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The Varieties of Building E[m]ergy Intensity

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ABSTRACT

In two subsequent offerings of a class at the University of Pennsylvania—Architecture 751: Ecology, Technology, and Design—student teams evaluated the e[m]ergy profiles of 18 different residential buildings, 6 attached buildings, 6 detached, single-family buildings, and 2 exceptional residences. The results exemplify the lessons and limitations of the study. Much of the variation in the results can be traced to the difficulty of accurately estimating of the amounts of construction materials in buildings, which introduce significant noise into the results. Increasing the number of studies will ameliorate that problem, as will more rigorous standardization of the methods and cross-checking by the student teams. The averages from this population can serve as an initial point of reference for future studies conducted with the same methodology.

In this population of buildings, the total amount of e[m]ergy involved in a household does not correlate particularly with the size of the building, the number of occupants, or its weight. Each of these can be considered a factor in their e[m]ergy intensity of households, but the variety itself suggests that a more comprehensive set of considerations has to be invoked. The conventional normalization of energy use per unit of floor area has been a particular limitation of reporting, which focuses attention only on the quality of building construction, not the total consumption of households. A first hypothesis to be tested is that total amounts of energy and e[m]ergy attributed to households can be better correlated with the wealth, status, and location of the household.

BUILDING TYPES AND ENERGY

The analogy between the varieties of livings species and the varieties of building types has been a subject of architectural speculation for at least two hundred years, and theories about the similarities have adapted as the science of evolution has itself evolved (Steadman, 2008). Early studies catalogued the visible features of architectural styles, but after Darwin's work the emphasis shifted to identifying different kinds of function in building and understanding the proliferation of specialized types as the population of people and buildings exploded. The principles of maximum em-power and the emergence of production hierarchies within self-organizing systems offers a broader explanation for the varieties of building types, which is that buildings are specialized tools developed to enhance the power of individuals and the larger social and economic systems in which they operate. E[m]ergy synthesis can provide new insights into the development and variety of building types and puts the ambitions for greater energy efficiency in a radically different context, the pursuit of power.

The data necessary to develop a full e[m]ergy accounting for buildings is not readily available, though in the US, explicit energy consumption has been tracked in increasing detail since the 1970s. If we look at the most recent energy data collected by the Department of Energy (DOE) for US buildings, reported in the Commercial Building Energy Consumption Survey (CBECS, 2003) and Residential

Energy Consumption Survey (RECS, 2005) we see the emergence of simple hierarchical relationship between the quantities of a building type and its energy use intensity, measured in kBTU/sf. See figure 1. The built area of the most common building type, the detached single-family home (SFH-Detached), is an order of magnitude larger than any other type (1.98 E11 SF) and has the lowest average rate of energy consumption per unit of area: 39.8 kBTU/sf. The next two largest areas of buildings are also both residential types, attached single-family homes (SFH-Attached) and multi-unit apartments (Apt 5 or More), and both have somewhat higher levels of energy consumption, 46 and 62.4 kBTU/sf. This is somewhat puzzling because for heating, cooling, and lighting, we expect attached and multi-unit buildings to be more efficient. However if we look at the average area per household, the detached buildings are 1.4 times larger than attached residences and 3.12 times larger than apartments in mult-unit buildings, which translates to correspondingly larger annual expenditures on energy: $2,060 per household for the detached and $1,598 and $1,070 for the attached and multi-unit residences. In other words, the larger detached buildings are more expensive to operate, which is partly ameliorated by their greater efficiency per unit of area.

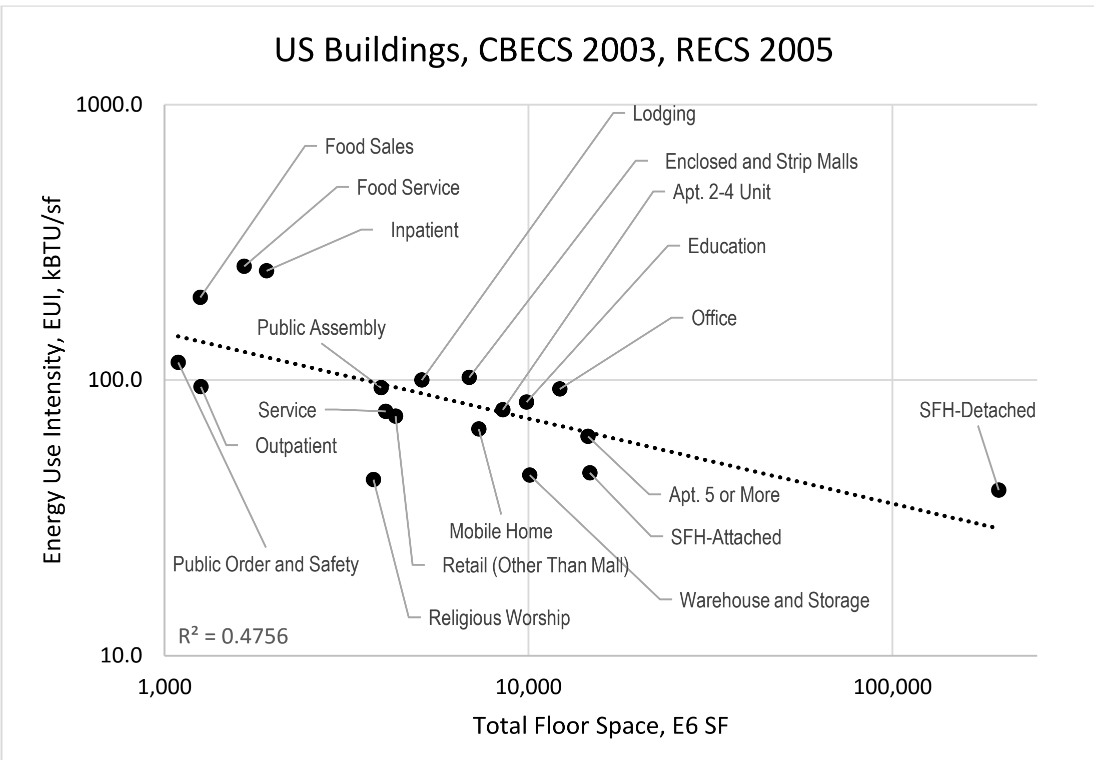

Figure 1. *Chart of building energy use intensity in US buildings from DOE survey data.*

