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Abstract

“Low Carbon Cities” is a concept that has primarily focused on ways to reduce the impacts of current energy consumption in transportation and buildings. What is often overlooked as part of the energy impact of urban areas is the built space itself—the streets, pavement, buildings, etc.—that are required to maintain such a dense arrangement of humans, and the energy used to manufacture, transport, and sell the consumption goods and services that urban residents purchase. A new model—the Urban Rapid Assessment Model (Urban RAM)—was built to provide a high-level breakdown of the major contributors to a given city's energy and carbon footprint when measured from the point of view of that city's inhabitants and their activities. By allocating both embodied and operational energy consumption to the various functions of city residents, such as living, commuting, shopping, or working, it is possible to understand better the drivers of urban emissions growth and areas of possible policy intervention. Urban RAM was applied to a case study of Suzhou, a city of 6 million near Shanghai. The model calculated a total annual energy footprint of ~111 billion MJ, of which three-quarters is energy embodied in the city’s infrastructure and goods and services consumption and the other 26% is operational energy. Of the embodied energy, nearly 80% came from goods and services that city residents consume each year, of which nearly half came from food and nearly one-quarter embodied in the clothing. Transportation dominated operational energy with 59% and residential buildings with 26%.

Introduction

Everyone knows that it takes energy to produce anything. The energy used in mining, transport, processing, manufacturing, delivery, management and disposal is “embodied” in every product we consume, from food to diapers to televisions and insurance policies (see, e.g. Costanza 1980, Odum 1996). Broadly speaking, the more processing and handling a product undergoes, the higher amount of embodied energy it contains. Traditional energy accounting, however, makes it difficult to assess the embodied energy of a product or service. Energy accounts customarily present current consumption, disaggregated into the major economic sectors of agriculture, industry, transportation, commerce, and households. As a result, the energy embodied in the breakfast food we eat, for example, is reported as energy consumption across all these sectors: the energy used in planting and harvesting is reported in the agricultural sector, the energy to move food to processing and sale in the transportation sector, the energy to process and package food in the industrial sector, the energy to wholesale or retail food in the commercial sector, and the energy to prepare and cook food in the residential sector. Consequently, it is very difficult to assess the full energy impact of our breakfast choices, even though the energy consumed at each step is expended as a result of human demand for food. Similarly, looking at the full range of urban energy consumption from this traditional framework diminishes the role of people in driving that consumption.

Because cities are the source of the majority of energy consumption in many industrial and high population countries, much research is underway to promote development of "Low Carbon Cities", a concept that to date has primarily focused on ways to reduce the impacts of current energy consumption in transportation and buildings. This is especially true in China, where urbanization has just reached the 50% level in 2011, and the government is projecting the urbanization of an additional 350 million people—greater than the population of the United States—over the next 15 years. All of these new urban residents will need accommodation, schooling, health care, appliances, energy supply, transportation, food, clothing, water, sewerage, and other services, and the potential energy impact is enormous. A typical Chinese urban resident consumes 3 times as much commercial energy as a rural resident (in total energy terms, rural residents consume more, but the majority is inefficiently combusted biomass, which is often ignored in energy reporting) (Aden, Fridley & Zheng 2009).

Consequently, the Chinese government has directed 5 cities and 3 provinces to develop low-carbon action plans to respond to growing urban energy needs (NDRC 2010). For the most part, these low-carbon action plans focus on ways to reduce the growth of current energy consumption and to supplant some portion of it with non-fossil energy sources.

But is a focus on current energy consumption enough? Analyzing the current energy consumption of a city alone can lead to conclusions that urban areas, particularly dense urban areas, are relatively efficient, largely because per-capita current energy consumption is lower than in dispersed urban or suburban arrangements. This is indeed often the case. But what is not typically measured as part of the energy impact of urban areas is the embodied energy of the built space itself—the streets, pavement, buildings, utilities, tunnels, etc.—that are required to maintain such a dense arrangement of humans, nor do energy measures take into account the energy used to manufacture, transport, and sell the vast array of consumption goods and services that urban residents purchase. Since urban areas exist for the sake of people, looking at the urban energy footprint from the point of view of its inhabitants' impact can provide additional insight into the nature of urban energy use.

