7%	6%
>90%	40,204	11%	5%	4%	5%	8%
>95% (highest income)	47,206	9%	5%	3%	3%	5%

Both lifecycle assessment and empirically-based agent-based modeling are data-intensive modeling techniques. This study brings together data and results from four collaborating international institutions--Shandong University collected the Jinan survey data, Tsinghua University collected the building LCA data, MIT cleaned the data and performed separate analysis, and LBNL added national and

[27] A copy of the survey form is included in the Appendix of this report.

[28] Tsinghua University. 2009. 北京居住建筑与商业建筑含能研究, 阶段报告, （第一部分：模型和数据）Energy Foundation Interim Report. Beijing: Energy Foundation. For more information see Aden N, et al. 2010. *Lifecycle Assessment of Beijing-Area Building Energy Use and Emissions: Summary Findings and Policy Applications*. Lawrence Berkeley National Laboratory Report LBNL-3939E.

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

local energy data for this analysis. Material intensity and energy use data are becoming more available at the local and national level in China; however, it is not clear whether the detailed data required for building LCA and survey-based Agent-Based Modeling of household direct and indirect energy use are consistent and reliable enough to support this type of analysis in a policy context.

3.3. Model Structure

LBNL developed an integrated modeling tool that combines process-based lifecycle assessment with agent-based building operational energy use, personal transport, and consumption modeling. The lifecycle assessment approach was used to quantify energy and carbon emissions embodied in building materials production, construction, maintenance, and demolition. To provide more comprehensive analysis, LBNL developed an agent-based model as described below. The building LCA portion of the model is based on spreadsheet-based lifecycle assessment modules covering each stage and component within the buildings' expected lifespan.

Table 3: 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

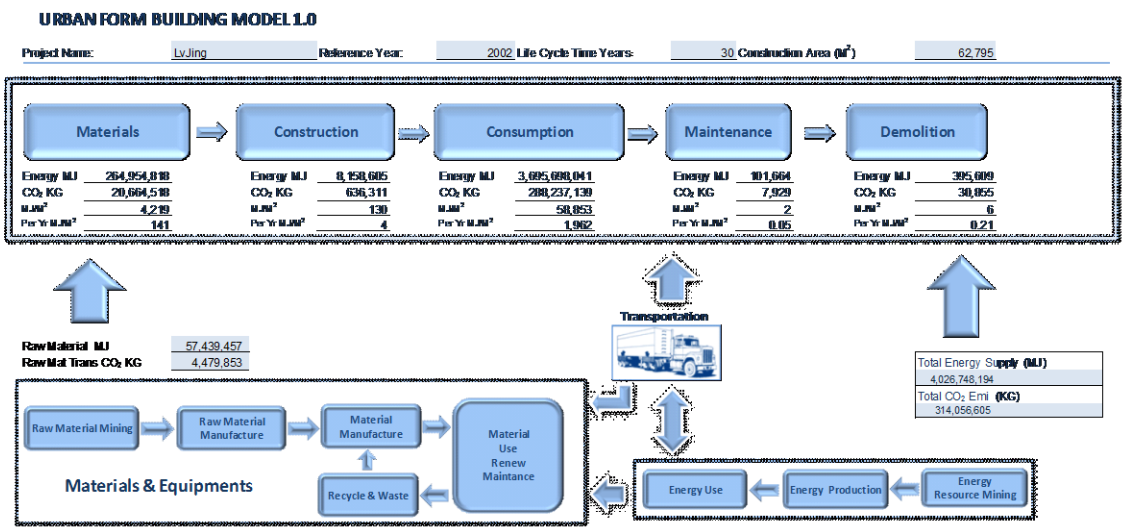
All forms of energy use including household electricity and diesel use for construction are aggregated into a common unit of primary-equivalent megajoules throughout the study to integrate inconsistent data sources (some data were in final, physical unit, while others were already aggregated), provide comparability, and enhance analytical flow. Table 3 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.[30] While it facilitates consistent analysis based on varied data sources, this study's aggregation of all energy use data limits energy-use and emissions results to approximate values based on national average fuel mix. A fuel-specific disaggregated approach would be a useful elaboration to include in future work--particularly regarding emission--if data are available. In this project 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 average carbon intensity of energy used in this study was 0.08 kg CO_2 per megajoule.[31] 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 of energy and electricity heat rates are fixed over the lifetime of each building. The carbon emissions analysis in this project is only useful for first order approximation of energy-use implications.

[30] National Bureau of Statistics. 2009. *China Energy Statistical Yearbook 2009*. Beijing: NBS.
[31] This figure is consistent with China's overall 2007 emissions of 6 billion tonnes carbon dioxide related to 82 exajoules of energy use.

3.3.1. Urban Form LCA Model

The urban form LCA model is comprised of six sections, as shown in Figure 2 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 development, for example covering the diesel fuel used by earth-moving equipment. Operation of the occupied buildings is the fourth and largest module of the model, in terms of energy use and related carbon dioxide emissions. The operational energy use and emissions are assessed by an agent based model separate from the LCA model as described below. 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 phase is calculated as the sum of these six components, as discussed after Table 3 above.

Figure 2: Structure of LBL Urban Form Assessment Model



The model is structured to display results for the lifetime of a single development--in this case the Lu Jing development in Jinan. Data in the building LCA model are based on six case study residential buildings in the Beijing area.[32] The Beijing residential building data vary widely among case studies and are a source of uncertainty in this analysis.[33] Comprehensive, Lu Jing specific building material use intensity and transportation data were not available for this study; therefore, Beijing residential building

[32] Tsinghua University. 2009. 北京居住建筑与商业建筑含能研究, 阶段报告, （第一部分：模型和数据）Energy Foundation Interim Report. Beijing: Energy Foundation.

[33] For more discussion of the Beijing building data quality and scope, see Aden N, et al. 2010. *Lifecycle Assessment of Beijing-Area Building Energy Use and Emissions: Summary Findings and Policy Applications*. Lawrence Berkeley National Laboratory Report LBNL-3939E.

data were used as proxies. Construction area and building construction-type data from the Lu Jing development were used to adjust the Beijing-based building LCA model inputs. Figure 2 shows the results of inputting Lu Jing development data into the building LCA model.