After the residential buildings, the next largest area is in office buildings & warehouses, then education, malls, lodging, and so on. There is a lot of variation in the correlation, but generally the more energy intensive the use of the building, the smaller the built area. It is fascinating to speculate about the different factors involved in each building type, and DOE has collected a lot of data to support deeper investigation, but the problem with only tracking direct energy consumption is that it neglects the many other forms of work and resources that flow through buildings and some important distinctions between the resources used to build and maintain buildings and those used by the activities conducted within them.

Looking at it from a broader perspective, buildings are tools that people use in their social and economic enterprises. It is as important to evaluate the work and resources involved in the activities housed by buildings, as it is to consider the purchased energies used in their operation. To understand the varieties of resource usage in buildings, graduate students at Penn have been asked to develop e[m]ergy models of houses and apartments from around the world, dividing the resource use into three broad categories—Site, Shelter, and Setting—distinguishing between the resources used to modify the climate (shelter), support the activities of work and living (setting), and address the issues of location (Site). The selection of projects includes many variations in size, types of construction, and climate captured in revealing e[m]ergy diagrams.

BUILDING E[M]ERGY SYNTHESIS

In two subsequent offerings of a class at the University of Pennsylvania—*Architecture 751: Ecology, Technology, and Design*—student teams selected 18 different residential buildings to evaluate. Most of the projects were chosen for convenience and access to data, and either belonged to the students or their families, while others were selected because they were published with environmental data.

Using the Ellis House example explained in *Architecture and Systems Ecology* (Braham, 2016), teams gathered demographic and consumption data for the building and estimated the amounts of specific materials in the buildings. Two methods were used: manual estimates of materials from drawings and the construction of a digital Building Information Model (BIM). The digital models use a more complete and standardized library of construction assemblies, so those projects typically accounted for more materials and had higher e[m]ergy estimates.

The e[m]ergy synthesis method applied to the projects was originally introduced at the 8th Biennial Emergy Research Conference (Braham & Yi, 2015). As explained in the conference presentation, the inputs were separated into three scopes or scales of activities: Site, Shelter, and Setting. "The first task of buildings is the enhancement of a location, whose value is determined by its relative position in the urban, spatial hierarchy. The second task of buildings is to modify the local climate—temperature, humidity, illumination levels, etc.—sheltering the occupants and making them comfortable. The final task is the provision of a setting for work and living, which facilitates the many different activities in which people are engaged." For the purposes of this comparison, the aspects of the Site were limited to the renewable resource inputs, excluding transportation and other site expenses.

To illustrate the process, assumptions, and calculations followed by the student teams, one of the case studies, the Lazzari residence, is presented in greater detail.

The Lazzari Residence is a detached, single family house built in 2008 for the four members of the Lazzari family. Located in Byram, a small town in Hinds County, Mississippi, the house was conceived to enhance the relationship of its inhabitants with the surrounding natural environment, providing abundant daylight and views with its large south facing windows and protected outdoor spaces with deep overhangs. As director of building sciences for a well-known Mississippian construction company, Patrik Lazzari had a good knowledge of green building practices. The house was positioned so that it maximizes the views but was still able to use the sun to heat the home in the winter when it is lower in the sky. The roof over hangs more on the south side to prevent the summer sun from heating. Also, the design incorporated further sustainability features to qualify for LEED certification, such as the installation of low-e glass windows and enhanced roof insulation, the implementation of a geothermal heat pump system, and a water reservoir to collect rainwater from the roof.

With an overall surface of 2,400 square foot, the residence is a one-story house that accommodates 4 people: 2 adults and 2 kids. Its design constitutes a modern interpretation of a traditional Southern dogtrot home, with the front doors opening directly into a central area that goes straight through to the back. The east wing is characterized by a large open space that connects the living room with the kitchen, the dining room, and a small sitting room. The west end of the house is dedicated to the "night" part of the house with one master bedroom, overlooking the wooded back yard, two children's rooms and two bathrooms. The south, east and north sides of the house are surrounded by a timber deck suspended above the sloping ground and designed to extend the living space of the house and to create a buffer between the indoor space and the outside.

With over 9,600 square foot of landscaped area, the house is surrounded by nature and designed to encourage the experience of the environment while ensuring a high level of privacy. On one hand this provides access to natural resources, like the well for the potable water, trees for shade and ventilation, wood for building materials, while on the other hand the distance from the city forces the Lazzari family to use two cars during weekly activities.

The home is heated and cooled with a ground-source heat pump that utilizes the stable conditions in the ground to reduce the monthly energy bill. Another advantage with the system is that there is no outside unit and no maintenance and the loop underground is covered with a 50-year warranty. A water tank was installed to collect the water directed from the roof through rain gutters, and provide all the water necessary for landscaping needs.

Through the analysis of the construction documents and the collaboration with the owner, a digital model of the building was created to estimate the quantity of materials involved. See Table 1. The study showed that the building makes extensive use of Autoclaved Aerated Concrete (AAC) blocks in particular for the foundation and perimeter walls: the concrete blocks have a very high insulation quality and they are fast and easy to install. Depending on the different areas and orientation of the house, the external walls are covered with specially made stucco, compatible with the blocks, or finished with timber cladding. The roof is built with wooden trusses fastened together with truss connector plates and finished with metal sheeting coated with a paint with solar reflective material, to provide combination of solar reflectance and infrared emittance. To build the house the timber was harvested from the large old-growth oak trees that had to be cut down to build the house. The trees were cut and the wood was stored on site for about a year to dry. When not available, further information about the building technology and construction was found investigating similar buildings and norms, as the DOE Databook.

