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ANALYSIS OF THE PERFORMANCE OF EARTHSHIP HOUSING IN VARIOUS GLOBAL CLIMATES

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ABSTRACT

Earthships are houses that use walls of recycled automobile tires packed with soil to retain a berm on three sides of the home while glazing on the sunny side (south in the Northern Hemisphere, north in the Southern Hemisphere) allows solar heat into the home's interior. This paper discusses the design and application of earthships and assesses the feasibility of earthships as sustainable and healthy places of residence. The paper begins by describing the aspects of earthship design which contribute to sustainability, including the construction of the thermal envelope and its effect on the thermal comfort of the occupants; the building's ability to harness renewable energy; and the catchwater and water reuse system. Each of these aspects is analyzed with computer models that simulate homes in four distinct climate zones to determine (a) whether the design meets the comfort, electrical, and water demand for each location, and (b) the financial implications for construction and operation of an earthship in each location in comparison with a standard wood-frame house. The study shows that earthships are a financially feasible design alternative for dry/arid, humid continental, and continental sub-arctic climates; but are not feasible for tropical wet/dry climates.

Keywords: earthships, passive solar housing, thermal mass, thermal comfort, energy simulation, sustainable living, photovoltaic electricity generation, gray water.

1. INTRODUCTION

Architect Michael Reynolds developed the earthship concept with the intention of creating self-sufficient living units from sustainable or recycled materials [1]. In a typical Northern Hemisphere earthship (Fig. 1) the west, north, and east exterior walls are constructed by stacking used automobile tires, each packed with 300 lbs. (136 kg) of soil, in brick-like fashion to a height of 8 ft. (2.4 m). Not only does this method of construction reuse material that would otherwise be discarded in landfills, but it has also been determined by Griepentrog [2] that rammed earth-filled tire walls provide safe and dependable support for the structure.

Fig. 1 One bedroom earthship located in Gamerco, New Mexico

The earthships, in concept, maintain a comfortable environment, produce their own electricity, collect their own potable water supply, and manage their own waste. The high density soil inside the tires, along with earth berms on the exterior of the walls, maximizes the thermal mass of the home. In conjunction with passive solar heating through glazing on the sunny side of the house, the large thermal mass stores heat and stabilizes the interior operative temperature.[1]

In Reynolds' concept, earthships are equipped with photovoltaic (PV) panels and/or small wind turbines and a battery bank to collect and store enough energy to adequately supply the house with electricity. The metal panel roof of an earthship collects run-off water in cisterns buried under the berm on each side of the house. This water is filtered and

[1] The operative temperature accounts for convective and radiative effects on occupants to provide a better indicator of thermal comfort than the conventional measurement of ambient air temperature.