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

URBAN FORM BUILDING RAW Materials

Project Name: LvJing Construction Year: 2,002 Construction Area (M2) 62,795

Raw Materials

Main Materials	Amount(KG)	Raw Materials	Raw Materials Amount (KG)	Manufacture Energy (MJ)	Transportation (MJ)
Cement	15384775	Limestone	20,000,208	600,006	10,800
Cement		Sandstone	1,230,782	36,923	665
Cement		Gypsum	769,239	23,077	415
Cement		Cement clay	3,076,955	92,309	1,662
Cement		Water	153,848	4,615	83
Steel	3007880.5	Water	133,342,350	4,000,271	72,005
Steel		Manganese ore	102,258	3,068	55
Steel		Limestone	676,773	20,303	365
Steel		Magnesium limestone	481,251	14,438	260
Steel		Fluorite	6,016	180	3.2
Steel		Iron-ore	3,350,779	100,523	1,809
Aluminum	179593.7	Water	2,945,337	88,360	1,590
Aluminum		Aluminum-ore	42,923	1,288	23
Aluminum		Limestone	718	22	0.4
Aluminum		Salt	2,873	86	1.6
Clay Standard Brick	1525918.5	Clay	3,814,796	114,444	2,060
Clay Standard Brick		Soot	16,785	504	9
Aeroconcrete	2141309.5	Limestone	741,535,480	22,246,064	400,429
Aeroconcrete		Sandstone	9,250,457	277,514	4,995
Aeroconcrete		Gypsum	14,346,774	430,403	7,747
Aeroconcrete		Cement clay	23,126,143	693,784	12,488
Aeroconcrete		Water	134,260,106	4,027,803	72,500
Aeroconcrete		Freestone	770,871,420	23,126,143	416,271
Aeroconcrete		Manganese ore	25,696	771	14
Aeroconcrete		Magnesium limestone	102,783	3,083	56
Aeroconcrete		Iron-ore	715,197	21,456	386
Aeroconcrete		Soot	7,325,420	219,763	3,956
Glass	270646.45	Water	146,420	4,393	79
Glass		Siliceous raw material	171,049	5,131	92
Glass		Sandstone	171,049	5,131	92
Glass		Magnesium limestone	40,597	1,218	22
Glass		Limestone	13,532	406	7
Glass		Mirabilite	2,706	81	1
Glass		Tin-ore	9	0.28	0.00
Glass		Salt	38,702	1,161	21
Ceramics	1965483.5	Water	458,744	13,762	248
Ceramics		Clay pits	1,503,988	45,120	812
Ceramics		Pyrophyllite	380,518	11,416	205
Ceramics		Kaolin	86,088	2,583	46
Ceramics		Feldspar	72,526	2,176	39
Ceramics		Lead frit	23,193	696	13
Ceramics		Sodium fluosilicate	1,179	35	1
Ceramics		Pencil stone	410,786	12,324	222
Ceramics		calcium carbonate	410,786	12,324	222
Copper	12559	Water	5,070,068	152,102	2,738
Copper		Copper ore	99,543	2,986	54
Copper		Limestone	18,085	543	10
Copper		Quartz	9,042	271	5
Copper		Cast iron Ball	2,198	66	1.2
Copper		Sulphuric acid	85,401	2,562	46
Copper		Magnesite brick	678	20	0.4
Copper		Coke	4,006	120	2.2
		Energy Consumption MJ		56,423,828	1,015,629
		Total Energy MJ			57,439,457
		CO2 Emission KG		4,400,642	79,212
		Total CO2 Emission			4,479,853

Source: LBNL China Building LCA Model (Aden, et al. 2010)

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 urban form buildings raw materials production module for LuJing based on the Beijing-area building case study data. 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.

The building material module quantifies 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" and "Equipment" subtotals. Figure 4 illustrates the key parameters of the building materials module; aside from material and equipment information, the module includes qualitative "household type" information regarding average unit area, occupancy, and density--these data are included for future research and do not influence current results.

Figure 4: Structure of Urban Form Building Material LCA Module

URBAN FORM BUILDING Materials

Project Name: LvJing | Construction Year: 2,002 | Construction Area (M2) 62,795 | Household Type: Family

Main Materials Manufacture / Transportation Energy Consumption

Index	Main Materials Names	Manufacture (MJ)	Transportation (MJ)
1	Section Steel	7,000,073	177,480
2	Steel Bar	61,429,209	1,557,478
3	Aluminum	47,793,475	385,535
4	Cement	80,923,917	3,773,623
5	Glass	5,426,461	32,829
6	Structure Ceramics	40,353,951	293,330
7	Clay Brick	2,976,411	335,877
8	Concrete	2,850,735	2,009,045
9	Wood	0	598,928
10	Copper	1,208,176	11,901
11	Sanitary Ceramics	188,385	20,722
		248,754,232	9,164,125

Equipments Manufacture / Transportation Energy Consumption

Index	Main Equipments Names	Manufacture (MJ)	Transportation (MJ)
1	Kitchen equipment	31,680	2,304
2	Bolts and Nuts	9,216	317
3	Accessories for pipes	46,080	2,592
4	Boilers and furnaces	92,160	5,568
5	Engines	83,520	3,888
6	Material moving/handling machinery	115,200	9,360
7	Stereo System	5,280	1,118
8	Household electric appliances	384,000	89,760
9	Cable communicating equipment	460,800	55,872
10	Power generating equipment	187,200	7,776
11	On-off controllers	307,200	21,504
12	Electric lighting	147,840	16,128
13	Light bulbs	24,000	3,898
14	Metal wired products	176,640	19,200
15	Chillers	221,760	18,144
16	Pumps and compressors	59,520	3,936
17	Room Air Condition	3,096,614	22,080
18	Fan Coil	778,406	17,280
19	Elevator	470,400	38,220
		6,697,517	338,945

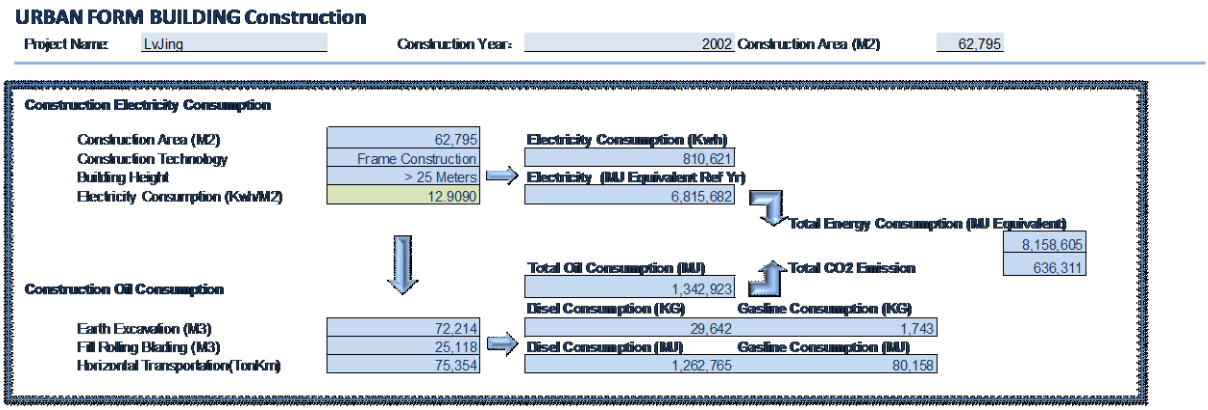
Manufacture (MJ)	255,451,748
Transportation (MJ)	9,503,070
Total (MJ)	264,954,818

Manufacturing CO2 (KG)	19,923,349
Transportation CO2 (KG)	741,169
Total CO2 Emi (KG)	20,664,518

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 the LuJing residential development was built using frame construction, which requires an average 130 MJ per square meter for earth excavation, blading, and other construction-related activities. 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

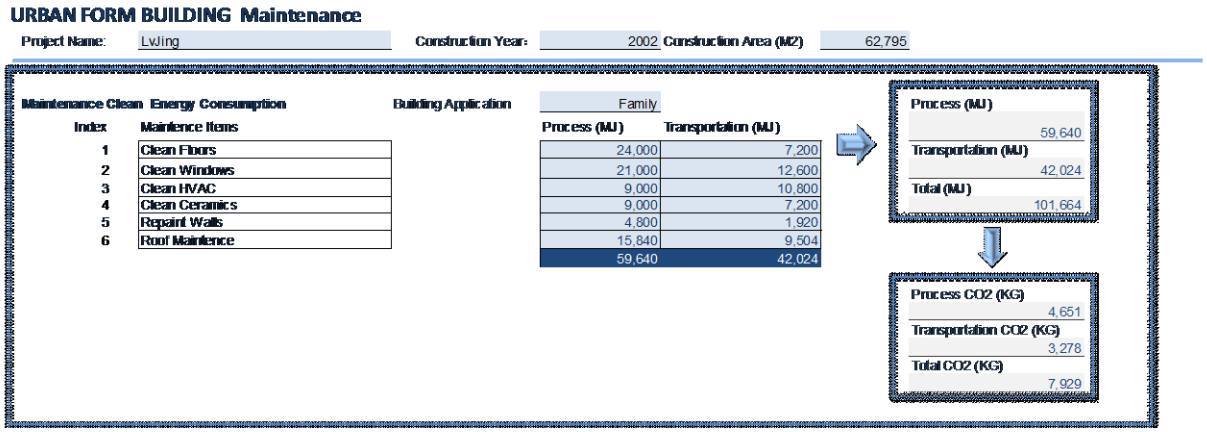
energy intensity, there is likely to be variation of construction energy use per square meter--this is an area that would benefit from further empirical research.

