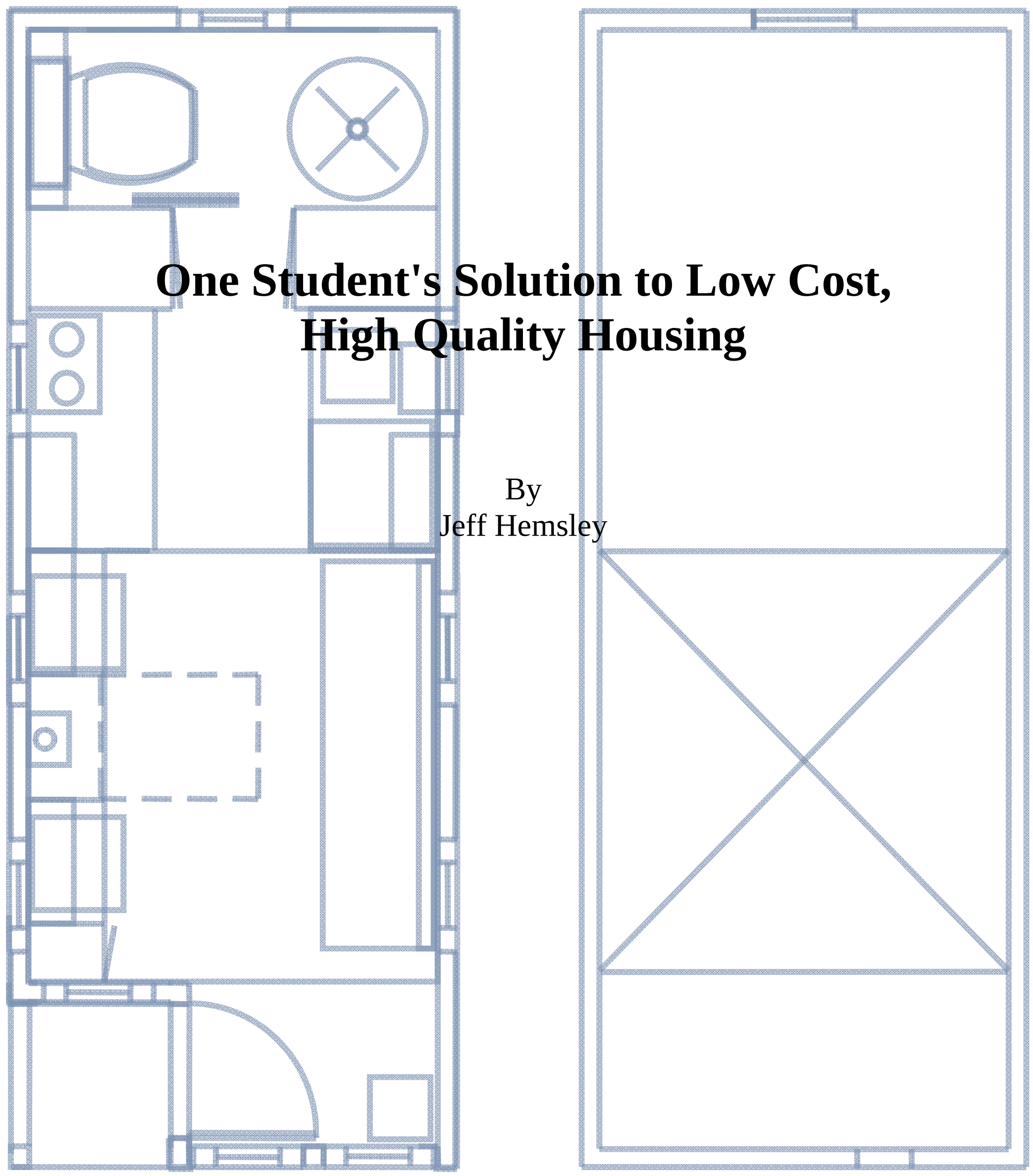

One Student's Solution to Low Cost, High Quality Housing

By
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Honors Seminar Project
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Abstract

As a soon-to-be PhD graduate student at the University of Washington, I find that issues concerning housing are of paramount concern to me. The Teachers Assistant stipend is not sufficient to cover housing and other expense. In addition, when I consider issues of indoor air quality, energy usage and other sustainability concerns, I find that the market doesn't provide a cost effective solution.

Recently constructed housing posses risks from indoor pollutants such as formaldehyde, while older units have different concerns. Newer models have more energy efficient appliances, but also more appliances that offset any gains from efficiency. Also, a trend toward larger and larger homes leads to increases in use of scarce resources, increases in waste, urban sprawl and, I will argue, increased conspicuous consumption and even longer commutes.

Without a market solution, I have opted to build a 206 square foot house on a utility trailer designed from the ground up to address these concerns. In the process of doing so, and of developing this research project, I used a simple method for estimating *total structure* R-value (a insulating measurement) for benchmarking purposes. The tiny house compares favorably in key comparisons, such as energy use per person and cost per person, against a typical house in the U.S.

An additional, anticipated advantage of the tiny house that I hope realize is greater freedom as a result of not having a mortgage, and from having lower expenses. Other tiny home builder/owners express similar motivations and advantages as those discussed here.