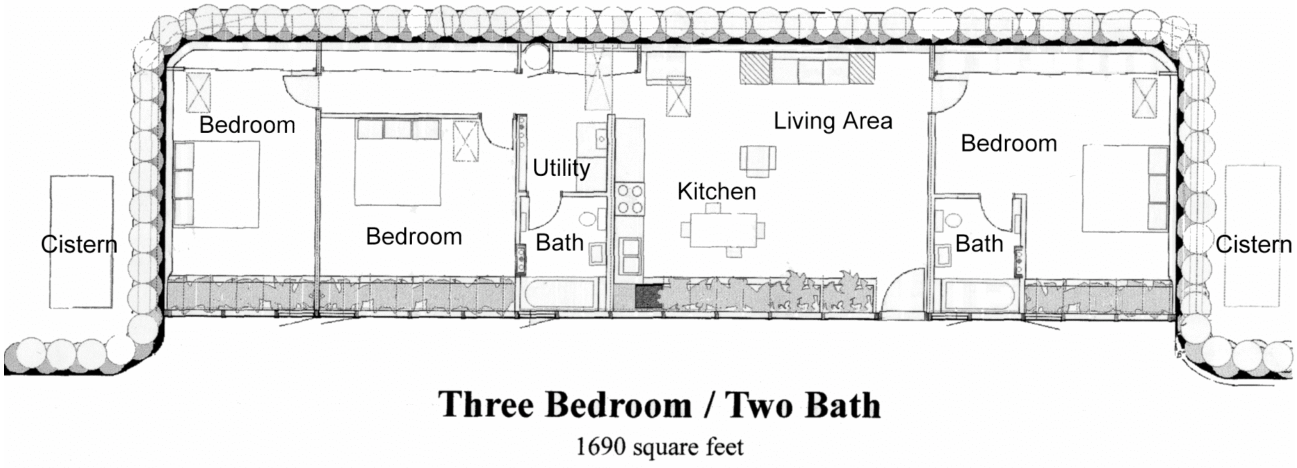


Fig. 2 Earthship Floor plan

pumped into a pressurized tank for household supply to showers, baths, and sinks. Drainage is cleaned and recycled for interior plants and toilets before it is discharged into a botanical waste treatment cell outside of the house.

The earthship concept, as envisioned by Reynolds, is suitable for all climate zones. However, there are no known studies that assess the feasibility of the earthship concept in terms of thermal comfort, electricity generation, water supply, or, ultimately, financial considerations.

This paper studies the feasibility of the earthship concept in terms of occupant comfort, electricity generation, and water supply. The goal is to determine which aspects of the earthship concept contribute to a sustainable and financially feasible way of living that is comparable to standard wood framed homes (with thermostat controlled central heating, grid-supplied electricity on-demand, and access to municipal running water). To achieve this goal, the study evaluates the performance of earthships in a variety of climates. Some site parameters that affect the performance of earthships such as solar radiation, outside air temperatures, and precipitation rates are consistent within climate zones. Other parameters such as wind, soil type, and obstructions to solar radiation (trees, hills, and other buildings) are very site specific and highly variable within a climate zone. For this study four specific cities have been selected to represent distinct climate zones:

- Anchorage, Alaska: Continental Sub-arctic
- Grand Rapids, Michigan: Humid Continental
- Albuquerque, New Mexico: Dry/Arid
- Honolulu, Hawaii: Tropical Wet/Dry

For site-specific details in these cities, the study assumes (a) local wind resources are not consistent within the climate zone (b) soil is available to form the berm and pack the tires, and (c) there are few obstructions to gathering solar energy.

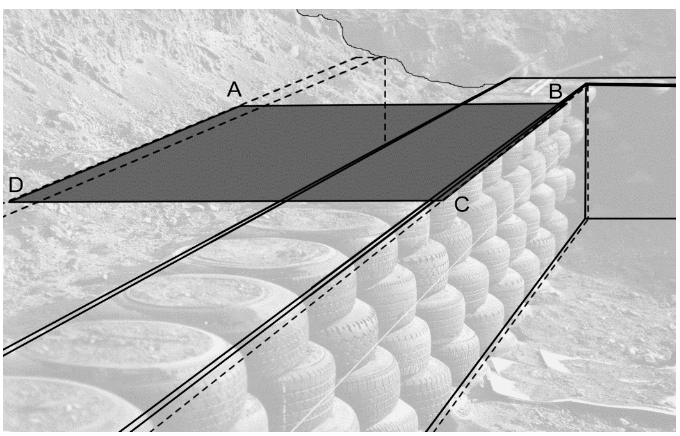
2. MODELING

For the purpose of this study, earthships are sized to accommodate four occupants, the typical family size in the United States [3]. Figure 2 shows the floor plan of the earthship used as a basis for thermal, electrical, water, and financial models. Variations to the design are applied where necessary to account for specific construction adaptations in each climate. For example, the glazing area of earthships in Anchorage and Grand Rapids is smaller than the glazing area of earthships in lower latitude locations to minimize radiative heat losses during long, dark winters.