Figure 5: Construction Module of Urban Form Building LCA Model



The maintenance module is divided into six key maintenance tasks, the most energy-intensive of which is floor cleaning due to its high frequency. The data in Figure 6 show energy requirements for maintenance of the LuJing residential development over its assumed 30-year lifespan. Results of the maintenance module are highly sensitive to equipment lifespan assumptions. 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 6: Maintenance Module of Urban Form Building LCA Model



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.[34]

Figure 7: Demolition Module of Urban Form Building LCA Model

URBAN FORM BUILDING Demolition

Project Name: LvJing | Construction Year: 2,002 | Construction Area (M2): 62,795

Building Destruction Consumption

Construction Area (M2)	62,795
Building Destruction	75,354
Blading	131,870
Crane Transportation	188,385

Energy Consumption (MJ)	395,609
Total CO2 Emission KG	30,855

Recycling Materials

Index	Main Materials Names	Recycle Rate (%)	Amount (KG)	Manufacture (MJ)	Transportation (MJ)	Recycle Energy (MJ)
1	Section Steel	70.00%	215,387	4,900,051	124,236	5,024,287
2	Steel Bar	70.00%	1,890,130	43,000,446	1,090,234	44,090,681
3	Aluminum	95.00%	170,614	45,403,802	366,258	45,770,060
4	Glass	80.00%	216,517	4,341,169	26,263	4,367,432
5	Copper	95.00%	11,931	1,219,353	21,476	1,240,829
					Recycle Energy (MJ)	100,493,288
					Reduction CO2 (KG)	7,837,734

Beyond accounting for the range of decommissioning impacts, another difficult aspect of demolition modeling is how to credit the embodied energy of materials recycling.[35] 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 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.[36] 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.

3.3.2. Agent Based Modeling (ABM)

Agent based models simulate the simultaneous operations and interactions of multiple agents in an attempt to assess their effects on the overall system. The fundamental ideas of agent based modeling are that simple behavior rules underlie complex phenomena and that the whole is greater than the sum of its parts. Beyond the agents themselves, the basic components of agent based models include

[34] 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.

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

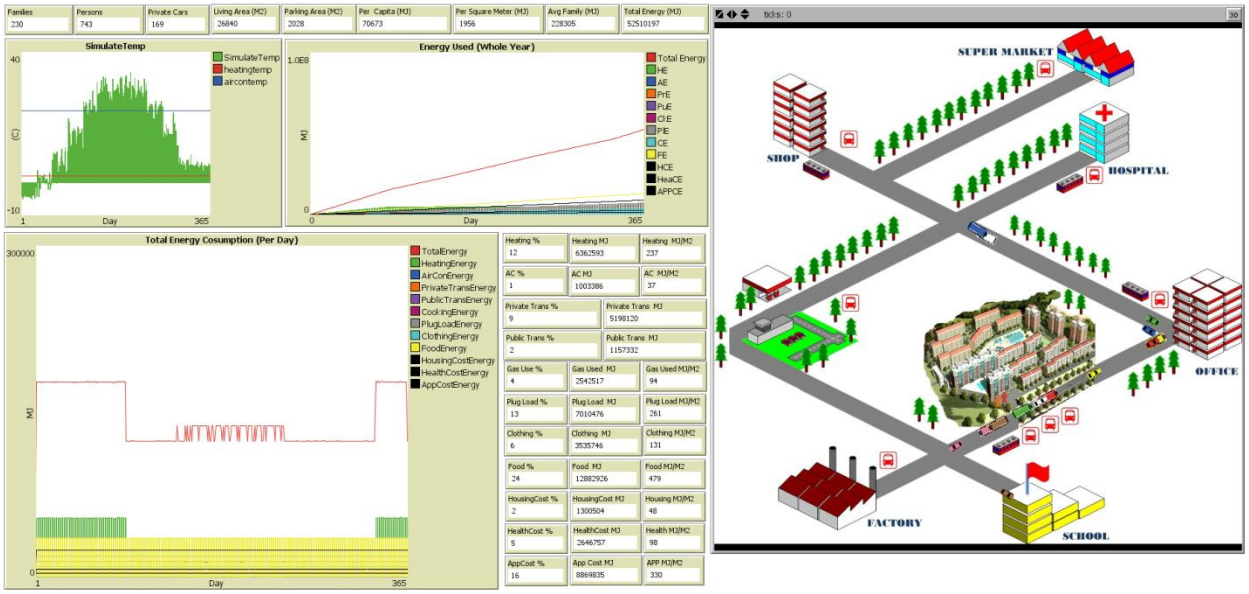
[36] Thormark C. 2000. "Environmental analysis of a building with reused building materials," *International Journal of Low Energy and Sustainable Buildings*, Vol. 1, 2000.

heuristics or learning rules, interaction topologies, and non-agent environments. In its first phase, this project focused on incorporating the household survey data into an ABM and did not utilize the full learning functionality of ABM. Instead, the results of this project were calculated on the basis of survey data--i.e., reported consumption and transportation behavior is treated as static throughout the 30-year lifespan of the residential building complex.

Agent based modeling is useful for observing a system over time when the system consists of independent actors who can follow a range of rules. For social phenomena, ABM can reveal macro-level trends that emerge from micro-level behavior, such as segregation or cooperation. It is often used to study biological phenomena, such as predator-prey models, the spread of a virus, or ant lines.

This project used NetLogo agent-based modeling software for analysis of building operational energy use and energy and emissions related to personal transport and consumption. NetLogo is an open-source modeling software developed by Northwestern University in the United States; it is freely available for download at http://ccl.northwestern.edu/netlogo/index.shtml. Within the NetLogo programming environment, agents are known as turtles that move around a grid according to simple behavioral rules. The urban form ABM uses household turtles whose behavior is modeled on the basis of collected survey data. The stochastic and rule-based aspect of the LuJing urban form ABM was daily temperature and its impact on heating and cooling energy use. Other aspects of the urban form ABM were aggregated using the household data as described below.

Figure 8: Snapshot of LBL Agent-Based Model of LuJing Residential Development



The LuJing urban form ABM supplements the building LCA model by quantifying operational energy use of buildings, embodied energy use related to personal consumption and direct energy use for transportation. Building operational energy use is comprised of heating, cooling, natural gas use, and electricity plug loads. The district heating period in Jinan is fixed at 120 days, from December 15 to March 31 each year. However, as mentioned above the actual energy used to heat buildings is also

influenced by outside temperature, which is modeled stochastically. Monte Carlo simulation was used to adjust monthly Jinan average temperature data to daily values.[37] Daily temperature variations influence total heating and cooling energy use in the urban form ABM.