One Student's Solution to Low Cost, High Quality Housing

By Jeff Hemsley

> As house size increases, resource use in buildings goes up, more land is occupied, increased impermeable surface results in more storm-water runoff, construction costs rise, and energy consumption increases. (Wilson and Boehland, 2005).

1. Introduction

According to Graduate Admission Information page on the University of Washington's web site, students are generally pay about $16,632 a year for rent[1], while the typical PhD student's stipend is about $20,000 a year. After taxes and rent there isn't much left to cover books, transportation, food and the occasional glass of strongish wine. The cost of rent is, therefore, a highly important factor when considering housing over the course of a PhD program. But for some, other issues, such as indoor air quality, carbon foot print, and sustainability are also highly important considerations.

Interestingly, rental cost may be independent of these other concerns. Newer, and often higher priced units, have modern amenities that often use less electricity per device, but the number of devices more than offsets the energy savings. Older units may have fewer energy dependent amenities, but suffer from minimal insulation, drafts and air leaks that make heating and cooling more expensive. Newer units often suffer from lower indoor air quality because building materials often release volatile organic compounds (VOC's), such as formaldehyde. Older units have either had sufficient time for the off gassing process to alleviate the VOC problem, or were built long enough ago that the building materials were more natural, for example, solid wood. But these older buildings may have lead and asbestos contamination.

These concerns, along with the noise pollution endemic in apartment buildings, might nudge a graduate student into considering alternative housing situations.

Certainly, owning a home would allow a graduate student more control over indoor air quality and energy usage, but the price of houses in Seattle eliminate ownership as an option. The issue of money aside, both new and old houses suffer the same VOC and carbon foot-print pitfalls as new and old apartments. A home also entails maintenance costs (time and money – both of which are in short supply for students) that

[1] http://www.grad.washington.edu/admissions/adminfo.html

are in someway proportional to the size of the house. And note that most homes are far larger than a graduate student needs. But even if money, time, and VOC's weren't an issue, a graduate student concerned about environmental and societal sustainability might find the idea of supporting the construction industry, by purchasing a home, repugnant.

The trend in the construction industry over the last few decades has been to build larger and larger homes. But larger homes require more energy and material to build (than a smaller home), cost more to heat and cool, create an incentive toward conspicuous consumption (who wants an empty 3rd, or 4th bedroom?), produce more waste (both during construction, during normal usage, and, eventually, upon demolition), contribute to urban sprawl, and, arguably, increases the time and distance of our commutes.

The logical option for our environmentally concerned PhD student, who is also the author of this paper, might be to build his own home. But given the concerns above, and a restrictive budget, only the very smallest house, built with natural, high quality building materials, heavily insulated, and designed and built from the ground up with systems that require little energy would suffice. The remaining problem, then, is one of building codes: the majority of municipalities have minimum size requirements and other constraints that eliminate this option.

However, trailers are not fixed structures and so have different legal requirements. Thus, the author is building a tiny mobile house. The remainder of this paper will explore some of the above issues and concerns and describe how building a tiny house on a 7 foot wide by 18 foot long utility trailer[2] addresses them. Section two will briefly examine VOC's as they pertain to construction and describe the structure of the tiny house and show how the design mitigates the risks from VOC's. The following section, three, deals with energy usage. Section four explores some of the implications of increasing home sizes and how living in a tiny house is one viable alternative. Section five presents a selection of comparisons between the tiny house and the median home, and the conclusion will discuss how others, besides the author, are turning to alternative, often tiny, homes as way to address their concerns about health, the environment, and sustainability.

2. VOC's & Structure

Background of volatile organic compounds (VOC)

According to the Environmental Protection Agency, concentrations of many pollutants[3] are higher indoors than out, even in non-industrial buildings. They state that:

> Known health effects of indoor pollutants include asthma; cancer; developmental defects and delays, including effects on vision, hearing, growth, intelligence, and learning; and effects on the cardiovascular

[2] Note that utility trailer measurements are for the deck of the trailer only, so the actual surface area of the trailer is larger. The actual tiny house measures about 19 feet by 7.5 feet, for a total of 206 square feet, of which part is a sleeping loft and storage.

[3] The EPA does not consider pesticide residue on food to be an indoor pollutant, though does consider them to be a likely cause of cancer in humans.

system (heart and lungs). Pollutants found in the indoor environment may also contribute to other health effects, including those of the reproductive and immune systems (EPA, Office of Air and Radiation, p. 4).

Most consumers are aware of lead, asbestoses, radon, and carbon monoxide as sources of indoor pollution. Government even regulates, or provides guidelines for dealing with these sources. Building codes require that sources of carbon monoxide, such as for heating and cooking, are vented in specific ways designed to reduce safety concerns. Lead pipes and lead based paint are no longer used in construction, though copper pipes are often connected using lead solder (EPA, *Lead in Drinking Water*). Indeed, from 1991 to 1994, the EPA states that nearly 900,000 children had dangerous levels of lead in their blood stream (EPA, Office of Air and Radiation, p. 5). And while asbestos is also not used in new construction, it still exists in many buildings. In California, apartment complexes that still have asbestos pipe insulation are required to post warning signs indicating that the building "may contain substances known to the state of California to cause cancer or birth defects."