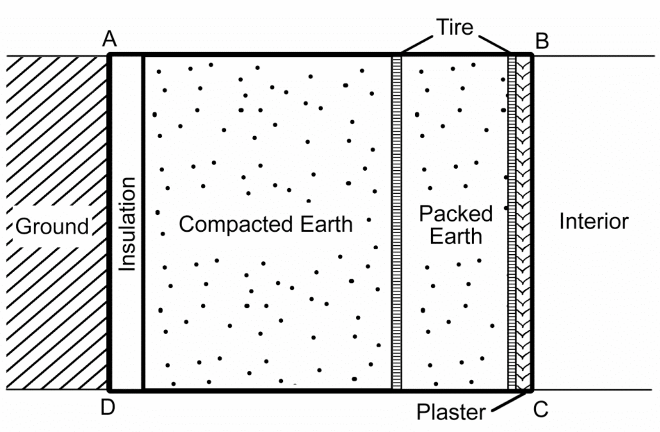
2.1 Thermal Comfort Model

Thermal comfort modeling has been performed using EnergyPlus [4], a program which allows the user to specify the physical construction of a building and provide pre-defined weather data files specific to each location. In EnergyPlus, surfaces (walls, ceilings and floors) are modeled as a composition of parallel layers with defined thermal properties (conductivity, specific heat, absorptance, and transmittance). Because the tire walls of earthships are not simple sheets of material, it is necessary to make a simplifying approximation for the round tires (Fig. 3). The tires are modeled as thin rubber sheets on either side of the packed earth inside the tires. Both the packed earth and the compacted earth of the berm are approximated as having the same thermal properties of concrete due to their high density. This approximation does not account for the seasonal moisture content of the compacted earth which has potential for affecting the thermal conductivity of the compacted earth layer and introduces a degree of uncertainty into the thermal comfort analysis. Earthship designs also call for a layer of rigid insulation positioned a few feet from the tire wall to keep heat stored in the thermal mass close to the home. On the other side of this insulation is, in physical construction, loose backfill which the model approximates as "ground." (In EnergyPlus, the term "ground" is used to identify surfaces of the building that are not exposed to the open air.) The temperatures along a "ground" boundary are pre-defined as constant monthly values calculated in EnergyPlus's ground contact model. This approximation is based on a simple model for slab floors and its applicability to earth sheltered construction has not been verified. Each earthship is also modeled with an insulated roof and double pane windows along the sunny side wall, both exposed to the open air; and a concrete slab floor between the interior and the "ground" boundary. Attributes of the earthships' thermal envelopes are shown in Table 1 below.

(a)



(b)



(c)

Fig. 3 Comparison between physical construction (a) and modeled construction (b) with EnergyPlus layers (c) (not to scale)

Table 1 Attributes of Thermal Envelope

	Honolulu & Albuquerque	Grand Rapids & Anchorage
Wall (R-Value)	25	25
Roof (R-Value)	71	71
Floor (R-Value)	2	15
Window (SHGC)	0.48	0.48
Window (U-Value)	0.31	0.31
Window-to-Floor Area Ratio	0.25	0.13

Note: R-value units are $ft^2h°F/Btu$, U-value units are $Btu/ft^2h°F$

The EnergyPlus thermal comfort model also uses daily, weekly, and annual schedules to simulate typical household activities that affect thermal performance. These schedules describe: (a) internal heat gains from occupants, lighting, and electric and gas equipment, (b) air flow via infiltration and ventilation, and (c) when shades are drawn over the glazing.

Earthship thermal comfort performance is simulated throughout the course of a year with one hour time-steps, thereby predicting the response of the interior operative temperature to both seasonal and daily weather patterns. For the environment inside an earthship to be considered comfortable, the operative temperature must be between 21°C and 28°C (70°F and 82°F)[2] [5]. Assuming that the earthships would not always maintain a temperature within this range, additional sub-models have been created with auxiliary gas heaters to control the minimum room temperature within the houses. The output from an EnergyPlus simulation displays the estimated amount of heating energy needed to ensure operation above the minimum comfortable operative temperature during the winter and the night.