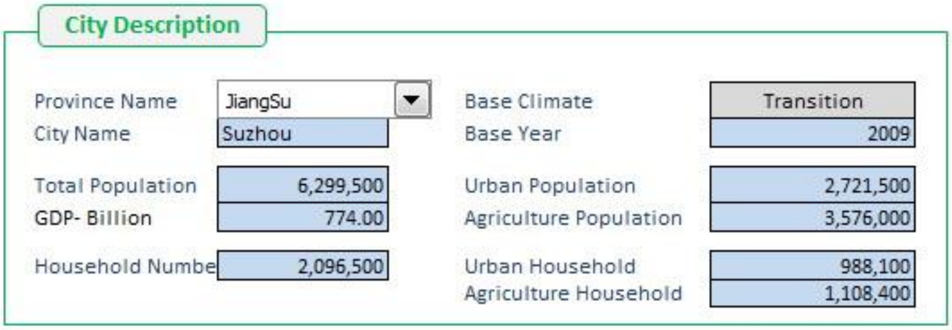
The Urban RAM Model

A model was developed by researchers at the Lawrence Berkeley National Laboratory in 2010 to calculate the energy footprint of urban residents in support of an ongoing series of training workshops on low-carbon city development for city officials in China, and thus was designed with Chinese data availability in mind. The goal was to minimize data input requirements in order to make it user-friendly for city planners. The model was named the "Urban Rapid Assessment Model," or Urban RAM. To minimize user concerns about software availability and unfamiliarity, the model was developed as a simple Excel macro-enabled workbook featuring navigation bar, data input sheets, results output in the form of tables and graphics and a database of underlying parameters and assumptions.

The model has 4 key input sheets: City Description, Income and Expenditures, Buildings, and Infrastructure and Transportation.

City Description

On the city description page, the user selects a province from a pull-down list, which then automatically selects the appropriate climate zone linked to heating and cooling energy consumption calculations. The other cells—population, GDP, and households—are entered by the user directly (Figure 1). Energy and emissions calculations are based on household numbers; population figures are entered to allow calculation of certain indicators on a per-capita basis. All data on this sheet are reported by China's National Bureau of Statistics (NBS).



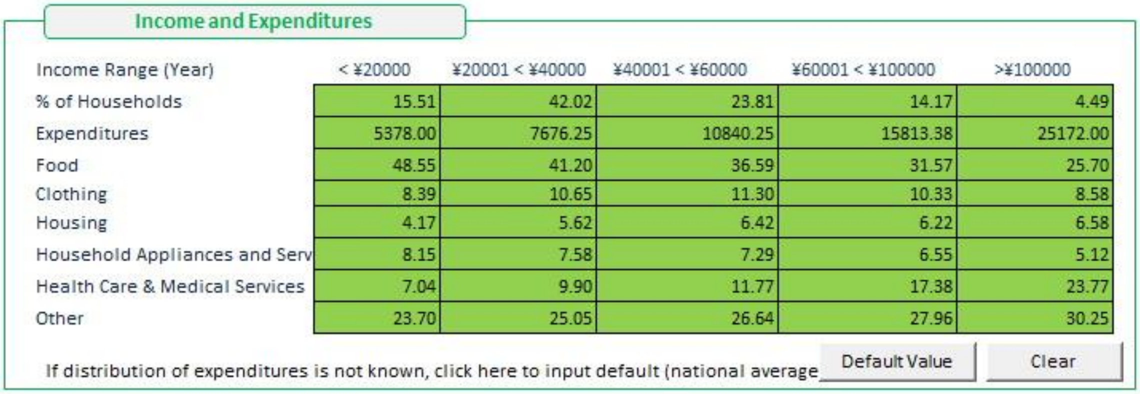
City Description

Province Name	JiangSu	Base Climate	Transition
City Name	Suzhou	Base Year	2009
Total Population	6,299,500	Urban Population	2,721,500
GDP- Billion	774.00	Agriculture Population	3,576,000
Household Numbe	2,096,500	Urban Household	988,100
		Agriculture Household	1,108,400

Figure 1. City Description Data Input

Income and Expenditures

Expenditure data are used to calculate the embodied energy and emissions of residents' annual household consumption. The user has the option of retaining the default input values (in green, based on China's national urban average), or can click Clear to enter data taken from the local statistical office (Figure 2). The income ranges are the midpoint of the 10 income categories as defined by the NBS. The cells can be returned to the default values by clicking the Default Value button. The "Other" category contains a variety of other expenditure categories, primarily education and recreation. These expenditure figures are then converted to MJ of energy consumption embodied in the purchased goods and services using China's 2005 Input-Output table.