More recently, FEMA's solution for temporary housing after Katrina heightened the public's awareness of formaldehyde emissions in mobile home trailers. Formaldehyde, which the EPA links to cancer (EPA, Office of Air and Radiation, p. 5), is used as a plasticizer in vinyl[4] and plastic products; as an adhesive for carpets; and is found in glues for particle board, plywood, and most engineered wood flooring[5]. These last are building materials that are commonly used in construction. Particle board is used for its light weight and low cost in various household applications such as cabinet doors and as a sub-surface for counter tops. It is also found in low cost furniture. Engineered wood flooring has the advantages of being inexpensive, light weight, and has more cross-ways strength than solid wood floors. Plywood has excellent strength characteristics and can be purchased in varying thicknesses and surface quality.

The discussion above highlights the advantages of some of these building materials. But for all of these advantages, Maddalena, et al. found air born concentrations of formaldehyde as high as 0.78ppm (parts per million) in the FEMA trailers (p. viii). The U.S. Consumer Product Safety Commission states that air born formaldehyde "at levels above 0.1 ppm ... can cause watery eyes, burning sensations in the eyes, nose and throat, nausea, coughing, chest tightness, wheezing, skin rashes, and allergic reactions. It also has been observed to cause cancer in scientific studies using laboratory animals and may cause cancer in humans" (CPSC, p. 3). Note that Maddalena, et al. suggests that the excessive levels found in the FEMA trailers were likely due to the high material surface area relative to the volume of the housing units. Put differently, much of the interior surface areas (floors, walls, seat cushions, and curtains) of the trailers, were made with materials containing formaldehyde (p. 14). In a more typical situation, a new or old home or apartment, sheet rock (gypsum board) covers the walls and ceiling and the ratio of the unit's volume to its remaining, potentially VOC emitting surface area would be much lower. Still, he notes that studies by the California Air Resource Board identify

[4] Maddalena, et al. found vinyl flooring to contain aldehydes, alkyl-benzenes, and ester alcohol – all potentially harmful VOC emitting chemicals (p. 13).
[5] The EPA also indicates that formaldehyde is found in permanent press fabric, draperies, and mattress ticking (EPA, *Indoor Air Pollution*, p. 14).

composite wood materials as the chief formaldehyde VOC's for standard building materials.

The Tiny House Structure

Until research finds clearly that formaldehyde doesn't cause cancer in humans, or that at some number of parts per million is safe, a prudent course of action would be to build structures without formaldehyde emitting materials. Minimally, the ratio of living space volume to surface area of formaldehyde-containing materials should be maximized. In our application, sheet rock is not an option for walls for two reasons: one, it is heavy, and being on trailer we want to keep the weight down, and two, this tiny house being on a trailer means the house will flex while being towed, which would crack the sheet rock. Plywood would fair better, but then we'd have a large surface area composite wood in a small area.

The solution is to use all solid wood products for the interior surfaces. Knotty Pine tongue and groove will be used for the interior walls as it has several qualities to recommend it. First, being solid wood it produces no VOC's. Second, it is only 1/4 inch thick, and so very light weight. Third, it is relatively easy to install. Unfinished, solid Douglas Fir[6] will be used for the flooring.

Plywood will be used in the construction of the tiny house, but only as exterior sheathing. Between the plywood sheathing and knotty pine will be standard pine 2X4 studs, 2 inches of expanded polystyrene insulation (sealed around its edges with a soy-based, spayable foam), a "still" air gap, and a vapor barrier[7] (see Appendix B for a figure). The manufacture of the insulation claims that it "contains no CFCs or formaldehyde" and "does not create decomposition gasses" (Carlisle). It is believed that these layers will drastically reduce any risk of VOC's from the plywood sheathing.

The floor and roof are of similar construction and all of the cabinets and furniture will be constructed out of solid wood. Since the EPA also notes paints and wood preservatives as sources of VOC's, finishes for the house will be oil and wax products and sealants and caulking will be soy based (EPA, *Indoor Air Pollution,* p. 13).

To finish the general description of the house, the foundation of the house is a duel axle, 7000 lb, gross vehicle weight, utility trailer designed to transport vehicles. The floor frame and base boards of the walls will be bolted to the trailer deck and trailer frame (tubular steel) respectively. There will be a small sleeping loft above the kitchen and bathroom area, roughly 4 feet, 10 inches high at it's peak. The total height of the house will be just under 14 feet – which clears highway over passes with room to spare.

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[6] Carpet is implicated in other indoor pollution problems such as animal dander, molds, dust mites and other biologicals (EPA, *Indoor Air Pollution*, P. 10). A solid wood floor is easier to keep clean, and so a better choice if these issues are a concern. Also, normally plywood is used as a sub-floor for ease of installation of wood floors. For the tiny house the flooring was nailed directly to the floor framing studs.

[7] The vapor barrier is made of 6 mm polyethylene plastic sheeting which is unreactive at room temperature and stable up to 95 degrees Celsius (Dynalab).

3. Energy

While modeling different sized houses with varying degrees of insulation, Wilson and Boehland found that "when the floor area of the house is halved, heating costs are slightly more than halved, whereas cooling costs are reduced by about a third" (p. 279).