[2] The comfortable temperature range varies slightly with the humidity ratio. The values given here correspond to a humidity ratio of 0.006. Also, it should be noted that this range represents the acceptable variation throughout the course of a year and is larger than the acceptable daily variation.

2.2 Electricity Usage Model

The electricity usage model uses a daily design load derived from the typical power draw of common household electronic devices. The electrical load calculations are based on three assumptions: (1) electric devices and appliances, when possible, are ENERGY STAR qualified (2) the daily load profile is constant throughout the course of the year (does not change for weekends or holidays, or from season to season), and (3) the daily load profile is consistent for all of the climate zones. The model uses a worst-case scenario for the electrical load profile throughout the day (Fig. 4) to size the electrical system for the generator (in kW) and battery storage (in kWh).

Because wind is a site specific parameter, the use of small wind turbines for distributed generation at the earthship site is not addressed in the electricity usage model. Conversely, since solar radiation is consistent within each climate zone, PV electricity generation is assumed. Electricity generation is modeled as a stand-alone system at each earthship site using the PV-DesignPro-S computer program [6]. This program contains a library of commercial standalone PV system components (panels, batteries, and inverters) and provides performance specifications. The user can select the number and arrangement (series or parallel) of the panels and batteries to simulate the year long performance of the system for a given daily electrical load and location. In modeling the PV systems for the earthship locations, the goal is to find the most cost effective arrangement of panels and batteries that supplies 100% of the home's electricity demand throughout the year. In locations with fewer hours of sunlight in a year this goal requires both (a) very large arrays of PV panels to collect what little energy is available there and (b) very large battery banks to store enough energy to power the home until the next sunlight appears.

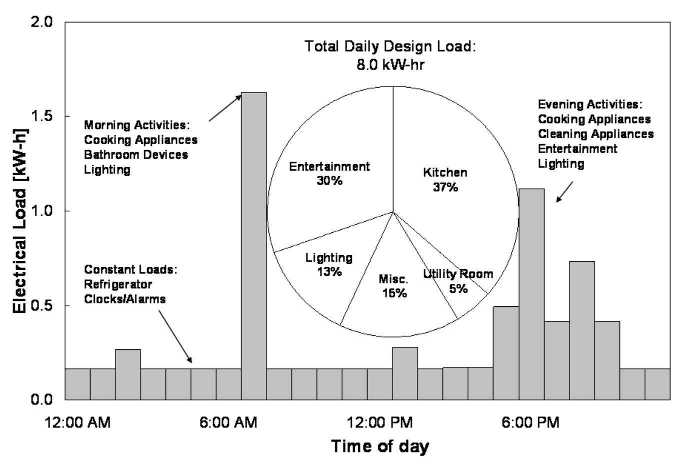


Fig. 4 Design distribution of worst–case daily electrical demand

2.3 Water Usage Model

Figure 5 illustrates the earthship water system. Precipitation runs off the roof (1), collects in a gutter, and deposits into a cistern (2) for long term storage. Water from the cistern is pumped through a filter and into a pressure tank (3) for potable, domestic use. Water in the pressure tank is used in showers, baths and sinks (4). Drainage flows through a grease interceptor (not pictured) and into an interior planter (5). Water not absorbed by plants gathers at the bottom of the planter where it can be pumped back into the bathroom for toilet flushing (6). Effluent from the toilet is discharged into a botanical treatment cell (7), which, in conjunction with a conventional septic tank, contains and treats the earthship's wastewater.