Income and Expendítures

Income Range (Year)	< ¥20000	¥20001 < ¥40000	¥40001 < ¥60000	¥60001 < ¥100000	>¥100000
% of Households	15.51	42.02	23.81	14.17	4.49
Expenditures	5378.00	7676.25	10840.25	15813.38	25172.00
Food	48.55	41.20	36.59	31.57	25.70
Clothing	8.39	10.65	11.30	10.33	8.58
Housing	4.17	5.62	6.42	6.22	6.58
Household Appliances and Serv	8.15	7.58	7.29	6.55	5.12
Health Care & Medical Services	7.04	9.90	11.77	17.38	23.77
Other	23.70	25.05	26.64	27.96	30.25

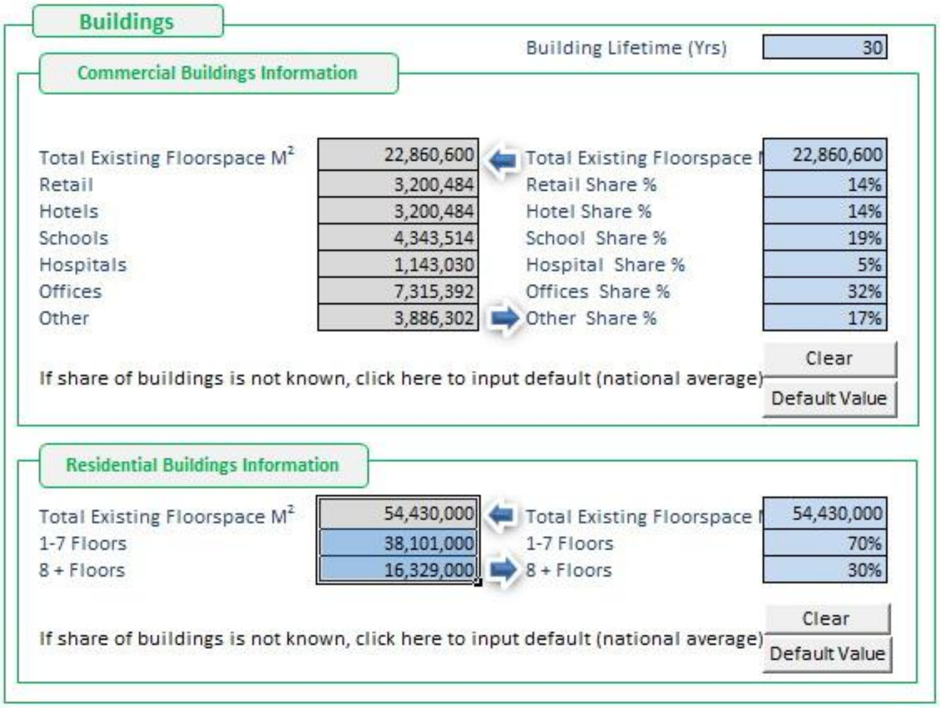
If distribution of expenditures is not known, click here to input default (national average

Figure 2. Income and Expenditures Data Sheet

Buildings

Operational and embodied energy calculations for buildings, both commercial buildings of 6 types (retail, hotel, school, hospital, office, and other) and residential buildings of two types (1-7 floors, and over 7 floors), are linked to building floorspace and the climate zone. The user has two options to calculate the distribution of floor space in commercial buildings (Figure 3). By providing a total existing floorspace figure and shares by building type in the right column, pressing the left-arrow will generate the floor area in square meters. Alternatively, actual floor space can be entered, and pressing the right arrow will generate the share distribution. Embodied and operational energy and emissions are calculated from floor area based on intensity values (MJ/m^2) based on China-specific studies (Zhou et al. 2011; Aden, Qin & Fridley 2010). Heating and cooling are adjusted for climate zone (commercial buildings are further adjusted by province), and the values differ by commercial building type. Similarly, residential floor area is the basis of energy and emissions calculations for both embodied and operational energy; operational energy is higher for the 7+-story buildings owing to additional elevator use. The share of under-7 and over-7 story buildings is provided as a default national average, but can be cleared and overwritten by the user based on local data.

Building lifetime is used to annualize the embodied energy of the buildings to a comparable basis with operational energy. Because China's buildings have such a short average lifetime of just 30 years, the annual embodied energy "consumption" is consequently relatively high.