Each component of the model contains assumptions. The personal transportation section, for example, assumes the following efficiencies by mode: 2.1 kWh per 100 km by E-bike, 2.65 MJ per km for cars, and 0.55 MJ per km for buses.[38] Transportation energy use is calculated in the model according to these efficiencies and travel data gathered in the household surveys. While personal transportation explicitly models energy used outside of the LuJing development, other operational energy is consumed within the boundaries of the residential complex. The boundaries of personal consumption are similarly complicated--while appliances and housing services are likely to be exclusively related to the LuJing residential development, clothing, healthcare, and to some degree food are likely to be used and provided outside of the residential complex. These categories were included in the interest of establishing a comprehensive modeling framework. Comparative analysis will be needed to assess whether these types of energy use are in fact influenced by urban form as opposed to income or other independent variables.

Embodied energy of personal consumption is comprised of five categories including food, clothing, housing services, appliances, and health care. This component is calculate according to reported household income, average expenditure by category in Jinan, and embodied energy according to the China 2005 I/O table. Both embodied and operational energy use are calculated on an annual household basis and then aggregated in the ABM results. The first phase of this project established a viable structure for linking the household data with the ABM approach, and thereby develop a bottom-up focus on peoples' central role in driving urban energy use and emissions.

3.4. Results

This study produced results data that are unique by virtue of their scale, scope and type. As discussed in Section 2, most of the existing literature focuses on building-, city-, or national-level analysis; this study covers multi-building neighborhood-scale development. Likewise, most existing studies focus exclusively on building operational energy use, e.g., by appliances, lighting, and equipment. This study also includes embodied energy related to personal consumption and buildings as well as personal transport. Table 4 shows the aggregate breakdown for embodied, operational, and transport energy use and emissions related to residents of the LuJing development.

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[37] U.S. Department of Energy, Building Technologies Program, http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=2_asia_wmo_region_2/country=CHN/cname=China.

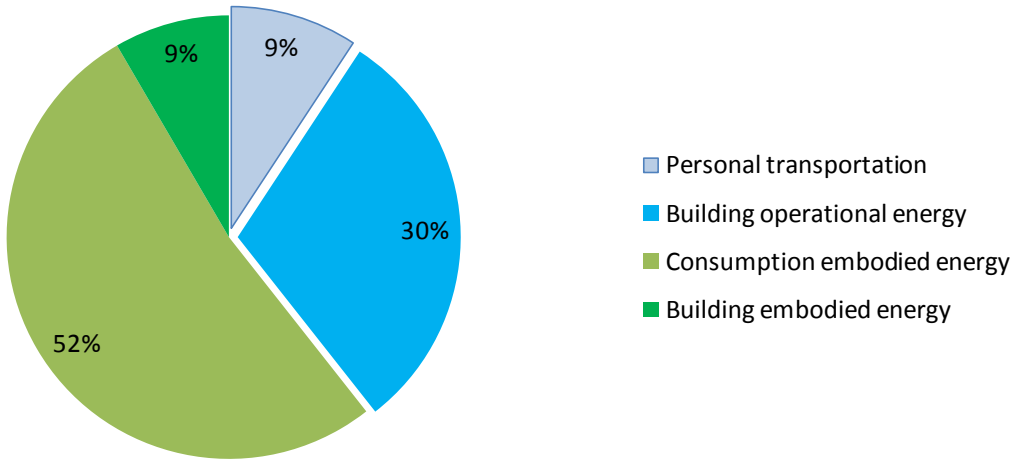
[38] These values are sourced from Cherry CR, et al. 2009. "Comparative environmental impacts of electric bikes in China," *Transportation Research Part D: Transport and Environment* 14, no. 5 (July 2009): 281-290. For additional information see Yan XY and Crookes RJ. (2010) "Energy demand and emissions from road transportation vehicles in China," *Progress in Energy and Combustion Science* 36, no. 6 (December 2010): 651-676.

Table 4: LuJing Embodied and Operational Energy Use and Emissions

	Annual Energy Use MJ/person/year	Lujing Lifetime CO_2 Emissions tonnes CO_2/urban form
Personal Consumption Embodied Energy	39,000	160,000
Building Lifecycle Embodied Energy	6,300	26,000
Building Operational Energy Use	23,000	93,000
Transportation Energy Use	7,000	28,000

The energy data in Table 4 are presented in annualized units and the emissions data are expressed in tonnes of carbon dioxide from the LuJing development per expected 30-year lifetime. Building embodied energy use is comprised of total lifecycle energy use averaged over the lifetime. Likewise, carbon dioxide emissions are based on a static assumption of frozen annual personal consumption, building operations, and personal transportation over a 30-year period. This broad range of end-use categories is used to provide a comprehensive assessment of the energy and carbon impact of urban residents. On an aggregate level, these results are consistent with published national energy use and population data. In 2007, China consumed 82 exajoules (EJ) of energy for a national-average amount of 62 GJ per person.[39] This study finds that residents of a luxury residential development in a prosperous city are responsible for an average annual 76 GJ per person, including per-capita portions of national industrial, transportation, and commercial energy used to support their final consumption of goods and services.

Figure 9: LuJing Residential Development Embodied and Operational Energy Use



Within the boundaries of this study, the embodied energy related to personal consumption comprises the dominant share of total energy use. Figure 9 illustrates the combined results of the ABM and LCA urban form assessment models--embodied energy of personal consumption comprises more than half of

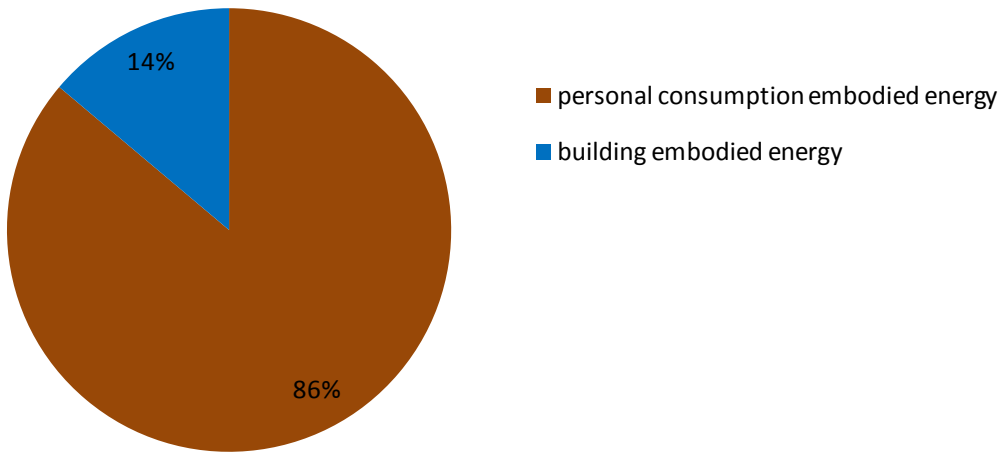
[39] NBS. 2009a. *China Energy Statistical Yearbook 2009*. Beijing: China National Statistics Press.

the total. LuJing is a luxury development. The high portion of personal consumption in total energy use may be related to the superblock urban form; however, further comparative study is needed to confirm an empirical link.