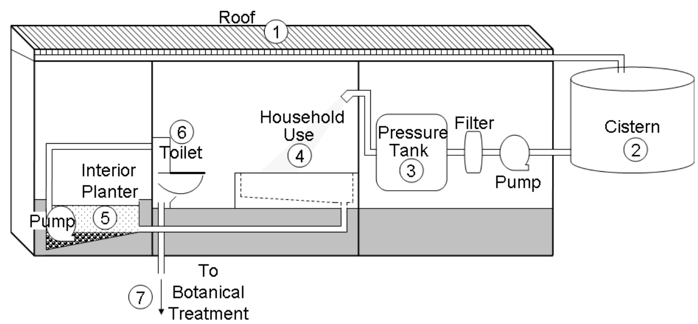


Fig. 5 Earthship catchwater and gray water system

Because the entire supply of water to an earthship is dependent on precipitation, a relatively simple model can evaluate the feasibility of the water system design. This model compares the amount of water demanded by the occupants (a family of four) and the amount of water supplied by local precipitation. The gray water system of an earthship conserves a significant amount of water, drastically reducing the required supply of water. Figure 6 compares the estimated daily use of water in earthships to the U.S. national average and to common homes making intentional efforts to use water efficiently (i.e. shorter showers and low flush toilets) [7].

The model of water supply utilizes the average precipitation for each city (in cm/year) and the surface area of the roof, 185 m^2 (1990 ft^2), to estimate the amount of collectable run-off water [8]. This estimate assumes that the entire precipitation incident upon the roof runs into the cisterns on either side of the house. In climates with wet and dry seasons, the cisterns in the model are sized to store any excess water from the wet season so that the supply would last into the dry season. Water stored for long periods may also require additional treatment to prevent microbial growth.

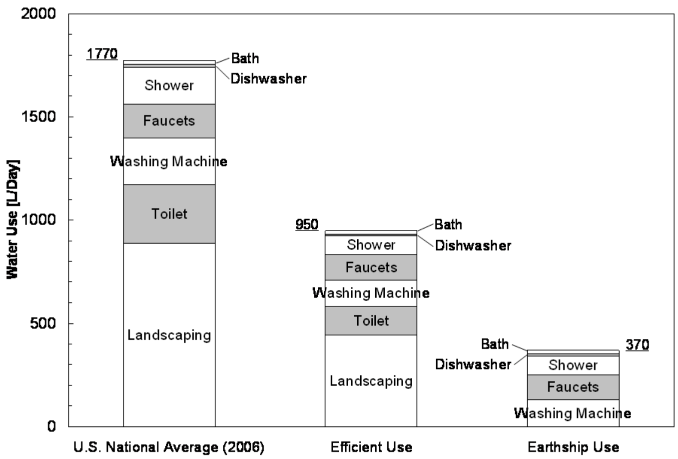


Fig. 6 Average Daily water use for a family of four

2.4 Financial Model

The financial model compares the present value (in 2006 dollars) of all construction and operation costs of the earthships with the costs for standard wood framed houses over a life of 45 years. The construction costs are estimated from location specific prices of material, labor, and equipment for each of the following [9]:

- Design and Drawings
- Excavation
- Physical Construction
- Electric Devices and Wiring
- Plumbing and Water Storage
- Engineering Fees

Earthship operation and maintenance costs arise from battery bank replacement (every 15 years), PV panel replacement (every 25 years); and gas (typically propane), electricity, and water consumption which are determined from the thermal comfort, electricity usage, and water usage models respectively. In addition to space heating, propane is also used for cooking, clothes drying, and on-demand water heating. The operating costs for future years are calculated based on projections of energy prices and rates of inflation [10, 11]. The net present value of all future operating costs is estimated using a set rate of return of 6%. The assumed economic conditions for the financial model are shown in Table 2.