Building Lifetime (Yrs) 30

Total Existing Floorspace M^2	22,860,600	Total Existing Floorspace	22,860,600
Retail	3,200,484	Retail Share %	14%
Hotels	3,200,484	Hotel Share %	14%
Schools	4,343,514	School Share %	19%
Hospitals	1,143,030	Hospital Share %	5%
Offices	7,315,392	Offices Share %	32%
Other	3,886,302	Other Share %	17%

If share of buildings is not known, click here to input default (national average)

Total Existing Floorspace M^2	54,430,000	Total Existing Floorspace	54,430,000
1-7 Floors	38,101,000	1-7 Floors	70%
8 + Floors	16,329,000	8 + Floors	30%

If share of buildings is not known, click here to input default (national average)

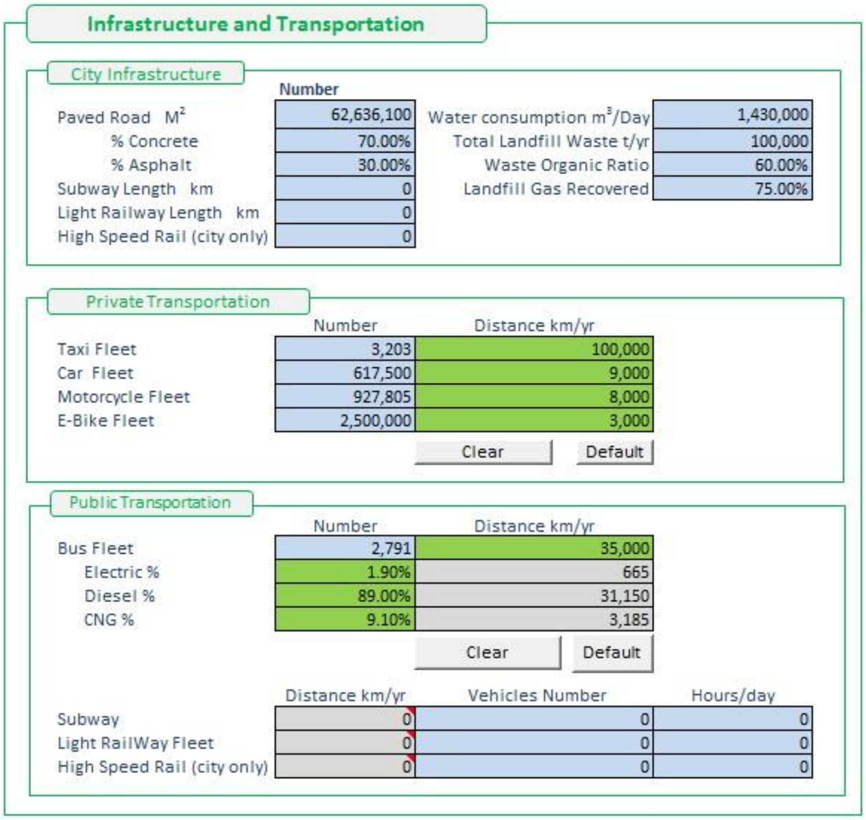
Figure 3. Buildings Data Input Sheet

Infrastructure and Transportation

The first section of this sheet is used to calculate the embodied energy of the city's infrastructure, including all paved areas and rail lines, if they exist, along with the operational energy for water pumping (water supply only; excludes water treatment). On the emissions side only, landfill methane emissions are calculated based on an estimated organic waste ratio and proportion of landfill methane that is captured. The balance of the methane is then converted to CO_2-equivalent in the emissions calculation (Figure 4)

The second section on private transportation is provided to calculate both the embodied and operational energy of private vehicles. Annual distance traveled by vehicle type is entered as a national average default but can be cleared and overwritten by the user. The third section on public transportation is used to calculate the embodied and operational energy of public transportation. The fuel share of the bus fleet is provided as an average default but can be overwritten by the user; the total kilometers travelled per year by fuel type is estimated to be the same proportion of the total as the fuel type. The default value is in total kilometers travelled per year (not passenger-kilometers). Similarly, energy and emissions from subway, light rail, and urban high-speed rail is calculated from the total distance travelled per year, but this figure is calculated based on vehicle number (e.g. total number of subway cars) plus hours of daily operation, so is not directly entered by the user.