The annual energy consumption was assessed from utility bills, along with water and gas usage. Also, the members of the household shared information about their regular activities and habits to identify food and supply consumption, solid waste and wastewater production, commuting patterns and other expenditures. The resource and e[m]ergy quantities for the house are summarized in Table 2, which is divided in categories of use.

Examining the data, the total e[m]ergy per category peaks in the building utilities, non-durable supplies, and other resources used in the kitchen material services and concentrated power. On the other hand, building utilities are notably low, confirming the investment made by the owner to improve building and system efficiency. Comparing this project with the other case studies, Lazzari Residence is located among the average results (next section), both in terms of e[m]ergy per square meter and per weight, while it is one of the lowest in terms of e[m]ergy per person.

The study also included an evaluation of possible improvements to household operation: non-durable supplies count for over 15% of the total e[m]ergy, indicating that a more frugal lifestyle, reducing consumption, would provide a major impact on total building e[m]ergy. Moreover, it has been noted that heating and cooling of the large central space might be expensive both in terms of energy consumption and costs: the ceiling height increases the air volume while the absence of barriers hinders individual adjustments increasing waste. From an architectural prospective the large central open space represents an interesting and modern solution, but in terms of energy performance it has several disadvantages that can be resolved with the design of a lightweight solution to separate the living room from the kitchen and dining to provide a higher level of accuracy in terms of conditioning setting. Ultimately the questions of efficiency turn into questions about the appropriate size (and power) of the house. The size of the house strongly affects energy consumption and construction e[m]ergy: for instance, reducing the dimensions of the living room or avoiding the extra bedroom, would definitively lead to a certain level of e[m]ergy reduction. On the other hand, the selection of the size of the house comes down to the means and status of the household, therefore a more feasible solution might be using the house more intensely, for example by periodically hosting an exchange student or a couple of friends.

Table 1. Construction materials for Lazzari House, 1919 Timberlake Place, Byram, MI, organized by 5 timeframes of replacement: structure, envelope, interiors, systems, and FF&E.

Note	Item	Specification	Raw data		UEV (E12 sej/unit)	Emergy (E16 sej)	Life span (yr)	Emergy intensity (E14 sej/yr)
Site work								
a	Topsoil loss	Excavated Ground	*2.59×10^5*	*kg*	2.24	57.91	80	72.38
b	Stair	Concrete, cast-in-place	*5361.4*	*kg*	2.26	1.21	40	3.03
b	Wall	Concrete, cast-in-place	*2027.5*	*kg*	2.26	0.46	40	1.15
b	Slab	Concrete, cast-in-place	*904.9*	*kg*	2.61	0.24	40	0.59
b	Deck	Wood plank, 2" Oak	*7142.5*	*kg*	1.47	1.05	40	2.62
a	Driveway	Asphalt (4" thickness)	*13331.8*	*kg*	4.51	6.01	40	15.03
a	Gravel base	Granular fill	*35552.6*	*kg*	2.24	7.96	80	9.95
		Site work totals	**3.23×10^5**			**74.84**		**104.76**
Structure								
d	Block Wall	Concrete Masonry Units	*87368.8*	*kg*	2.17	19.79	78	24.3
b	Roof rafter	2×10, 24" O.C.	*3155.2*	*kg*	1.42	0.44	65	0.68
b	Roof sheathing	1/2" plywood	*2490.9*	*kg*	2.32	0.57	65	0.88
		Structure totals	**9.30×10^4**			**2.00**		**25.93**
External Envelope								
b	Vapor barrier	0.23" HDPE	*31.9*	*kg*	8.49	0.03	78	0.04
b	Slab on grade	Concrete, cast-in-place	*181964.1*	*kg*	2.32	42.27	78	54.15
c	Steel	5.4% of concrete	*7823.6*	*kg*	6.68	5.23	78	6.70
d	Insulation	1" Exp. Polystyrene	*86*	*kg*	11.1	0.09	67	0.14
d	Finish	Cement Base Stucco	*8478*	*kg*	3.72	3.15	50	6.31
b	Binder	0.1" Mortar	*481.2*	*kg*	3.72	0.17	50	0.35
b	Vapor barrier	HDPE	*20.1*	*kg*	8.49	0.02	50	0.03
d	Insulation	2" Exp. Polystyrene	*405.4*	*kg*	11.1	0.45	67	0.67
e	Board	5/8" Gypsum	*2226.7*	*kg*	1.61	0.36	52	0.69
b	Finish	Acrylic paint	*30.8*	*kg*	25.5	0.08	10	0.79
b	Roofing	Asphalt shingle 1/4"	*3333.2*	*kg*	4.42	14.72	31	0.47
b	Insulation	Fiberglass, 2" batt	*68*	*kg*	3.86	0.02	67	0.04
d	Underlayment	15lb felt paper	*340.1*	*kg*	6.92	0.23	31	0.75
b	Frame	Wood	*112.1*	*kg*	3.38	0.04	31	0.12
b	Glass	Glass	*162.7*	*kg*	12.7	0.69	33	2.10
b	Finishing	Acrylic paint	*34.1*	*kg*	24.5	0.08	12	0.69
b	Frame/Panel	Wood	*112.1*	*kg*	3.38	0.04	31	0.12
b	Glass	Glass	*162.1*	*kg*	12.7	0.20	31	0.66
b	Casing frame	Aluminum sash	*243.5*	*kg*	20.4	0.49	31	1.60
b	Finish	Acrylic Paint	*22.4*	*kg*	24.5	0.05	12	0.46
		Envelope totals	**2.07×10^5**			**68.32**		**124.36**
Interior & Finishes								
b	Frame	2×10, 24" O.C.	*1818.5*	*kg*	1.42	0.25	65	0.39
e	Board	5/8" Gypsum	*2486.7*	*kg*	1.61	0.40	52	0.77
b	Finish	Acrylic Paint	*49.6*	*kg*	24.5	0.12	11	1.10
b	Finish	Acrylic Paint	*44.4*	*kg*	24.5	0.10	11	0.99
b	Floor finish	7/8" Hardwood	*6128.7*	*kg*	1.42	0.87	57	1.53
b	Finish	Acrylic paint	*1.1*	*kg*	24.5	0.00	11	0.02
b	Frame	2×4, 16" O.C.	*2313.4*	*kg*	1.42	0.32	65	0.50
e	Board	1/2" Gypsum (2ply)	*6285.5*	*kg*	1.61	1.01	52	1.95
b	Finish	Acrylic paint	*139.5*	*kg*	24.5	0.34	11	3.11