The energy efficiency of a building, in terms of heating and cooling, is a function several elements. Insulation and the degree to which it is air tight are important as are the area of exposed "glazed" surfaces (generally windows). Wilson and Boehland state that all else being equal, the larger the total surface area of the structure, the worse it performs in terms of energy consumption (p. 280). This means a simple box, or a structure like a geodesic dome (which enjoys a lower ratio of surface area to floor area), will perform better than a building with complex geometry, as in some custom homes. Larger buildings also suffer a distance penalty when conveying heated, or cooled air, or water, by virtue of the fact that ducts and pipes are longer. Hot (cold) air transported through ducts suffers heat loss (rise) due to many factors[8]. Researchers at Berkeley National Laboratory suggest that a typical duct system in California "wastes about 40% of the power it consumes on hot days" (Energy Performance of Buildings Group, web page).

Certainly, heating and cooling aren't the only activities that draw energy. Table 1 lists a selection of appliances and there total consumption in America, in billions of kilowatt hours, for 2005.

Appliance	Billon kWh	Percent	Appliance	Billon kWh	Percent
Air-Conditioning	182.8	16.0%	Dishwasher	29.0	2.5%
Refrigerators	156.1	13.7%	Electric Oven	21.0	1.8%
Space Heating	115.5	10.1%	Microwave Oven	19.3	1.7%
Water Heating	104.1	9.1%	PC (Desk Top)	17.2	1.5%
Lighting	100.5	8.8%	VCR/DVD	11.3	1.0%
Clothes Dryer	65.9	5.8%	Cable Boxes	2.9	0.3%
Freezer	39.3	3.5%	Satellite Dish	1.8	0.2%
Furnace Fan	38.2	3.3%	PC (Lap Top)	1.3	0.1%
Color TV	33.1	2.9%	Other Appliances	169.7	14.9%
Electric Range Top	32.0	2.8%			

Table 1 *Source: Department of Energy*

As a nation, we spend 33.1 billion kilowatt hours of electricity to watch TV even while complaining that nothing is on[9]. Laptops use less energy than desktop PCs, and the generally ignored, out-of-sight-out-mind furnace fan is responsible for a shocking 3.3% of our electric consumption. We consistently use electricity without an awareness of our

[8] Berkeley National Laboratory's Energy Performance of Buildings Group has a site with extensive information and research on the conveyance of hot/cold air through ducts, but some of the key losses come from leakage, oversized ducts, and little/no/improper insulation.

[9] The Economist noted that American's spend, on average, "8 hours and 11 minutes every day" watching TV (2007). So we spend roughly 34% of our time on it. But, combining TV, VCR/DVD, Cable Boxes and Satellite Dishes, we can see that we only spend 4.2% of our electric consumption on it. This would seem like a good deal until we note that the New York Times quoted a study by researchers at the University of Maryland who showed a negative correlation between hours watching TV and general happiness (2008).

usage. And our usage and pollution is trending upward along with our house sizes. Figure 1 shows the growth in houses sizes, energy use and release of CO_2 from 1980 to 2006.

Our tiny house addresses these energy concerns in three main ways. First, its size and insulation mean heating costs will be minimal. Second, being a tiny house there isn't room for most of the appliances used in a typical American home. Third, the appliances used in the house have been selected for low energy consumption.

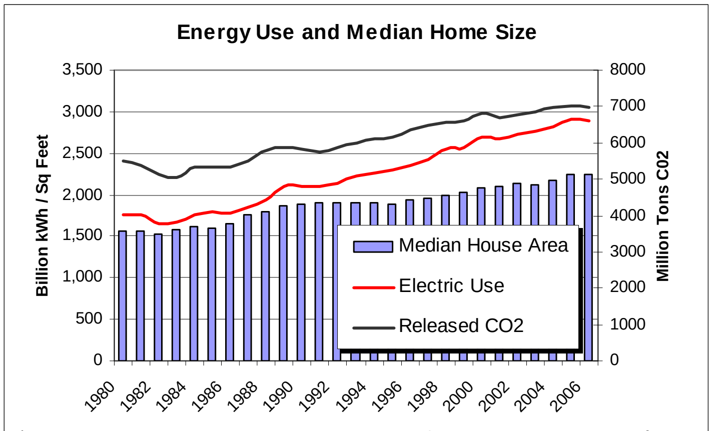

Figure 1 Data: Census Bureau, Department of Energy

As mentioned in the previous section, the tiny house will have 2 inches of expanded polystyrene insulation and a "still" air gap (of 1.5 inches) in its walls. These make up the bulk of our insulation, but the inner and outer siding, vapor barrier and sheathing also contribute (see Appendix B). Generally, the "R-value"[10] is used to express the insulating value of a wall or building material. Strictly speaking, it's a measure of thermal resistance. It is important to note that even if an insulation with a high R-value is installed, the structure of the wall (ie. studs), building geometry, windows, doors all contribute (often negatively) to the total building envelope's R-value. Other factors, such as poor sealing (allowing drafts) also reduce a structures energy performance. Using a very rough calculation technique[11], the estimated R-value for the total tiny house is 11.7, which is quite sufficient for a climate such as Seattle's.

The appliances in the tiny house will include a small, 5.5 cubic foot refrigerator, a propane stove, and a mix of compact fluorescent lamps (CFL) and light emitting diode (LED) lamps (see Appendix C for electrical usage estimates). Heat will be provided by a propane powered boat heater, and hot water will come from an on-demand propane hot water heater designed for mobile homes. Electrical outlets such as those found in a typical house will be available for laptops, an alarm clock, recharges (cell phones, shavers, etc.) and a small stereo system. Each of these has been selected for low energy draw such that we calculate a need for less than 15 amps (typical electric service is for 100 amps) at 110 volts. This means the tiny house shall require one heavy duty extension cord. It also means that our overall carbon foot print will be significantly lower than the typical 100 amp household.