As the case with buildings, total embodied energy is annualized by dividing by the average lifetime of infrastructure and transportation equipment. These lifetime figures are not entered by the user.



	Number
Paved Road M^2	62,636,100
% Concrete	70.00%
% Asphalt	30.00%
Subway Length km	0
Light Railway Length km	0
High Speed Rail (city only)	0

Water consumption m^3/Day	1,430,000
Total Landfill Waste t/yr	100,000
Waste Organic Ratio	60.00%
Landfill Gas Recovered	75.00%

	Number	Distance km/yr
Taxi Fleet	3,203	100,000
Car Fleet	617,500	9,000
Motorcycle Fleet	927,805	8,000
E-Bike Fleet	2,500,000	3,000

	Number	Distance km/yr
Bus Fleet	2,791	35,000
Electric %	1.90%	665
Diesel %	89.00%	31,150
CNG %	9.10%	3,185

	Distance km/yr	Vehicles Number	Hours/day
Subway	0	0	0
Light RailWay Fleet	0	0	0
High Speed Rail (city only)	0	0	0

Figure 4. Infrastructure and Transportation Data Sheet

Model Implementation

The test city for the model was Suzhou, a large city of 6 million population located west of Shanghai in Jiangsu province. Suzhou is a prosperous city with an economy dominated by heavy industry, which accounts for 80% of the city's energy consumption. It is home to Shagang, the 7th largest steel producer in the world with an output in 2009 of 26 million tonnes, equivalent to 45% of total US production in that year. Much of this steel, however, is not consumed by Suzhou residents, and thus this large industrial component falls out of the model; instead Suzhou steel consumption is captured in the infrastructure and building use of steel and in the steel used to make products consumed by the residents, such as automobiles and refrigerators. Similarly, Suzhou residents eat food that is in part not locally grown, but the energy used to produce and transport this food to Suzhou is included in the calculation. In this way, the model creates a picture of Suzhou energy consumption oriented towards the people who are responsible for its consumption, and excludes energy consumption of those goods and services produced in Suzhou and consumed elsewhere. In this model approach, industry essentially falls out of the calculation, since its output appears elsewhere as either operational or embodied energy.

Overall Findings

The results for Suzhou are shown in Table 1, indicating that the city's annual energy footprint, in both current and
embodied terms,
totals about 124 billion MJ per year, equivalent in energy to about 21 million barrels of oil. CO_2 emissions, including landfill methane, totals about 9.7 million tonnes, or about 2 tonnes per capita per year.

Table 1. Annual Energy and Emissions Footprint

Total Energy MJ/Year	124,477,176,330
Total CO_2 e Emission Tonnes/Year	9,726,083
CO_2 e Tons/Capita Annual	2
CO_2 e Tons/Household Annual	5
Embodied Energy MJ/Year	84,421,112,596
Embodied CO_2 e Tons/Year	6,584,223
Operation Energy MJ/Year	40,056,063,733
Operation CO_2 e Emission Tons/Year	3,141,860
Commercial Building Energy MJ/M^2 Annual	452
Commercial Building Embodied Energy MJ/M^2 Annual	213
Commercial Building Operational Energy MJ/M^2 Annual	239
Residential Building Energy MJ/M^2 Annual	386
Residential Building Embodied Energy MJ/M^2 Annual	201
Residential Building Operational Energy MJ/M^2 Annual	185
City Infrastructure Embodied Energy MJ/Capita Annual	1,227
Transportation Energy MJ/Capita Annual	5,103
Private Transportation Energy MJ/Capita Annual	3,526
Public Transportation Energy MJ/Capita Annual	48

Of the total energy footprint, however, over two-thirds is energy that is embodied in the infrastructure and in the consumption of goods and services in the city (Figure 5), while only one-third is operational energy (current consumption)—the energy used to light, cool, heat, run equipment such as water pumps and televisions, and to run vehicles.