Note	Item	Specification	Raw data		UEV (E12 sej/unit)	Emergy (E16 sej)	Life span (yr)	Emergy intensity (E14 sej/yr)
		Interior totals	**1.93×10^4**			**3.44**		**10.37**
Systems: HVAC, Electric, Plumb.								
b	Rain Gutter	0.03" Aluminum Alloy	*53.1*	*kg*	21.3	0.18	38	0.28
b	Furnace	Fumac, Bryant 355AAV	*92.1*	*kg*	10.8	0.10	19	0.52
b	Air conditioner	AC, Bryant 552A	*76.2*	*kg*	10.8	0.08	15	0.54
c	Duct	Galvanized steel	*1330.2*	*kg*	6.73	0.89	17	5.27
b	Water heater	Machinery	*95.3*	*kg*	10.8	0.10	14	0.73
d	Electric wiring	PVC insulated copper wire	*183.0*	*kg*	109	2.00	67	2.98
c	Plumbing pipe	Carbon steel (supply)	*163.9*	*kg*	6.68	0.11	47	0.23
b		PVC (drainage)	*119.1*	*kg*	9.45	0.13	47	0.24
		Systems totals	**2.11×10^3**			**3.51**		**10.80**
Furniture, Fixtures, Equipment								
b	Bathtub	Porcelain	*35.4*	*kg*	4.93	0.02	30	0.06
b	Shower base	Terrazzo	*69*	*kg*	4.93	0.03	30	0.11
b	Toilets	Porcelain	*247.2*	*kg*	4.93	0.12	30	0.40
b	Lavatories	Porcelain	*95.3*	*kg*	4.93	0.05	30	0.16
a	Cabinets	Kitchen Cabinets	*571.2*	*kg*	6.73	0.38	35	1.10
a	Lighting	Incandescent Bulbs	*1.7*	*kg*	6.87	0.00	24	0.00
a	Washer	Washer, Frigidaire	*99.8*	*kg*	10.8	0.10	15	0.71
a	Dryer	Dryer, Frigidaire	*58.5*	*kg*	10.8	0.06	15	0.42
a	Dishwasher	Dishwasher, Frigidaire	*35.8*	*kg*	10.8	0.04	15	0.26
b	Electric oven,	Wall-oven, electric	*63.5*	*kg*	10.8	0.07	15	0.45
a	Gas range	Cooktop range, gas	*17.7*	*kg*	10.8	0.01	15	0.12
b	Refrigerator	LG LRFC21755	*126.1*	*kg*	10.8	0.14	15	0.90
a	Microwave	Microwave Oven	*13.6*	*kg*	10.8	0.01	15	0.09
a	Computer	Computer	*27.3*	*kg*	32.0	0.08	7	1.25
		FF&E totals	**1.46×10^3**			**1.14**		**6.07**
Totals (w/o utilities)			**3.23×10^5**	*kg*		**96.70**		**177.50**

Note: UEVs are relative to the baseline of 1.52×10^{25} sej/yr. **a**. Cabezas et al. 2010, **b**. Buranakarn. 1998, **c**. Haukoos. 1995, **d**. Meillaud et al. 2005, **e**. Odum. 1996.

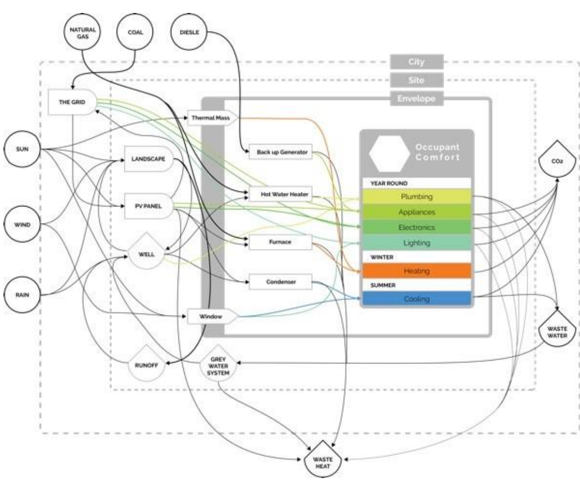

Figure 2. *Energy-e[m]ergy diagram of Lazzari House.*

Table 2. E[m]ergy Synthesis, Lazzari House, 1919 Timberlake Place, Byram, MI, apportioned to three scopes, and divided by activity.