The tiny house will also have a small bathroom and kitchen. Water from the sink and shower will drain into a gray water holding tank, and the toilet will be one of the

[10] The Oak Ridge National Laboratory's *Insulation Fact Sheet* (see references) site and Wikapedia both have information on R-Values. The *Insulation Fact Sheet* has a simple calculator for overall wall R-Value, but the calculator is general and makes a number of assumptions about building construction that don't apply to the tiny house.

[11] Realistic R-value calculations are complex and have to do with many factors. See appendix A for more information.

commercially available composting toilets. The gray water will be used for watering yard and garden plants, which requires that only biodegradable soaps be used.

All water, electric and gas hookups and systems are designed to meet typical recreational vehicle standards.

4. Sustainability

This paper opens with a quote from Wilson and Boehland that highlights how growing house sizes in the U.S. result in growing resource use in terms of building materials and energy used. In 2004, California's Integrated Waste Management Board found that nearly 22% of solid waste (typically going to land fill) came from construction and demolition (10.8% from residential only). Lumber accounted for an estimated 3,881,214 tons in the waste flow for 2003 (CIWMB, p. 4).

The trend in developing larger, single family dwellings, also results in urban sprawl. Robinson et al. show that between 1974 and 1998, "Settled lands became more contiguous while rural and wildland areas became more fragmented. Interior forest habitat in wildland areas decreased by 41%. Single-family housing was the primary cause of land conversion" (p. 51).

While house sizes have increased, the size of households (number of people in a home) have fallen. Between 1978 and 2007, the housing square footage per person went from 587 to 873 square feet (data based on housing occupied by households, thus second and third homes are not reflected), a gain of about 49%. Figure 2 illustrates this.

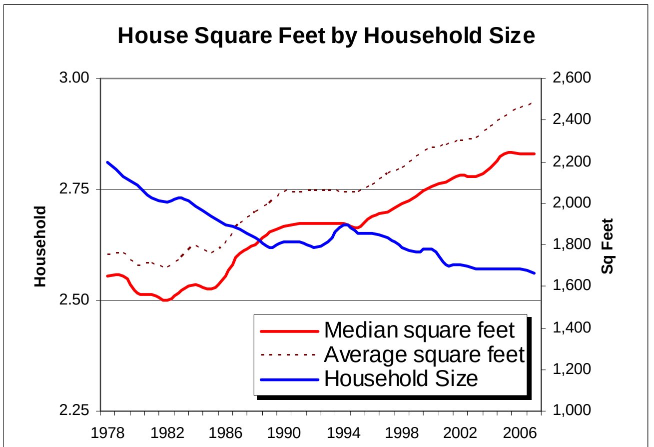

Figure 2

Interestingly, despite this gain of individual square footage, between 1984 and 2008 self storage rental units grew from 289.7 million square feet to 2.35 billion square feet – an astonishing growth rate of over 700%. At the end of 2008, there was 20.8 square feet of rentable storage per household, or about 7.4 square feet of storage for every person in the U.S., for a total (sq. feet in house plus storage) of around 880 sq feet. The Self Storage Association, the source for these storage numbers, says that "it took the self storage industry more than 25 years to build its first billion square feet of space; it added the second billion square feet in just 8 years (1998-2005)" (SSA, web page).

Another interesting observation is that over the same time frame that house sizes and storage facilities have been growing, so have commute distances. Note that larger houses require larger lots. They also require more furniture and amenities to fill them, which could have translated to a corresponding growth in retail space square footage, with accompanying growth in lot (for parking and building) sizes. Add the growth of storage facilities, and their lots, and one wonders how much the expanded commute is related to the shear growth of square footage that consumers are demanding. Is this sustainable?

Brian Kermath, at the University of Wisconsin's Global Environmental Management Education Center, in answering the question "What Is Sustainability & How Do We Get There?", states that:

> ... calls for sustainability grew out of a need for real change — out of concerns that economic growth-based development efforts were performing poorly in meeting human needs and improving human welfare in many regions, while simultaneously depleting resources rapidly, degrading the environment, pushing environmental thresholds in unprecedented ways, and compromising ambitious nature conservation efforts (Kermath, 2009).

Larger houses may contribute to economic growth through increased consumption of material and energy resources, increased consumer goods consumption, on going increased usage of energy goods, increased services such as storage facilities to store consumption overflow, and increased consumption related to increases in commute distances. But larger houses may also contribute to growing land fill, which contributes to pollution, growing automobile exhaust related to longer commutes, reduced open space from sprawl, and over consumption of scarce resources.

California's Integrated Waste Management Board states that "the concept of sustainable building incorporates and integrates a variety of strategies during the design, construction and operation of building projects" (IWMB, p. 29).

From its very design, and through construction, the tiny house addresses sustainability in three important ways. First, its size alone means that the number of resources that went into building it, and will go into maintaining it, are far less than that of a typical, newly built, house. Second, extreme care has been used in ordering and using materials to reduce waste. As an example, the floor, made from Douglas Fir, required 532 linear feet of wood. Typically, it is suggested that builders procure 5% to 7% more than the strict linear footage to accommodate loss and waste. Upon completing our floor, we had about 4.5 feet of scraps left: about 0.8% of waste.