Table 2 Economic conditions for financial model

Commodity	Price (2006 Dollars)	Quantity	Nominal Escalation Rate
Propane	$0.53	L	3.9%
Electricity	$0.09	kWh	2.6%
Water	$0.71	1000 L	2.7%

Inflation Rate = 2.7%,   Rate of Return = 6.0%

The goal of the financial model is to compare the life time costs of earthships and standard wood framed houses. The standard wood framed houses in the model used the same floor plan as the earthships shown in Figure 2. Wood framed walls with standard batt insulation replace the tire walls in the floor plan and each of the exterior walls is exposed to the open air. To be consistent with the earthship models, the houses in the wood framed models are assumed to purchase electricity and water from local providers, and are heated using propane. Additionally, these houses pay a sewage service charge of $1.06 (2006 dollars) for every thousand liters of water [11].

Although monetary value is a convenient and commonly used indicator of feasibility, there is value in earthships that cannot be represented by a dollar amount. There is value in reusing materials such as automobile tires that otherwise produce an expensive and inconvenient waste. Tire wall construction can make a significant contribution to sustaining the environment by reducing the human impact on the earth and conserving resources needed to construct and operate every home.

3. MODEL RESULTS

The results of this study compare the performance of earthships and standard wood framed houses relative to thermal comfort, electricity supply, water supply, and life-time finances. In cases where the results reveal that Reynolds' ideal earthship compromises living standards or financial feasibility, alterations are made in the modeled earthship design to achieve a feasible and practical way of living. (The following sections explain any alterations made to the models and compare the performance of the altered and ideal earthships.)

3.1 Thermal Comfort Model Results

To verify the accuracy of the thermal model, inside and outside temperature data was recorded at an existing earthship located in Gamerco, New Mexico (the same earthship as seen in Fig. 1). To measure the inside air temperature, one thermocouple was positioned at head level in the middle of the main living area. Another thermocouple, used to measure the outside air temperature, was positioned in the shade (to minimize the effects of solar radiation) just outside of the entrance to the house. The recorded outside air temperatures were used in an EnergyPlus simulation to predict the resulting inside air temperatures. The thermal model for this simulation was identical to the thermal models presented in this paper; except that it was scaled down to represent the actual size of the New Mexico earthship.

A comparison between the measured inside temperatures and the predicted inside temperatures is shown in Figure 7. The predicted interior temperature tracks the measured interior temperature quite closely. However, the predicted interior temperature has a smaller response to sudden changes in the