3.4.1. Embodied Energy and Emissions

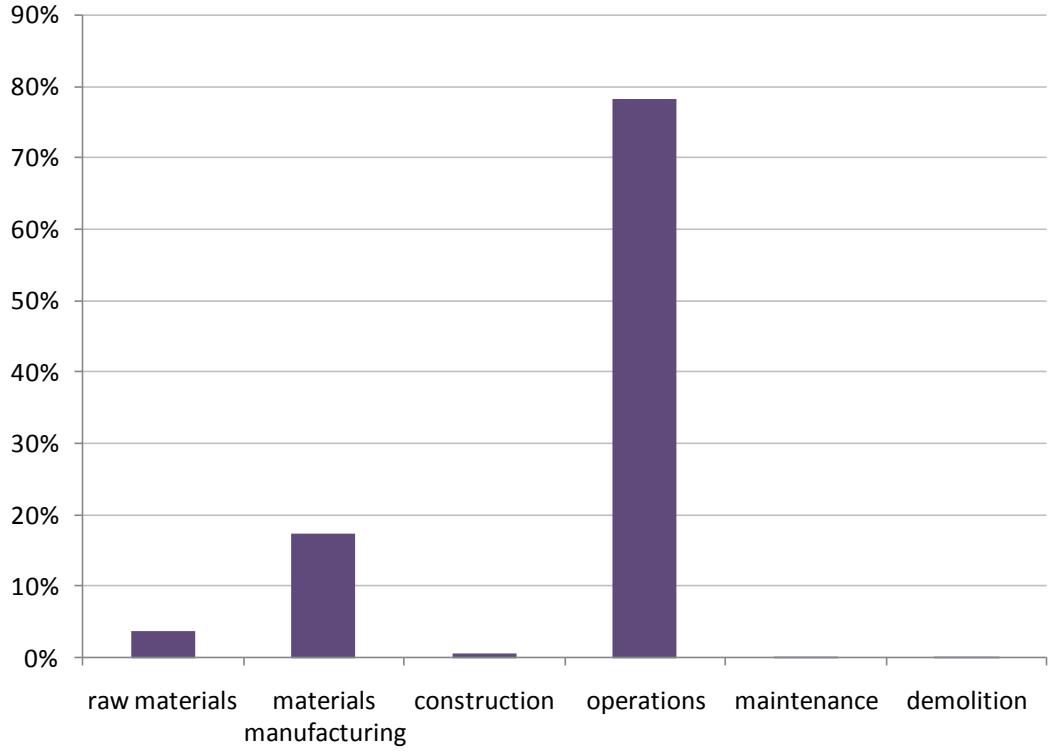
The embodied energy calculated in this study includes personal household consumption- and building-related sources. Building embodied energy is calculated in the LCA and personal consumption embodied energy is calculated in the ABM. Figure 10 shows that, of the use categories counted in this study, personal consumption is more than six times larger than residential buildings as a source of Lu Jing-related embodied energy use on an annualized basis. Beyond the personal consumption categories covered here and buildings, public infrastructure, government services, and international trade have related embodied energy components that have not been included in this study.

Figure 10: Structure of LuJing Embodied Energy Use



Building embodied energy is comprised of five categories: raw material extraction and processing, materials manufacturing, construction, maintenance, and demolition. For the LuJing development, the largest source of building embodied energy use is materials manufacturing. Figure 11 combines the five categories of building embodied energy with ABM-derived building operational energy use. In this model building operational energy use is comprised of heating, air conditioning, cooking and water heating, and electricity plug loads.

Figure 11: Portions of LuJing Buildings-Related Total Lifetime Energy Use by Phase

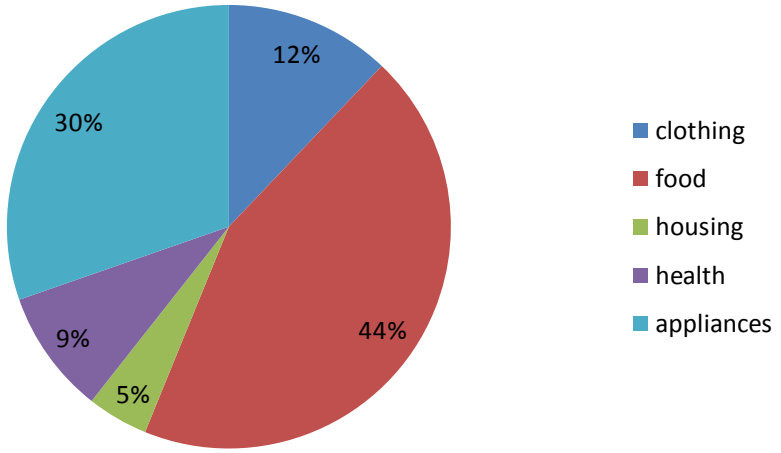


Building operational energy use comprised 78% of total lifetime energy use, while materials accounted for 21%. This general result confirms earlier research on building lifecycle energy use. Fernandez (2007), for example, estimates that building operations comprise an average 80% of total building lifecycle energy use in China.[40] Maintenance and demolition of the LuJing development are estimated to require 100 GJ and 400 GJ, respectively over the expected 30 year lifetime of the buildings. However, they appear as almost-zero in Figure 11 because these amounts are less than 0.5% of total lifetime energy use.

Personal consumption embodied energy is also comprised of five categories: food, clothing, appliances, healthcare, and housing services. Figure 12 illustrates the breakdown of consumption-related embodied energy among LuJing residents. Food and household appliances (that is, the production, not operations, of appliances) account for three quarters of consumption-related embodied energy use. Housing services are the smallest category of tracked expenditures, accounting for total LuJing embodied energy of three terajoules (TJ) per year.

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

Figure 12: Structure of LuJing Household Consumption-related Embodied Energy



Within the boundaries of this analysis, food is the single largest category of energy use, accounting for 23% of total modeled energy. Comparison of the large shares of food- and clothing-related energy use with their expenditure levels illustrates the energy intensiveness of these sectors--clothing accounts for 12% of personal consumption-related energy use, but only 5-9% of typical Jinan household expenditure, depending on income level. Similarly, food accounts for 44% of personal consumption related energy but only 9-37% of typical Jinan residential expenditure, depending on income level (see Table 2). For comparison, estimates of the energy requirement of food production in the United States range from 11-16% of total energy use.[41] This is consistent in the sense that non-food energy use levels are much higher in the U.S. due to higher car ownership levels, larger houses, and different consumer behavior. Furthermore, the food portion of total energy use is comparatively high due to the exclusion of public infrastructure from this study's scope of analysis. In economics, Engel's law observes that the portion of income spent on food falls as income rises, even if the actual expenditure on food rises. According to data gathered by China's National Bureau of Statistics (NBS), the Engel coefficient for urban households steadily dropped from 58% in 1978 to 37% in 2009.[42] If China continues to follow Engel's law, it is likely that the food portion of household expenditures will decline toward U.S. levels. The food portion of total energy use depends on changing diets, imports, transport distance, and eating out---additional comparative analysis is needed to identify links between urban form and food-related energy use.