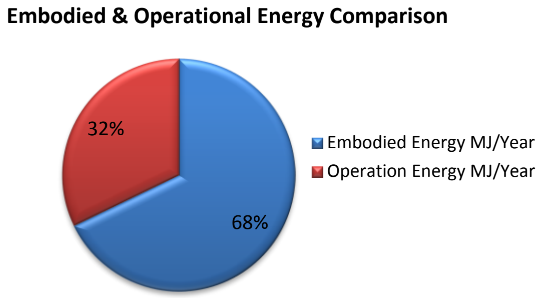


Figure 5. Structure of Suzhou's Energy Footprint

Not surprising, nearly 60% of the operational energy comes from transportation, with another 25% from the energy used in residential buildings, including heating, cooling, water heating, lighting, appliances, and miscellaneous plug loads (Figure 6). Suzhou is located in an area of China that did not formerly allow heating in buildings in winter, so heating in residential buildings today is supplied largely by mini-split heat pump air conditioners running on electricity. In Suzhou, nearly every household, urban and agricultural, owns a refrigerator, TV, clothes washer, and air conditioner. Commercial buildings account for a lower share than residential buildings because of China's overall lower building energy intensity and the higher share of the agricultural and industrial workforce. Water and waste account for 5% of the city's operational energy use, but this accounting includes only the energy to supply the 522 million tonnes of fresh water per year but excludes the energy use in waste water treatment. For landfills, it assumed that 60% of the waste is organic based on national average estimates (Wei 2003). In the absence of Chinese data, it is assumed that 75% of the landfill methane is recovered based on California's experience (CEC 2002).

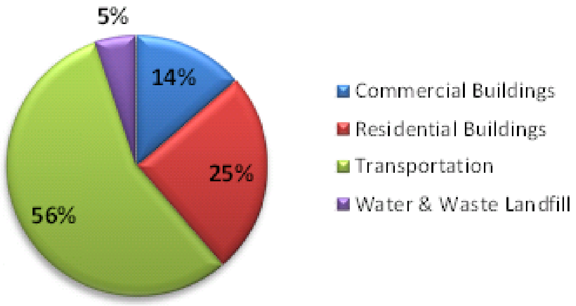


Figure 6. Structure of Operational Energy Use

Even though commercial buildings are generally more materially intensive (i.e., use more concrete, steel, aluminum and other building materials per square meter) than residential buildings, the dominance of residential floorspace in the total building stock (54 million m^2 vs 23 million m^2 for commercial) results in a larger embodied energy footprint for residential buildings (Figure 7). Even then, the embodied energy of all buildings along with the 63 million m^2 of pavement in the city accounts for only about 28% of the total annualized embodied energy calculation. Vehicles, including cars, taxis, buses, e-bikes, and motorcycles, contribute 11% of the annualized embodied energy, the relatively high share compared to buildings and pavement in part a function of their shorter lifetimes. The remaining 61% consists of the embodied energy in the products and services that the residents of the city consume each year, based upon household expenditure patterns.

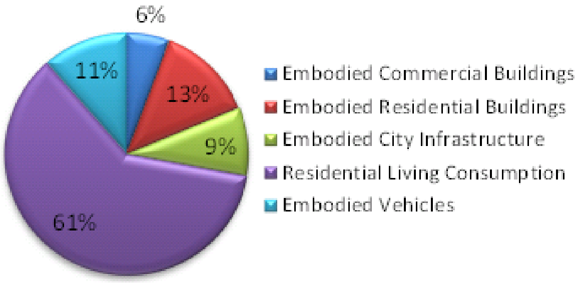


Figure7. Structure of Embodied Energy

Transporting People

The transportation infrastructure in a city serves to support the movement of vehicles carrying both passengers and freight (including non-commercial freight such as mail). Owing to a lack of data from which to estimate freight turnover and vehicle use in Suzhou, freight activity has been omitted from this version of the model; the results here focus on the impact of moving people. As shown in Figure 8, transportation energy use is completely dominated by private transportation choices, with the public transportation system contributing only about 1% of the total. Suzhou is currently building a subway system designed for a total of 109 stations over 140 kilometers, and the first line of 24 stations over 25 kilometers is expected to be completed in 2012. Consequently, public transportation is provided only through the city bus system.

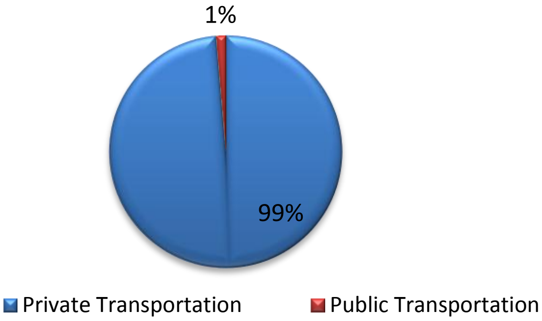


Figure8. Structure of Transportation Operational Energy Use

Suzhou has a car ownership rate of 29 per 100 households, and among private transportation choices, car energy use accounts for over 70% of the total (Figure 9). Suzhou is also known as China's "E-Bike

Heaven" with over 2.5 million e-bikes in use, the highest density in China (Gulugendou 2009). Even so, the greater efficiency of this mode of passenger transport results in the entire fleet consuming just 2% of total passenger transport energy consumption.