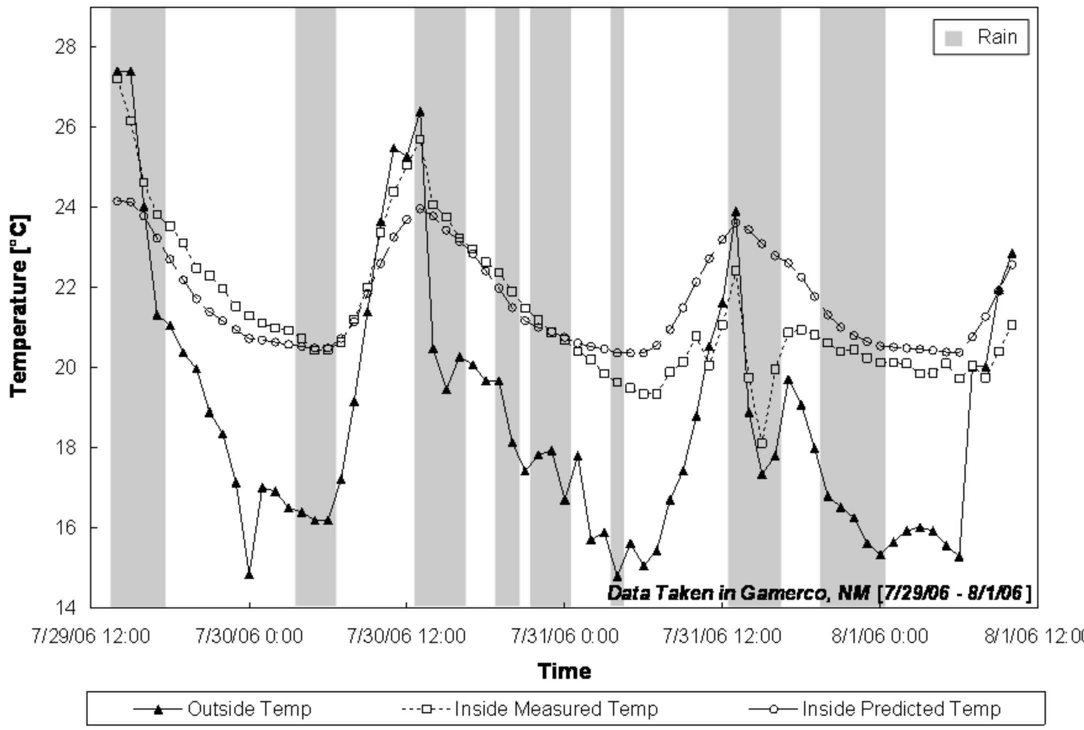


Fig. 7 Comparison of inside temperatures measured in an actual earthship and the inside temperatures predicted by the earthship thermal model

outside temperature (noon peak temperatures and during rainy hours) causing error in the prediction of up to 3°C (5.4°F). A source of error in the prediction is the model's inability to account for specific occupant activities. For example, between 10:00 AM and 5:00 PM on July 31, occupants had been working inside the house with the door open allowing air infiltration that is not scheduled into the model. Despite the model's discrepancies, the EnergyPlus simulation still matches the measured temperature within 1°C (1.8°F) for much of the time. From this comparison it has been determined that the EnergyPlus thermal models are sufficiently accurate for the purpose of this study.

Figure 8 illustrates the predicted thermal performance of three-bedroom earthships (Fig. 2) in each location. Each graph shows the predicted average operative temperature inside the ideal earthship (in black) as well as the predicted operative temperature inside an earthship with auxiliary heating (in dark gray). Acceptable thermal comfort is defined by the comfort range (between the two dotted lines). (Light gray lines show outside temperatures in each location.) In the low latitude cities, Albuquerque and Honolulu, the operative temperature remains within the comfort range for most of the year except in the winter when radiation from the low winter sun is more direct on the glazing and causes large fluctuations in the daily temperature. Earthships without auxiliary heating in Anchorage and Grand Rapids, though not considered comfortable in the winter months, are still able to reduce their heating loads by maintaining operative temperatures within 10°C of the comfort range.

Earthships in continental sub-arctic (Anchorage) and humid continental (Grand Rapids) climates cannot provide comfortable environments for their occupants, but their design reduces the home's dependence on energy for heating. For this reason, the earthship financial models for the Anchorage and Grand Rapids locations have been altered to include auxiliary propane heaters.

3.2 Electricity Usage Model Results

In a standard house, the grid supplies 100% of the occupants' electricity demand. The most cost effective arrangement of PV panels and batteries that meets this requirement for earthships is shown in Table 3. The approximate upfront cost represents the prices for the panels, batteries, inverter and charge controller, but not installation and labor. These costs were determined from the correlations in Figures 9 and 10 which represent retail PV and battery prices [12]. Installation and labor are included in the total cost