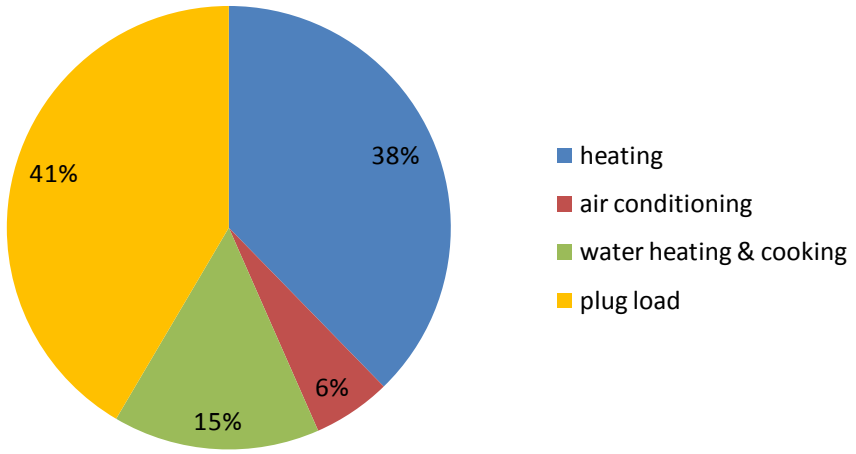
3.4.2. Building Operational Energy and Emissions

Operational energy in this study is quantified in the agent based model; it is comprised of five categories including heating, air conditioning, household gas use (for cooking and hot water), electricity plug loads

[41] Cuéllar AD and Webber ME. 2010. "Wasted Food, Wasted Energy: The Embedded Energy in Food Waste in the United States," *Environmental Science & Technology* 44, no. 16 (2010): 6464-6469.
[42] NBS. 2010. *China Statistical Yearbook 2010*. Beijing: China National Statistics Press.

(for equipment and appliances), and personal transportation. Figure 13 illustrates the buildings operational energy use of LuJing residents by category.

Figure 13: Structure of LuJing Buildings' Operational Energy Use

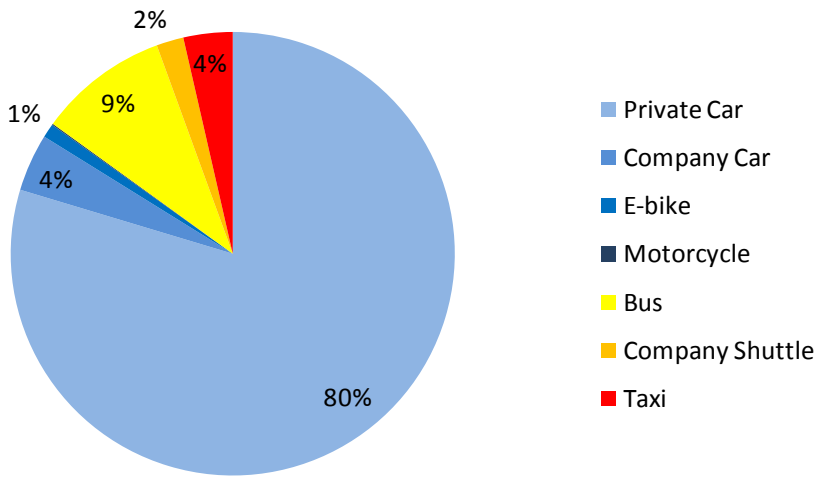


The largest categories of operational energy use are plug load and heating. These data are derived from household energy use survey data, for example using adjusted reported electricity use to calculate plug loads. Plug load electricity was calculated by deducting electricity for air conditioning usage from total reported electricity consumption per household, based on Jinan climate data. Within the LuJing buildings, plug loads and heating are the largest energy uses, followed by cooking, water heating, and air conditioning. The large share of heating energy use is consistent with Jinan's location in the cold-winter zone of northern China.

3.4.3. Personal Transportation Energy and Emissions

Transportation energy use is 20 GJ per household per year--an amount that is likely to grow with car ownership. Figure 14 shows the breakdown between public and private transportation energy use among LuJing residents. Private transportation is comprised of private cars, company cars, E-bicycles, and motorcycles. Public transportation is comprised of bus, company shuttle, and taxis; for Lu Jing residents, public transport comprised 15% of personal transport energy use.

Figure 14: LuJing Personal Transportation Energy Use by Mode



Car ownership among LuJing households was reported as 60%, with 13% owning multiple cars. In comparison, the national average vehicle ownership rate was 11 cars per 100 households for urban residents in 2009.[43] Figure 14 illustrates the dominance of private vehicles in personal transportation energy use among LuJing residents. Whereas private cars accounted for 80% of transport energy use, they only accounted for 51% of total kilometers traveled by surveyed households (1.6 million km per year by private car)--this illustrates the inefficiency of private vehicles and suggests that private transportation has potential for efficiency improvement through mode switching and technology improvement. Survey data indicate that the most common purpose of car usage among LuJing residents was commuting. Public buses, on the other hand, account for 29% of LuJing residents' kilometers traveled, but only 9% of total transport energy use.

Table 5: LuJing and China Average Urban Household Vehicle Ownership Rates (2008)

	Car	Motorcycle	E-Bike	Bicycle
LuJing Survey Results (% HH)	60%	4%	26%	57%
LuJing Survey Results (per 100 HH)	73%	4%	29%	90%
China National Average (NBS; per 100 HH)	11%	22%	N/A	96%*

* National average bicycle ownership rates are only reported for rural households.

Table 5 shows the comparison of LuJing and national average (per 100 household) vehicle ownership rates. According to the survey results, LuJing residents have a higher ownership rate for cars and a lower rate for motorcycles, electric bicycles, and regular bicycles. LuJing residents' demonstrated preference for private cars suggest that vehicle efficiency improvements would be a more feasible means of lowering transport energy use than promotion of motorcycles, E-bikes, and bicycles.

[43] NBS. 2010. *China Statistical Yearbook 2010*. Beijing: China National Statistics Press.

4. Overall Findings

This study used a different approach than standard studies of building or city-level energy use. Rather than disaggregating top-down reported energy data, this study used case study and survey data to construct an urban form energy and emissions footprint assessment, with particular focus on residents' behavior. In addition to using bottom-up methods, this study allocated energy consumption from related sectors to the point of final household consumption instead of the point of primary production, as is done in standard balance tables. Food-related energy use, for example, includes the agriculture sector energy required to plant, harvest, and transport the products, industry energy for processing, and commercial sector energy for wholesale and retail services. All of these portions are assigned to the Jinan residents personal consumption footprint in this assessment in order to quantify the impact of consumption choices.

By broadening the scope of analysis beyond residential buildings, this study highlights the full impact of individual behavior with its end-user orientation. Another example is the modeling of personal transport behavior and mode choice. Personal transportation energy use is calculated on the basis of survey results and published efficiency values by mode. The results of this study illustrate that mode shifting to private cars accounts for the largest portion of personal transportation energy use among affluent urban residents.

The lifecycle assessment of LuJing development buildings indicated that the operational phase of building energy comprised more than three quarters of lifecycle energy use and emissions. This suggests that buildings operational energy use are an important area for achieving additional efficiency improvements. However, the most significant finding of this study is that LuJing residents' personal consumption-related energy use exceeded their direct energy use and the embodied energy of the buildings they inhabit, combined. Additional research is needed to determine the applicability of these findings to other Chinese urban forms.

5. Policy Linkages

The LCA and ABM modeling approaches used in this study each have separate potential policy linkages. The LCA potion can inform building codes and supply chain efficiency policies with quantitative, building-specific data on the lifecycle energy requirements and emissions. By quantifying the broader energy and emissions footprint of the urban form, the ABM portion of this study can be used to evaluate the impacts of behaviorally and spatially-linked policies such as taxation and land-use zoning.