Note	Item	Data	Unit	Unit Solar Emergy	Life	Solar E[m]ergy	Solar E[m]ergy
		Units	Unit	sej/Unit	Years	E12 sej/yr	E12 eej/yr
SITE							
Renewable Inputs							
1	Sunlight	6.32E+12	J/yr	1		**6**	
2	Rain (chemical potential)	3.29E+09	J/yr	2.48E+04		**82**	
3	Rain (geo potential)	9.17E+06	J/yr	1.43E+04		**0.13**	
4	Wind (kinetic energy)	2.20E+11	J/yr	1.07E+03		**236**	
						Subtotal	**324**
				Subtotal, building as Site			**324**
SHELTER							
Building Construction, Shelter							
5	Structure (deprec.)	2.00E+17	J/yr	Table 1	77	**2,588**	
5	External Envelope (deprec.)	6.86E+17	J/yr	Table 1	55	**12,436**	
5	Systems (prorated, deprec.)	1.19E+16	J/yr	Table 1	32	**366**	
13	Labor, Homeowner	2.65E+07	J/yr	2.80E+07		**743**	
						Subtotal	**16,133**
Building Construction, Utilities							
12	Heating	1.78E+10	J/yr	1.78E+05		**3,164**	
12	Cooling	3.67E+09	J/yr	2.77E+05		**1,016**	
12	Ventilation, mechanical	0.00E+00	J/yr	2.77E+05		**0**	
12	Illumination	2.34E+09	J/yr	2.77E+05		**649**	
						Subtotal	**4,829**
				Subtotal, building as Shelter			**20,961**
SETTING							
Building Construction, Setting							
5	Interiors & Finishes (deprec.)	3.44E+16	J/yr	Table 1	33	**1,037**	
5	Furniture, Fixt., Equip. (deprec.)	1.14E+16	J/yr	Table 1	19	**607**	
5	Systems (prorated, deprec.)	2.32E+16	J/yr	Table 1	32	**715**	
						Subtotal	**2,360**
Kitchen, Material Services & Concentrated Power							
7	Water	4.22E+04	J/yr	3.01E+08		**13**	
8	Wastewater	4.22E+04	J/yr	3.00E+10		**1,267**	
7	Water - Heating	7.19E+08	J/yr	1.78E+05		**128**	
9	Food	1.53E+10	J/yr	3.22E+06		**49,215**	
12	Food – Refrigeration	1.55E+09	J/yr	2.77E+05		**428**	
	Food – Cooking, Gas	7.29E+08	J/yr	1.78E+05		**130**	
7	Food – Cooking, Elec.	7.29E+08	J/yr	2.77E+05		**202**	
9	Solid Waste	1.47E+03	Kg/yr	1.61E+12		**2,362**	
						Subtotal	**53,745**
Bathroom, Material Services & Concentrated Power							
7	Water	2.42E+05	L/yr	3.01E+08		**73**	
8	Wastewater	2.42E+05	L/yr	3.00E+10		**7,269**	
7	Water – Heating	4.12E+09	J/yr	1.78E+05		**734**	
						Subtotal	**8,076**
Laundry, Material Services & Concentrated Power							
7	Water	9.89E+04	J/yr	1.78E+05		**30**	
8	Wastewater	9.89E+04	J/yr	2.77E+05		**2,973**	
7	Water – Heating	1.69E+09	J/yr	1.78E+05		**300**	
7	Elec – Wet Cleaning	1.30E+09	J/yr	2.77E+05		**359**	
Work & Entertainment, Material Services & Concentrated Power							
10	Non-durable Supplies	8.18E+03	$/yr	2.50E+12		**20,440**	
11	Solid Waste	1.47E+03	Kg/yr	1.61E+12		**2,362**	
7	Elec. – Electronics	3.71E+09	J/yr	2.77E+05		**1,027**	
						Subtotal	**23,829**
				Subtotal, building as Setting			**91,672**
				TOTAL EMERGY			**112,957**

EIGHTEEN RESIDENTIAL BUILDINGS

Of the 18 buildings included in the study, 8 were attached buildings (rowhouses, twins, duplexes, or apartments), 8 were detached, single-family houses, and 2 were exceptional forms of residence—Jangbogo Station in Antarctica and the International Space Station—to test the limits of conventional assumptions about residential construction. One of the enduring problems of environmental building design is the determination of meaningful norms or points of comparison for evaluation. As illustrated in the first section of this paper, building energy use is typically normalized to floor area and compared to buildings of similar types of use. This provides a valuable tool for analyzing the quality of building construction, but reveals little about the effects of building size or location and completely obscures the varieties and inequalities among buildings built for the same purpose. Using the techniques of e[m]ergy synthesis can reveal the full environmental costs and interconnections of buildings and provides a more comprehensive basis for evaluation.

E[m]ergy synthesis summaries similar to the Lazzari house were prepared for all 18 buildings and the results presented in Table 3 and charted in Figure 3. To facilitate comparison, the total e[m]ergy of each building is divided into the three categories, Shelter, Setting, and Site, with Site reporting only the renewable inputs to each project. 18 buildings ultimately provide a very small sample from which to draw any larger conclusions, and the challenges of standardizing (and checking) the estimates of the building construction proved the most difficult. Variations in assumptions about the many different construction materials, and differences in technique made it difficult to verify many of quantities, though many obvious oversights were corrected (one house originally reported over 100,000 kg of paint). The method of assessing material quantities, Manual or Digital—are also noted in the table, though did not ultimately correlate with the total weight in the construction estimates.

This comparison highlights the importance of a standardized technique for evaluating building construction. There are no published surveys or databases of material quantities used in building construction to draw on, so many of the variations in these results stem from differences in the methods and assumptions of the estimates. Conversely, the 18 projects are of very different forms of construction, from different periods, climates, and even cultures. In general, the detached single-family residences were larger and involved a greater weight of construction per household, though there were exceptions like the Float House, whose construction was very lightweight, and 2043 Spruce, an apartment in a typical brick rowhouse, which weighed substantially more than the other attached dwellings. However, weight does not translate directly to e[m]ergy, since the older buildings tended to be built of less e[m]ergy intensive materials.

The two exceptional residences, the ISSS and Jangbobo Station, provided interesting points of comparison. Jangbobo's intensity per unit area falls within the standard deviation of the other terrestrial buildings. It turns out the delivering prefabricated construction by ship is relatively efficient, and the building was well designed for its climate. The transportation of materials to the ISSS on the other hand is extravagantly expensive, but its value derives from the importance of research in space A study of Biosphrere II, which can also be considered a residence, wasn't fully completed, but its results suggested that the higher than normal energy consumption of the building was more than offset by the closed-loop production of food and other goods.

Table 3. E[m]ergy Analysis organized in three scales of use: Site, Shelter, Setting.