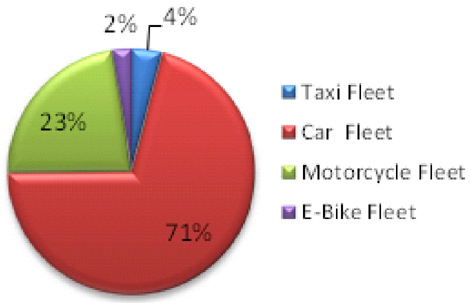


Figure 9. Structure of Private Transportation **Operational Energy**

What People Buy

The energy used to heat, cool, light, and operate appliances in Suzhou households totals about 10 billion MJ, accounting for about a quarter of total operational energy use. Of much greater consequence is the contribution from the embodied energy of the goods and services that these households consume on an annual basis. To determine this, we looked at the distribution of expenditures by income level, and used input-output calculations based on China's 2005 input-output tables to calculate the energy use for each expenditure category.

What is apparent in Figure 2 is that even at the highest income categories, food still accounts for the largest portion of household expenditures, in contrast to the US where food expenditures (as a share of disposable income) has steadily declined since 1947, reaching 9.4% in 2009 (USDA 2009). Typically, expenditures on food decline as a proportion of income as incomes rise, allowing greater expenditures in other categories. For China, the dominant role of food expenditures means that food dominates the composition of embodied energy as well (Figure 10), accounting for over half of the energy footprint of household consumption, despite the fact that the embodied energy intensity of food is relatively low.

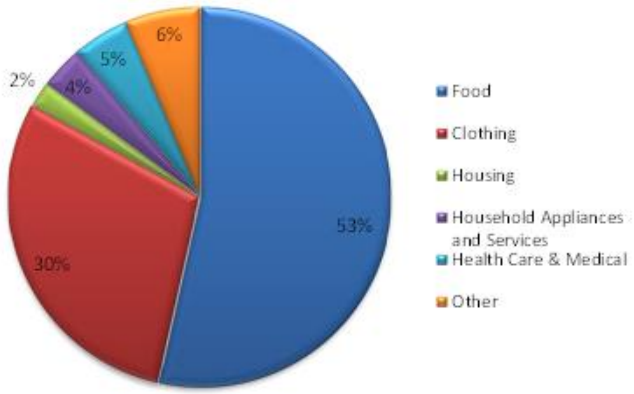


Figure 5. Structure of Residential Consumption Embodied Energy

Clothing purchases, accounting for about 10% of monetary expenditures, translated into 30% of total embodied energy consumption, in part owing to the high proportion (over 40%) of coal-based electricity in China's textile industry fuel mix (NBS 2012).

On a per-capita basis, however, the embodied energy of food remains fairly low in comparison to countries with advanced industrial agriculture such as the US or the EU. The embodied energy in the food supply totalled nearly 27 billion MJ, or about 28 MJ/person/day (Table 2). Assuming each person consumes about 10 MJ of food energy per day (including waste), this suggests that 2.8 MJ of energy were required to supply 1 MJ of food energy to each urban resident. In the US, the equivalent figure for input energy would be about 10 MJ per MJ of food energy consumed (Canning et al. 2010).

Table 2. Residential Consumption Embodied Energy Consumption

	Energy Consumption MJ
Food	27,406,240,581
Clothing	15,114,742,669
Housing	1,096,210,033
Household Appliances and Services	1,873,550,220
Health Care & Medical	2,466,777,002
Other	3,266,752,821

Buildings for People to Work, Buy, Learn, Reside Temporarily, and Be Sick

The commercial sector of a city provides accommodation for the variety of activities that its inhabitants do on a daily basis. In this model, the commercial sector is divided into six types of buildings: retail, hotels, schools, hospitals, office buildings, and other. Different building types employ different construction methods and materials, and thus the embodied energy of each type differs. Similarly, the nature of the activity in each building type differs, and thus the operational energy use of each type varies. For example, hospitals tend to be low-rise buildings with high demands for hot water; as seen in Figure 11, the operational energy of hospitals is more than twice that of the embodied component. Similarly, in retail buildings, the extensive use of lighting, air conditioning and heating also keeps operational energy high. Office buildings constitute many of the high-rise structures of the city, with more intensive use of materials and have high embodied energy intensities but have fewer hours of operations each week than other building types.