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 generalizeability 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 are also likely to 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.[44] 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.[45] 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.[46] 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.[47] 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 15 shows a plot of annual energy use versus annualized embodied energy for LuJing as well as ten Beijing-area residential and commercial case study buildings.[48] 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.

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[44] 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.

[45] 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.

[46] 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.

[47] 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.

[48] 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.

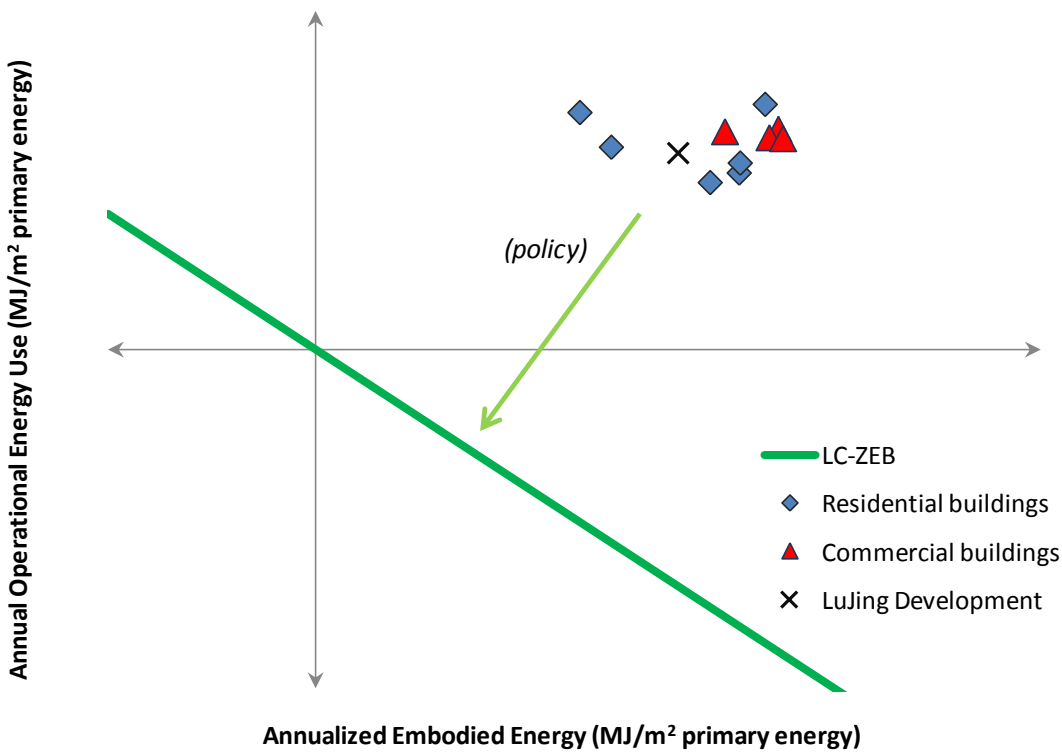
$$ALCE = AEU + AEE$$

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. In this case negative annual energy use describes buildings with net positive onsite renewable electricity generation and negative annualized embodied energy refers to buildings comprised of recycled or re-purposed materials that would otherwise require additional energy for processing or decommissioning. The LC-ZEB approach helps to resolve the potential tradeoffs between operational and embodied energy efficiency. The diagonal arrow in Figure 15 illustrates the potential effect of LCA-based policy moving building performance toward an idealized LC-ZEB line.

Figure 15: Annualized lifecycle energy of LuJing compared to 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."[49] 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 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.

The agent based model used in this study linked bottom-up building energy-use and emissions data with survey-based household behavior data. The bottom-up approach used in the ABM contrasts with the top-down approach of existing urban energy modeling tools described in Table 1. On a policy level, this type of disaggregated, bottom-up analysis can help to differentiate the energy and emissions effects of different urban form typologies and control for income-related effects. Regarding the untapped heuristic capabilities of ABM, this approach can also provide a useful simulation tool for quantifying the individual and collective effects of behavior-related policies such as consumption taxes.

Aside from embodied energy, the urban form model developed here has four useful policy applications. First, it can be useful for evaluating consumption and behavior-related policies such as taxes by introducing cost differences among transport modes, for example, and evaluating resulting changes of household and urban form behavior. Second, the model can help to identify opportunities for production and supply-chain efficiency improvements and emissions mitigation through personal consumption footprint analysis and benchmarking. Third, the model can provide a framework for evaluating the impacts of land use zoning including the impacts of higher density and transit-oriented design. Finally, the model can quantify the effects of economic structural change and contextualize the need for fiscal incentives for transition from industry to service-related growth. In order to model the relationship between urban form and economic structural change, the model would need to be further broadened to include the infrastructure and supporting industrial requirements related to different urban forms. In the ABM, this would include the energy and emissions related to public areas such as outdoor lighting, parking infrastructure, and elevators and how these vary among different urban forms. The question in this case is which types of urban form cause the least increase in industrial energy use.

This urban form assessment model is unique in its neighborhood-level focus. In this sense, it joins a large group of sub-national energy efficiency and environmental policies in the U.S. Table 6 shows four key energy efficiency and environmental policies in California. Given the large scale of urbanization in China, what is the most appropriate level of energy efficiency and emissions mitigation policies?

[49] 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)

Table 6: California State- and City-Level Energy and Environmental Policies

Policy	Scope	Purpose
California Environmental Quality Act (CEQA)	All state and local agencies must conduct environmental impact assessments	Establish a statewide environmental policy as well as a protocol for identifying and addressing environmental impacts
AB 32	The Air Resources Board of the California Environmental Protection Agency is responsible for overseeing government action to achieve the 2020 target.	Established target whereby California's 2020 emissions be reduced to 1990 levels, a roughly 25% reduction below business as usual estimates.
California Title 24	Applies to all new building permit applications in the state of California	Established energy efficiency standards for residential and non-residential buildings in 1978, subsequently updated in 2008.
California SB 375	Covers all state metropolitan areas; implemented by regional planning agencies	Anti-sprawl legislation for transportation and housing planning; signed in 2008

Cities play a central role in energy efficiency and emissions mitigation policies insofar as they are the locus of urbanization and related industrial energy demand growth. However, cities do not always have the political authority or jurisdiction to implement effective policies. The state-level policies described in Table 6 illustrate the approach that California has taken to regulating energy use and emissions. The last two policies, Title 24 and SB 375, are implemented directly by regional and municipal urban planning agencies. In California these policies influence urban and sub-urban development in support of emissions reductions targets. The model developed in this report could be used to evaluate the impact of these types of policies on urban form energy use and emissions in China and understand the role of national, provincial, city, and neighborhood-level policy mechanisms.

6. Conclusions and Further Work

As a proof of concept, this study found that lifecycle assessment and agent-based models can be useful for quantifying broad energy and emissions impacts of a given urban form. By capturing a range of related externalities and effects, lifecycle assessment is an appropriate tool for evaluating physical forms. The use of ABM to model actual survey-based data reversed the usual producer orientation of energy use data to highlight the role of individual behavior and personal consumption in urban form energy use. However, full utilization of LCA and ABM model capabilities requires more data than were available for this project.

The building LCA portion of the model developed in this project shows 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 model developed here can be useful for quantifying dynamics of building lifecycle energy use and emissions, and for identifying opportunities for efficiency improvements.

Each of the five modules of the 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 Beijing case study building material data onto the Lu Jing development 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. 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 model was 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 enduring data so much as an indicator of potential work to come.