Case Study	Bldg Type	Met hod	Total e[m]ergy	Shelter	Setting	Site	Occ	Wght	Area	Sej/ Occ	Sej/ Wght	Sej/ Area
			sej E+17	sej E+16	sej E+16	sej E+13	#	kg E+05	m^2	sej/# E+16	sej/kg E+11	sej/m^2 E+14
2421 Christian Street, Philadelphia, PA	Attached	M	1.10	1.25	9.75	1.50	6	1.16	167	1.83	9.45	6.58
3853 Lancaster Ave., Philadelphia, PA	Attached	M	0.46	0.48	0.37	336.50	1	1.87	50	4.60	2.45	9.28
Beijing Apartment, China	Attached	M	1.36	2.63	10.96	6.00	4	1.44	84	3.40	9.45	16.20
2043 Spruce Street, Philadelphia, PA	Attached	D	1.25	3.72	8.81	1.70	3	5.90	82	4.18	2.12	15.29
43 Ludlow Street, Philadelphia, PA	Attached	M	2.01	10.57	9.56	3.00	4	1.04	164	5.03	19.36	12.28
68 Nethompson Street, Portland, OR	Attached	D	0.69	0.92	5.70	338.90	2	0.30	392	3.48	22.63	1.78
2052 Cherry Street, Philadelphia, PA	Attached	n/a	1.38	1.72	12.12	1.20	5	0.10	392	2.77	133.18	3.53
450 Domino Lane, Philadelphia, PA	Attached	D	0.95	1.95	7.61	2.50	2	0.76	56	4.78	12.58	17.17
415 Thayer, Swarthmore, PA	Detached	D	1.72	6.73	10.46	0.40	4	12.86	390	4.30	1.33	4.41
1919 Timberlake Place, Byram, MS	Detached	D	1.12	2.09	9.16	32.40	4	3.23	209	2.82	3.49	5.40
2 Center Place, Palm Coast, FL	Detached	M	1.59	5.32	10.57	0.40	3	13.9	458	5.30	1.14	3.47
Float House, New Orleans, LA	Detached	M	1.28	3.31	9.56	1.00	6	9.79	88	2.14	1.62	14.65
113 Locust Grove, Pittstown, NJ	Detached	D	1.14	1.25	9.88	337.70	3	17.76	418	3.82	0.64	2.74
609 Crescent Drive, Beverly Hills, CA	Detached	n/a	1.08	1.62	8.84	347.90	3	9.86	377	3.60	1.09	2.86
Ecosense House, Victoria, BC, Canada	Detached	M	1.39	2.34	11.56	13.20	6	14.18	200	2.32	0.98	6.96
168 Main Street, Leesburg, GA	Detached	M	0.77	2.35	5.37	32.60	2	2.66	188	3.87	2.90	4.12
Averages			1.21	3.02	8.99	91.1				3.64	14.9	7.92
			sej E+19	sej E+17	sej E+18	sej E+16		kg E+06	m^2 E+0	Sej/# E+17	sej/kg E+12	sej/m^2 E+15
Jangbogo Antarctica Station	Research	D	1.67	82.70	8.45	7.06	62	97.51	4.31	2.70	0.17	3.89
International Space Station	Research	n/a	36.18	8.24	3,600	1,646	7	3.41	43.56	5,168.8	1,061	83.05

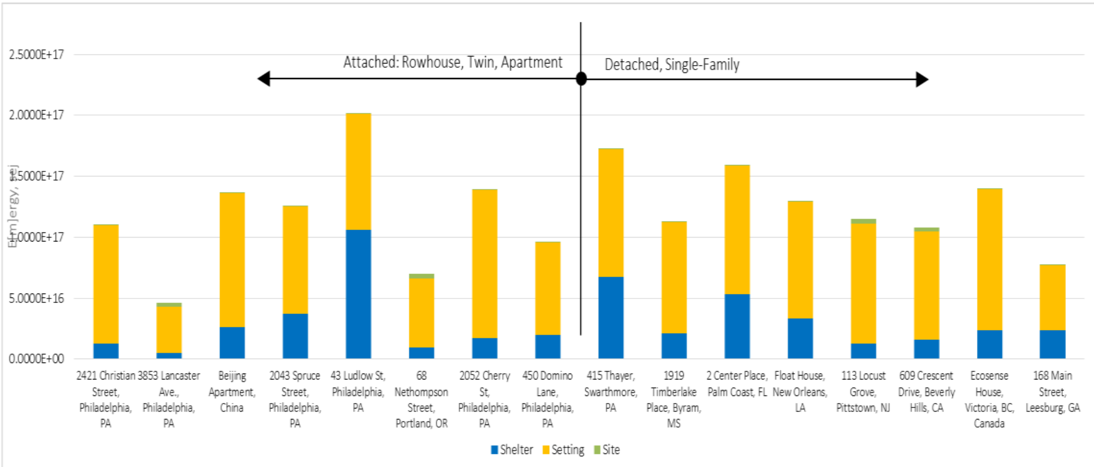

Figure 3. *Chart of total e[m]ergy for 16 buildings, apportioned by Shelter, Setting, Site*

The normalized energy consumption data for the buildings shown in Figure 4 basically corresponds to the national data reported by DOE. Most of the attached buildings have higher energy per unit of area than the detached buildings, though there are variations for climate, and surprises, such as the higher energy consumption of the Float House.