Third, where possible, materials used have been "reuse", or recycled materials. We were able to obtain free 2x4s and other wood via friends and Craig's List.

5. General Comparisons

We now look at some general comparisons between the median house and our tiny house. The comparisons are imperfect for a number of reasons, including the fact that the energy usage is from 2005 data, while the housing data is from 2007. Additionally, the tiny house is not yet fully built so the listed cost is an estimate. Still, some of the comparisons listed in table 2 are informative. To aid in comparing a column for ratio (tiny house / median home) has been used.

Note that the cost per square foot is greater for the tiny house. A number of reasons account for this. First, walls are more expensive to build than open spaces and the tiny house will have a greater ratio of wall surface to total building area. Second, the tiny house uses solid wood in places where sheet rock or cheaper materials would normally be used. In fact, we'd expect the cost per square footage of the tiny house to be significantly larger if a construction crew built it and wages had to be paid.

	Median Home	**Tiny Home**	**Ratio: tiny/median**
Household size	2.56	2	0.78
SqFt	2235	206	0.09
Cost to build	$206,759.85	$21,375.00	0.10
kWh/household/year	10,656	3262.00	0.31
SqFt/person	873	103	0.12
Cost/person	$80,766	$10,688	0.13
kWh/person	4163	1631	0.39
Cost/SqFt	$92.51	$103.76	1.12
kWh/SqFt	4163	1631	0.39
Cost/kWh	$19.40	$6.55	0.34
SqFt/kWh	0.21	0.06	0.30
kWh/cost	0.052	0.153	2.96

Table 2

Household sizes data: U.S. Census
House sq footage and cost: NAHB
Energy data: DOE

The cost per person ratio is 0.13, which simply reflects the fact that even though the tiny house is more expensive to build per square foot, the over all cost per person is much less than that of the median home. The kWh/Person ratio of 0.39 reflects the choice to use fewer appliances.

Unfortunately, since the tiny house is not yet finished, no data is available concerning heating costs, which, according to the Department of Energy, is generally a large portion of energy consumption. However, we expect this comparison to be highly favorable because of the size and design of the tiny house[12].

Conclusion

Christer Sanne argues that consumers in America may not be the rational choice makers that classical economics supposes them to be. Sanne argues that part of what drives over consumption is a structural lock-in, wherein government policy, as well as "producers and businesses construct the field of consumption to satisfy their interests" (p. 273). In the case of housing, the government provides an incentive to buy larger homes by allowing a tax deduction based on interest paid on mortgages. The construction industry probably makes more profit on larger homes than smaller ones, so they have an incentive to keep building larger homes. And as we have seen, it is arguably the case that larger homes lead to greater consumption.

[12] Some tiny house owners report winter heating costs as low as $5 using small propane boat heaters.

In addition, over consumption is fueled by human's desire to signal their social status to those around them and to affirm what they believe (or want) to be true about themselves (Sanne, p. 275). In primitive cultures the size and number of beads one owned and displayed signaled their standing in society. Have our houses become our beads? Are we locked-in to them?

The author's tiny house is based on plans purchased from the Tumbleweed Tiny House Company[13]. This company is a fairly visible facet of a growing interest in tiny houses and has been featured on CNN, Oprah, and CBS. Resources, such as *The Small Living Journal*[14] and *The Small House Society*[15], as well as numerous blogs and forums are devoted to the topic of living in smaller spaces[16]. Those moving in a direction of living smaller cite the same reasons as your author: an interest in the environment, general sustainability, and lower cost.

But a noticeable undercurrent is an unstated recognition that purchasing a large home locks the owner into a lifestyle of greater consumption, which often requires longer and longer working hours and growing debt to pay for. Indeed, until recently, the mass media frequently mentioned American's growing debt and falling savings rates, and yet, as we've seen, house sizes were growing. Now we see a collapsing housing market and increasing levels of mortgage delinquencies and foreclosures.

Advocates of smaller homes are looking for a higher quality, simpler, environmentally friendly life that does not lock them into a work-spend-debt spiral. Since the market is not satisfying this - admittedly limited - demand, the author and others are finding creative ways to do it on their own. This has a side benefit of creating a sense of community among these like minded individuals.

[13] http://www.tumbleweedhouses.com/
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[16] See appendix D

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Appendix A: Simple R-Value Calculation

Realistic R-value calculations for an overall building envelope (including windows, insulated or open cavities, areas of structural support, corners, roofs, doors, and floors) are complex and depends on many factors. However, shown below is a simple approach to finding rough number that can be used for estimating and benchmarking[17].

First, obtain per inch estimates of your building materials. These can be found at various sites including ColoradoEnergy.org, Wikipedia, and E-Star (see references).

Identify the types of wall structure used in your building. For example, in the case of the tiny house, we identify: insulated wall cavities (IWC), wall structure (WS), windows[18] (W), door (D). For each of these, multiply the widths of the materials by their per-inch-R-values. Note these values, and add them for each type. The manufacture of the windows provides u-values for windows, which is the inverse of the R-value, and our custom door has been calculated separately. The following table illustrates the process thus far:

IWC material	IWC R-values	WS materials	WS R-value
Extruded Polystyrene	10	2x4 stud	4.38
Plywood Sheathing	0.47	Plywood Sheathing	0.47
Interior siding	0.8	Interior siding	0.8
Exterior Siding	0.8	Exterior Siding	0.8
Air Space (still)	1.5		
R-value Sums	**13.57**		**6.45**
Window (R-value)	**2.86**		
Door (R-value)	**1.9**		

Next calculate the area of each of these wall section types, and from the total, determine the percent of each. Next, for each type, multiply the percent and R-values for the weighted R-value. Sum these weighted R-values for a very rough estimate of the total building envelope R-value.