The most useful elaboration of the building LCA portion of the model would be to further generalize it for comparative analysis. Scenario analysis could be used for benchmarking and identification of policy priorities. If the model is 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 model, 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 a more explicit spatial scaling mechanism for modeling neighborhood and city-level energy use and emissions, i.e. to account for scaling effects in public infrastructure and transportation.

This project used agent-based modeling to broaden beyond building energy use and organize personal consumption-related energy use data around the point of final use, in this case the urban resident. Agent-based modeling was used because of its ability to calculate aggregate, systemic effects of individual behavior. However, this project did not fully utilize the stochastic and heuristic capabilities of ABM. This project used Monte Carlo simulation of temperature variations to describe heating and cooling energy use, but insufficient data were available characterize the stochastic elements of personal consumption, transportation, and building operational energy use. The capability of agent-based models to capture dynamic behavior and individual learning can be useful for understanding the impact of a given urban form or related policy on total energy use. The heuristic capabilities of ABM could be useful for characterizing the spread of behavioral changes among residents (e.g., transitioning from public to private transportation among households), quantifying residents' response to price adjustments or land-use policies, and on a higher level understanding tradeoffs between the three

parameters of energy use and emissions, cost, and comfort/livability among different urban forms. Additional data to support the stochastic and heuristic capabilities of ABM could provide a more solid connection between factors influencing individual human behavior and the mitigation of energy use and emissions growth in China's ongoing urbanization.

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Appendix 1: Survey Form

Jinan Urban Residents' Residential and Passenger Transport Energy Consumption Survey in 2009

Date:_____ Time:_____ *Questionnaire #_____*

Neighborhood:_____ Surveyor:_____ Recorder:_____

Building Year: □Before Liberation □1950s □1960s □1970s □1980s □1990s □2000 or later

Building Construction Structure (# of Stories___) :

□Timber □Masonry Timber □Masonry Concrete □Reinforced Concrete □Steel

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Family and Travel Information

1. There are _____family members in your household, among which _____ of them are employed.

2. Household Type:

□Single □Couple □Couple with Kid □Parents with Married Children □Grandparents and Kid □Three Generations

3. Family Members and Weekly Travel Activities:

Family Member	Sex	Age	Occupation	Monthly Income	Weekly Travel Activities					
						Purpose	Mode	Frequency	Distance	Time Taken (min)
1					*weekdays*					
					weekends					
2					*weekdays*					
					weekends					
3					*weekdays*					
					weekends					

4					*weekdays*					
					weekends					
5					*weekdays*					
					weekends					

Sex： a.Male b.Female

Age： a.<20 b.20~30 c.30~40 d.40~50 e.50~60 f.>60

Occupation：a.Teacher/Professor b.Student c.Worker d.Government official e.Company employee f.service/self-employed g.Peasant h.Unemployed i.Retired j. other

Monthly Income：a.below 600 b.600~1,000 c.1,000~2,000 d.2,000~~5,000 e.5,000~10,000 f.>10,000

Trip Purpose：a.work b.school c.shopping d.hospital e.visit,entertainment f.other

Mode：a.walk b.bicycle c.electric bike/scooter d.motorcycle e.taxi f.private car g.company car h.bus/BRT i.company shuttle

Frequency：number of trips made per week, a one-way trip counts as one, and a round trip is counted as two trips

Vehicle Ownership and Usage (Select one or two answers)

4. Number of Private Cars_____ *（If zero, jump to the next question）*

Main Purpose of Owning a Car：

□commute □pick up kids □shopping □leisure and travel □household urgencies □other _____

(The following question a) b) and c) are for each vehicle)

a) This vehicle is_____ years old，annual mileage driven_____， fuel economy_____liter/100km

b) gas_____ yuan/month ； insurance and maintenance_____ yuan/year; other fees _____ yuan/year

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐not specified space（street, sidewalk）

5. If your family does not have a car, do you plan to buy one？

□Yes，main purpose is：

□commute □pick up kids □shopping □leisure and travel □household urgencies □other _____

□No，because：

□no need of one □the vehicle is too expensive □gas and maintenance is too expensive □congestion □lack of parking □not environmentally friendly □other _____

6. Number of Motorcycles_____ *(The following question a) b) and c) are for each vehicle)*

a) This vehicle is_____ years old，annual mileage driven_____，fuel economy_____liter/100km

b) gas_____ yuan/month ；insurance and maintenance_____ yuan/year; other fees _____ yuan/year

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

7. Number of Electric Bicycle/Scooter_____*(The following question a) b) and c) are for each vehicle)*

a) This vehicle is_____ years old，has changed battery for_____times，needs to charge every_____days,; and the power of the vehicle is_____KW

b) Maintenance Cost_____yuan/year.

c) Parking space（☐own|☐rent）：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

8. Number of Bicycles_____, have lost _____ bicycles ; parking at：

☐neighborhood underground parking ____yuan/month ☐neighborhood parking lot ____yuan/month

☐parking outside the neighborhood ____ yuan/month ☐at home/in the yard

☐not specified space（street, sidewalk）

Residential and Household Energy Consumption

9. You are currently：□Renting □Homeowner □Homeowner (still paying mortgage)

10. If renting，the rent is: ____ yuan/month，if still paying mortgage，mortgage payment is: ____yuan/month.

11. Your home has：a) ____bedrooms ，and b) ____dining rooms; c) at the _____th floor （☐top floor）

12. Housing Area：a) Living Area_____M^2，b) construction area _____M^2

13. Your monthly electricity bill is：_____yuan （or_____Kw.h）

14. Gas Source：□Natural Gas（pipeline） □Coal Gas（pipeline） □LPG（gas pitcher_____kg）

Monthly Consumption_____M^3/pitchers （or_____yuan）

15. How much coal does your household consumes each year?_____yuan (identify what kind of coal briquette)

16. Heating facility your household is using：

☐Neighborhood centralized heating，heating bill：_____yuan/season

☐Honeycomb-shaped briquet，average usage amount：_____ton/season

☐Electric heating facility（air conditioning, electric heater） □Other(specify)：

17. Main Electric Devices：

☐Air conditioner Count:___ Power:___p ☐Refrigerator Count:___ Size:___Liter

☐Television Count:___ Size:___Liter ☐Desktop Computer Count:___ Use Frequency:_:___hours/day

18. Type of Water Heater： ☐Electric Water Heater ☐Gas Water Heater ☐Solar Power Water Heater

19. Telecommunication: a) internet access at home? □Yes □No; b) # of cell phones _____ currently in use.

Attitudes towards Travel and Residence

For each statement, express your level of agreement: 1 = strongly disagree, 3 = neutral, 5 = strongly agree

20. Driving is a sign of prestige	1	2	3	4	5
21. Having too many cars is the main reason of traffic congestion	1	2	3	4	5
22. Taking public transit is convenient	1	2	3	4	5
23. I enjoy bicycling	1	2	3	4	5
24. Time spent traveling is wasted time for me	1	2	3	4	5
25. Transportation convenience is important in choosing the residence	1	2	3	4	5
26. I prefer living around people who are similar to me	1	2	3	4	5
27. Living in a gated community is a sign of prestige	1	2	3	4	5
28. I think gated community provides better security	1	2	3	4	5
29. I prefer to have shops and services such as laundry, barber and restaurants	1	2	3	4	5
30. My family pays close attention to saving water, gas or electricity	1	2	3	4	5