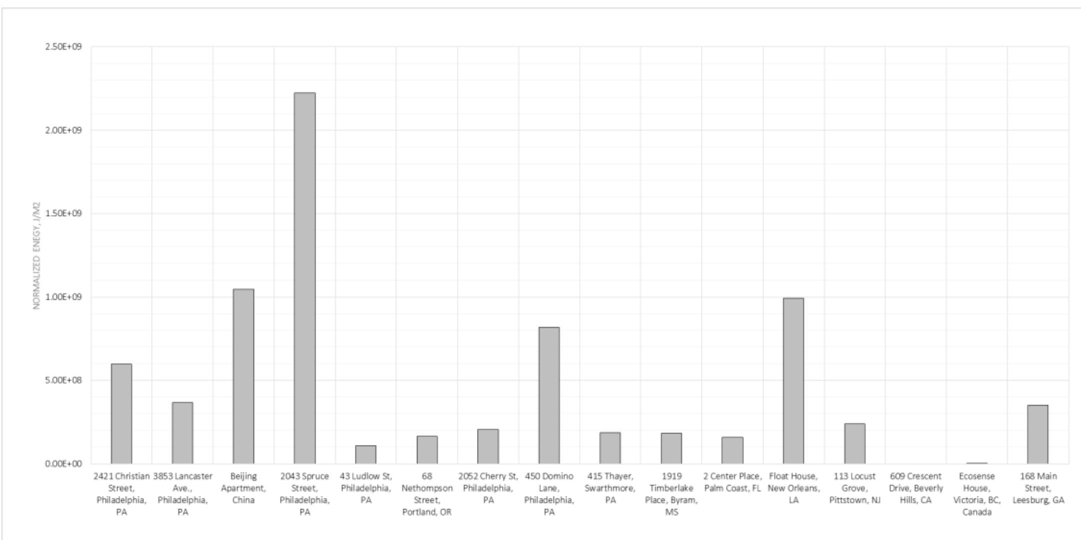

Figure 4. *Chart of normalized energy use for 16 buildings, J/m^2*

The e[m]ergy totals were normalized to floor area and number of occupants, and charted in Figure 5. The results of the area normalization revealed notable variations that mostly reflect differences in construction, age, and climate. The normalization per occupant produced a more consistent result, reflecting perhaps the variations in wealth of the households or cites. A more detailed breakdown of normalized intensity by the three categories in Figure 6 shows the frequently larger amount of resource flows involved with the activities of the occupants, reminding us that it is much easier to engineer building envelopes than it is to engineer the occupants.

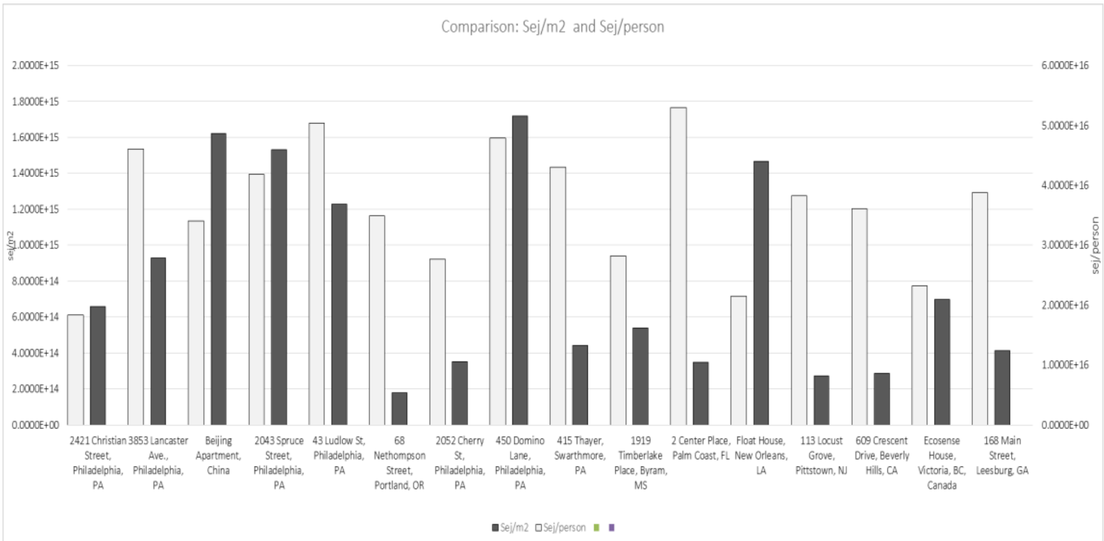

Figure 5. *Chart of total e[m]ergy normalized to floor area and number of occupants*

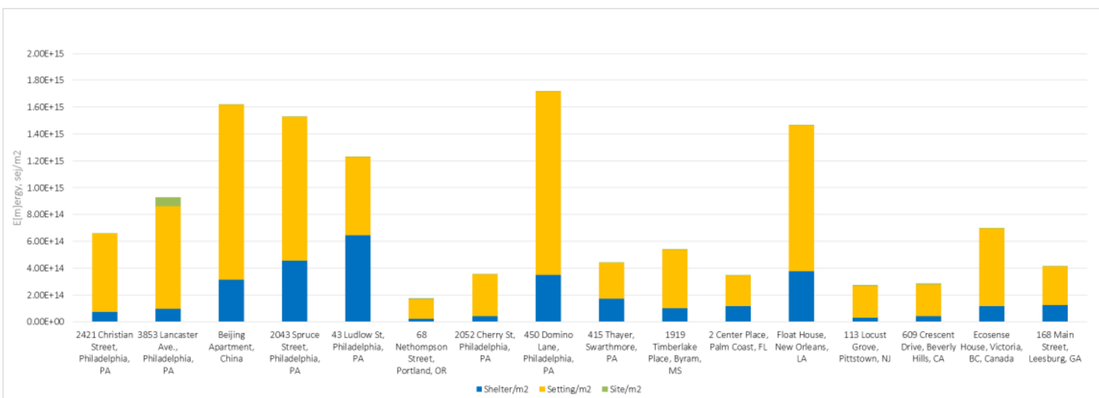

Figure 6. *Chart of total e[m]ergy normalized to floor area by category*

CONCLUSIONS

The range of results visible in Figures 5 and 6 exemplify the lessons and limitations of this study. Much of the variation can be traced to the estimates of the amounts of construction materials, which introduce significant noise into the results. Increasing the number of studies will ameliorate that problem, as will more rigorous standardization of the methods and cross-checking by the student teams. The averages from this population can serve as an initial point of reference for future studies conducted with the same methodology.