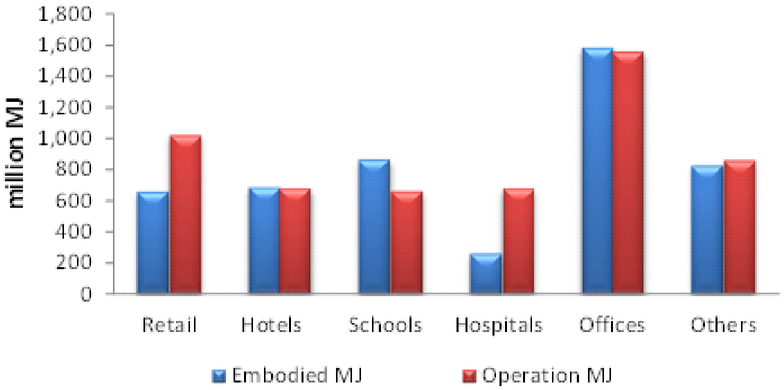


Figure 11. Operational and Embodied Energy in Commercial Buildings

Implications

This approach to looking at the energy footprint of a city based on the impacts of the city's inhabitants shows, in the case of Suzhou, that personal consumption of goods and services accounts for the largest (41%) contribution to energy footprint of the city, and this figure would likely remain around 40% even with inclusion of details omitted in this version of the model (mainly freight transport and water treatment).

For a policy-maker, the high proportion of goods and services in the city's energy footprint suggests that addressing supply-chain inefficiencies and growing consumerism have important energy implications. Of the supply-chain issues that need to be considered, the food supply chain appears to be dominant given its high share of energy embodied in household consumption, even at the highest income levels.

Developing long-distance or international food supply chains as in the US would dramatically raise the energy demand of each resident and further decrease the food energy return on investment to less than the 0.4 it is today. It also makes apparent the impact of increasing wealth as rising household income is translated into higher consumption, which in turn has corresponded to higher embodied energy in the case of Suzhou. Rising consumerism and its related embodied energy impacts could be partially offset by programs encouraging rental instead of ownership of some equipment and services, and through minimizing disposability of products.

In addition, this approach highlights the impact of building lifetime: design and code requirements that would raise the lifetime of buildings from the current 30 years to a US average of about 75 years (or a UK average of over 100 years) would further decrease the contribution of the embodied energy in buildings to even a lower proportion than found here. Similarly, it suggests that "green buildings" with low or net-zero operational energy may not be "green" at all if the embodied energy of the materials used in the building is considered in the calculation.

This exercise also adds a different perspective to the impact of such popular programs such as encouraging CFL use or buying more fuel efficient cars: though important in their own right as a matter of waste reduction, the contribution to changing the overall energy picture is quite small. As the physicist Geoffrey Scott noted in his own study of urban forms: "the societal consumption driven by the process of urbanization — our collective desire for iPads, Frappuccinos and the latest fashions — more than outweighs the ecological benefits of local mass transit" (Lehrer 2010).

Conclusion

Through the Suzhou case study presented in this paper, the Urban RAM model help policymakers better understand the major components driving energy consumption and related CO_2 emissions in their urban areas and thus identify possible areas of policy intervention. In the case of Suzhou, the energy embodied in city infrastructure and the residents' goods and services consumption exceeded operational energy by a factor of three. Suzhou's embodied energy in turn was dominated by good and services, of which nearly half came from food and nearly one-quarter from clothing, with energy embodied in infrastructure representing only 20% of the total. Accounting for only a quarter of the total annual energy footprint, operational energy was dominated by transportation with 59% and residential buildings with 26%. While the results of the Urban RAM should not be seen as providing an exhaustive and precise inventory of urban energy use and emissions, they nevertheless highlight important policy implications on not only energy and emission sources, but also on broader issues such as building lifetime, supply-chain impacts, and the net energy impact of "green" technologies.

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