Type	Area (inches)	% of envelope	R-value	Weighted R-value
IWC	79850	79%	13.57	10.7
WS	13890	14%	6.45	0.9
W	6200	6%	2.86	0.2
D	1728	2%	1.9	0.0
sums	**101668**			**11.7**

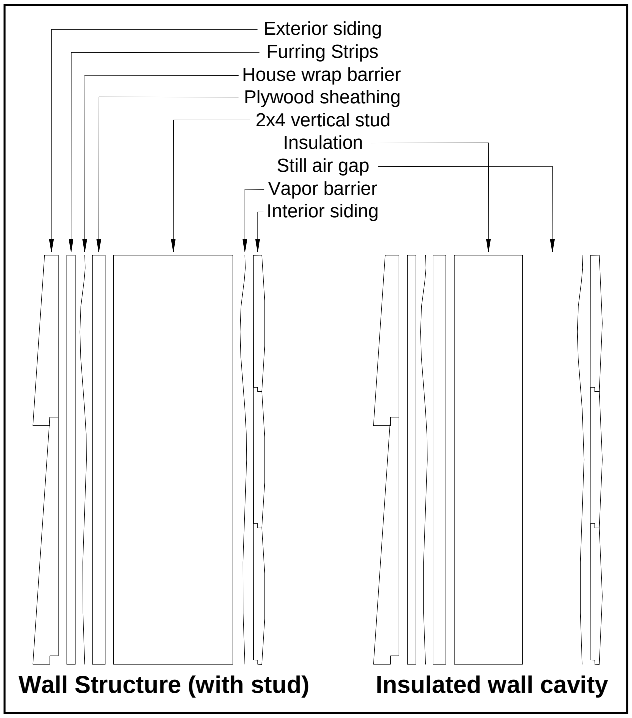
See appendix D for links and resources.

[17] This is adapted from a formula for finding U-values from Coloradoenergy.org
Formula: Assembly R-value = 1 / (Assembly U-value) = 1 / (U-studs x % + U-cavity x %)

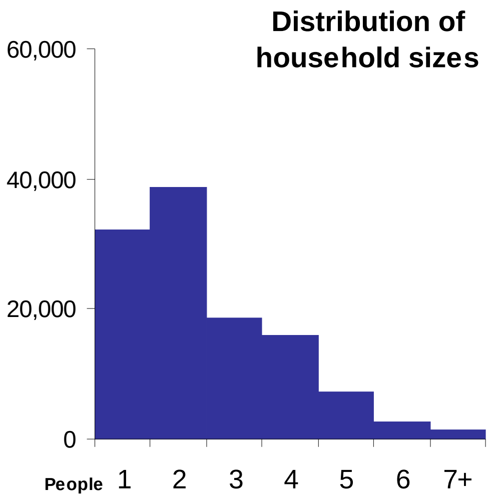
[18] The windows are double pane windows with a coating that blocks UV and infrared heat to help reduce heat transfer.

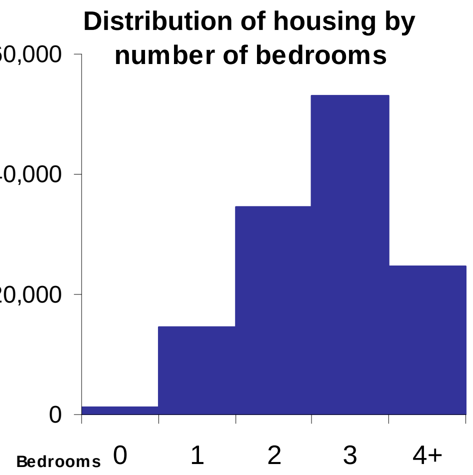
Appendix B: Additional Figures

The image to the right shows two wall cross sections in exploded view: first, a structural section where 2x4 studs are, second, between the studs. Without insulation the space between studs is an empty cavity, or a still air gap. The tiny house has 2 inches of expanded polystyrene insulation and 1.5 inches of still air (the actual width of a 2x4 is 3.5 inches) in the cavity. Around the edges of the insulation is a soy based spay insulation that seals the insulation in (not in this figure). Also, note that furring strips are .25 x 1.5 inch slats that attach to the sheathing at about 16 inch intervals. The siding is attached to the furring such that between the siding and sheathing is an air gap, the purpose of which is to assist in the drying out of the siding after rain.



The graphs below shows the distribution of household sizes in the US for 2007, and the distribution of housing by number of bedrooms. Note that the bulk of households are made up of one or two people, and that the bulk of housing has about 3 bedrooms.





Appendix C: Electrical Use Estimates

When planning a limited electrical system, the first step is to fully understand the needs of the system. While designing the electrical system for the house the table below was created for this purpose.