The total amount of e[m]ergy involved in a household does not correlate particularly with the size of the building, the number of occupants, or its weight. Each of these can be considered a factor in their e[m]ergy intensity of households, but the variety itself suggests that a more comprehensive set of considerations has to be invoked. The conventional normalization of energy use per unit of floor area has been a particular limitation of reporting, which focuses attention only on the quality of building construction, not the total consumption of households. A first hypothesis to be tested is that total amounts of energy and e[m]ergy attributed to households can be better correlated with the wealth, status, and location of the household.

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NOTES, TABLE 2

Note: UEVs are relative to the baseline of 1.52×10^{25} sej/yr.

1. Sunlight

Annual energy (J/yr) = (Average total annual insolation) * (Site area) = (Wh/yr/ m^2) * (3600 J/Wh) * (m^2)

Source: GHI (global horizontal irradiance), TMY3 data sets, NREL 2005

2. Rain (chemical)

Chemical potential energy of rain (J/yr) = (Annual rainfall rate) * (Site area) * (Gibbs’ free energy of water) * (1-Runoff coefficient) = (m/yr) * (m^2) * (106 g/m^3) * (4.72 J/g) * (1-Runoff coefficient)

Transformity = 3.05E+4 sej/J

Formula for Gibbs’ free energy of rain, Lu et al. 2009

3. Rain (geopotential)

Geopotential energy of rain (J/yr) = (Annual rainfall rate) * (Footprint) * (Runoff rate) * (Density of water) * (Average elevation) * (Gravity) = (m/yr) * (m^2) * (%) * (1000 kg/ m^3) * (m) * (9.8 m/s^2)

Annual rainfall rate (m/yr) from TMY3 data, NREL 2005

Transformity = 1.76E+4 sej/J, Campbell 2009

4. Wind (kinetic energy)
Kinetic energy of wind (J/yr) = (Site area) * (Air density) * (Drag coefficient) * (Geostrophic velocity)3 * (Seconds per year) = (m^2) * (1.25 kg/ m^3) * (Drag coefficient) * $(m/s)^3$ * (31,700,000 s/yr)
Drag coefficient, Garrat 1977
Transformity = 1.11E+3 sej/J, Odum 1996
5. Building construction (depreciated)
Building annual depreciation (sej/yr) = (Weight of material) * (UEV) / (Lifespan) = (kg) * (sej/kg) / (yrs)
See Table 2.
7. Water
Annual consumption of water (L/yr) = (Number of people) * (Days per year) * (Liters of water per person each day) = (# people) * (365 days/yr) * (L/day per capita)
Transformity = 2.05E+9 sej/L, Buenfil 2000
Annual consumption of water – AWWARF 1999
8. Wastewater
Volume wastewater (L/yr) = (Annual consumption of water) * (Percent of water used indoors) = (L/yr) * (%)
Transformity = 3.54E+9 sej/L, Bjorklund 2001
9. Food
Food consumption (J/yr) = (Number of people) * (Calories consumed each day per capita) * (Days per year) * (Joules per calorie) = (# people) * (2,500 Cal/day/person) *(365 days/yr) * (4,187 J/Cal)
Transformity = 1.26E+6 sej/J, Johansson et al. 2000
10. Supplies
Annual consumption ($/yr) = (0.96 * Household income) * (Percent of income for non-durables) = (0.96 * $) * (%)
Transformity = 2.50E+12 sej/$, NEAD, 2012
Average % income spent on non-durable goods – Bureau of Labor Statistics 2013
11. Solid waste
Solid waste (kg/yr) = (Number of people) * (Annual waste per capita) = (# people) * (kg/person/yr)
Transformity = 2.97E+11 sej/kg, Brown, 2000
12. Utilities
Utility breakdown based on End Uses Survey (US DOE 2012)
Transformity Fuels
Natural Gas = 1.85E+05 SeJ/J, Hard Coal = 1.37E+05 SeJ/J, Oil (#10, Diesel) = 1.89E+05 SeJ/J, Brown, 2011
US Electricity Fuel Mix

	% Mix	sej/J		(%)*(sej/J)% Mix 2010 EIA Annual Energy Report
Coal	47.42%	2.87E+05	1.36E+05	Brown, 2012
Natural Gas	19.40%	2.85E+05	5.53E+04	Hayha, 2011, Brown, 2012
Oil	0.95%	5.69E+05	5.41E+03	Brown, 2012
Nuclear	20.83%	3.36E+05	7.00E+04	Hayha, 2011, Odum, 1996
Hydro	6.27%	1.12E+05	7.02E+03	Hayha, 2011, Brown, 2004
Wind	2.28%	1.10E+05	2.51E+03	Hayha, 2011, Brown, 2004
Wood	0.86%	3.20E+05	2.75E+03	Odum, 1996
Geothermal	0.37%	2.47E+05	9.14E+02	Brown, 2002
Biomass	0.69%	8.15E+05	5.62E+03	Odum, 1996
Solar PV 0.03%	2.70E+04	8.10E+00	Brown, 2012	
Other	0.90%	3.11E+05	2.80E+03	avg.
US Electric Mix	100%			2.88E+05 sej/j

13. Labor, homeowner
Labor, site (J/yr) = (Hours worked by occupants per year) * (Calories consumed per day) * (Joules per calorie)/(Hours per workday) = (hr/yr) * (2,500 Cal/day) * (4,186 J/Cal)/(8 hr/day)
Labor, shelter (J/yr) = (Hours worked by occupants per year) * (Calories consumed per day) * (Joules per calorie)/(Hours per workday)
= (hr/yr) * (2,500 Cal/day) * (4,186 J/Cal)/(8 hr/day)
Transformity= 3.92+7 sej/J, (Income per adult * sej/$) + (sej of food)]/(Joules of food), Brandt-Williams 2002
Labor time: Bureau of Labor Statistics, 2013