Item	Watts	Amps	Volts	Use hrs	kW	kWh/day	kWh/year
Printer	480.00	4.00	120.00	0.2	0.480	0.096	35.04
refrigerator	240.00	2.00	120.00	24	0.240	5.760	2102
Laptop	180.00	1.50	120.00	4	0.180	0.720	262.8
Laptop	180.00	1.50	120.00	1	0.180	0.180	65.70
Monitor	144.00	1.20	120.00	4	0.144	0.576	210.2
computer speakers	144.00	1.20	120.00	2	0.144	0.288	105.1
Full spectrum light	60.00	0.50	120.00	8	0.060	0.480	175.2
Fan	60.00	0.50	120.00	2	0.060	0.120	43.80
Heater Fan	42.00	0.35	120.00	2	0.042	0.084	30.66
Compost toilet fan	42.00	0.35	120.00	2	0.042	0.084	30.66
Hair clipper	38.40	0.32	120.00	0.1	0.038	0.004	1.402
Stereo	24.00	0.20	120.00	4	0.024	0.096	35.04
Hot Water Heater	18.00	0.15	120.00	0.1	0.018	0.002	0.657
Clock / Alarm / Radio	15.00	0.125	120.00	24	0.015	0.360	131.4
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Florescent Light	13.00	0.11	120.00	1	0.013	0.013	4.745
Shave Charger	10.20	0.09	120.00	0.25	0.010	0.003	0.931
Phone Charger	10.20	0.09	120.00	0.2	0.010	0.002	0.745
Camera batt Charger	10.20	0.09	120.00	0.1	0.010	0.001	0.372
Toothbrush	8.40	0.07	120.00	0.2	0.008	0.002	0.613
AA batt charger	8.40	0.07	120.00	0.1	0.008	0.001	0.307
TOTAL	**1792.80**	**14.94**			**1.79**	**8.94**	**3261.56**

Appendix D: Resources & More Information

See these resources for more information on R-values:

- http://www.coloradoenergy.org/procorner/stuff/r-values.htm
- http://www.ornl.gov/sci/roofs+walls/insulation/ins_02.html
- http://www.jeld-wen.com/performanceratings/documents/Wood-Custom-Thermal-Ratings.pdf
- http://en.wikipedia.org/wiki/R-value_(insulation)

Tiny House Resources:

- Coming Unmoored: http://www.unmoored.net/
- Little Diggs: http://www.littlediggs.com/
- Little Green House: http://thelittlegreenhouse.wordpress.com/
- Living Small: http://livingsmall.wordpress.com/
- ProHousing site: http://www.konzak.com/prohousing/accessory.html
- Shedworking site: http://www.shedworking.co.uk/
- small house musings: http://smallhousemusings.blogspot.com/
- Small House Society: http://www.resourcesforlife.com/small-house-society
- Sustainable Elegance: http://www.sustainableelegance.com/
- Tiny Free House: http://www.tinyfreehouse.com/
- Tiny House Design: http://www.tinyhousedesign.com/
- TinyHouses.net site: http://tinyhouses.net/
- Kent Griswold's Blog: http://kentgriswold.com/

Tiny Stick Built:

- Arvesund: http://www.arvesund.se/
- Cusato Cottages: http://www.cusatocottages.com/
- Greystokes: http://www.greystokes.com/
- Martin House-To-Go: http://martinhousetogo.com/
- Sherpa Cabins, Inc.: http://www.sherpacabins.com/
- Tiny Texas Houses: http://www.tinytexashouses.com/
- Tortoise Shell Home: http://www.tortoiseshellhome.com/
- Tumbleweed Tiny House Company: http://www.tumbleweedhouses.com/

Tiny Straw Bale Houses:

- Building with Awareness: http://buildingwithawareness.com/
- Strawbale.com: http://www.strawbale.com/cmd.php?af=640350

Tiny Timber Frame:

- Arlington Frame Company: http://www.arlingtontimberframes.com/smalltimberframebuildings.htm
- Jamaica Cottage Shop: http://jamaicacottageshop.com/
- Shelter Home Institute: http://www.shelterinstitute.com/
- Timberlast: http://www.timberlast.com/

Tiny Log Houses:

- Conestoga Log Cabins: http://www.conestogalogcabins.com/
- Greenleaf Cabins: http://www.greenleafforestry.com/greenleafcabins.htm
- Louis Lake Lodge Cabin Kits: http://www.louislake.com/pages/kits.html
- Montana Mobile Cabins: http://www.montanamobilecabins.com/

Tiny Prefab Houses:

- ideabox: http://www.ideabox.us/
- kitHAUS: http://www.kithaus.com/
- MetroShed: http://metroshed.com/
- M-Finity: http://www.m-finity.com/
- Modern Cabana: http://www.moderncabana.com/
- Modern-Shed: http://modern-shed.com/
- PowerHouse: http://www.powerhouse-enterprises.com/
- V2World: http://www.v2world.net/
- weeHouse site: http://weehouse.com/flash/SFWA_index.html

Yurts:

- Colorado Yurt Company: http://coloradoyurt1-px.rtrk.com/
- EcoShack: http://www.ecoshack.com/
- Go Yurt: http://goyurt.com/
- Pacific Yurts: http://pacificyurts.com/
- Rainier Yurts: http://www.rainieryurts.com/
- Red Sky Shelters: http://www.redskyshelters.com/
- Yurta: http://www.yurta.bakerygroup.com/

(Excluding R-value information, link list courtesy Kent Griswold at http://tinyhouseblog.com/links/)