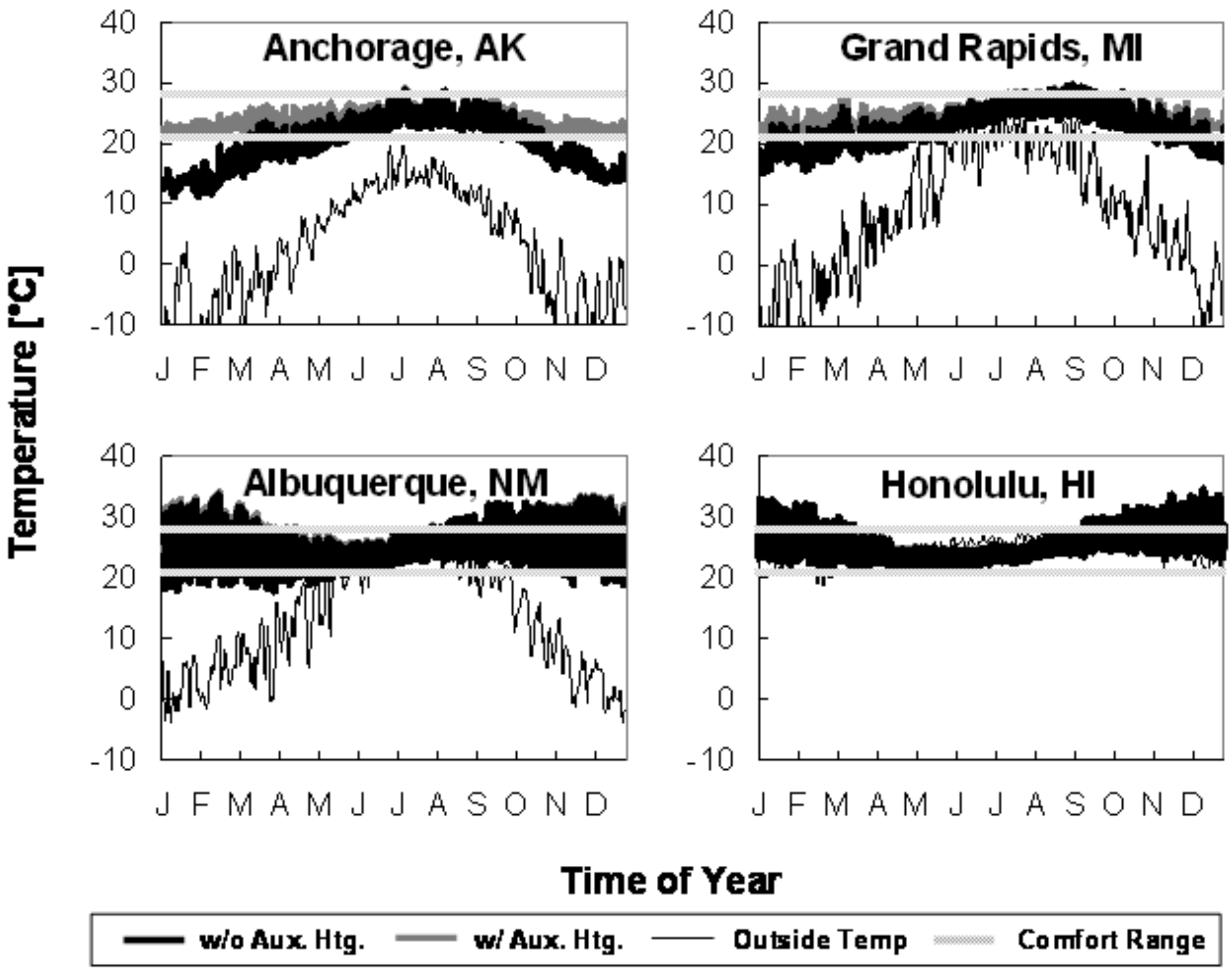


Fig. 8 Inside and outside temperatures for earthships in each city

of the earthships, and is addressed with the financial model results.

Large enough PV systems are modeled to power earthships in all four locations, but the high upfront costs detract from the practicality of a completely self-sufficient earthship.

Table 3 PV requirements to supply 100% of the annual electrical demand of an earthship

Location	Required PV Power Rating (kW)	Required Battery Capacity (kWh)	Approximate Upfront Cost (2006 Dollars)
Anchorage, AK	**11.2**	**265**	**$105,100**
Grand Rapids, MI	6.0	65	$48,000
Albuquerque, NM	2.6	53	$29,700
Honolulu, HI	2.4	53	$28,900

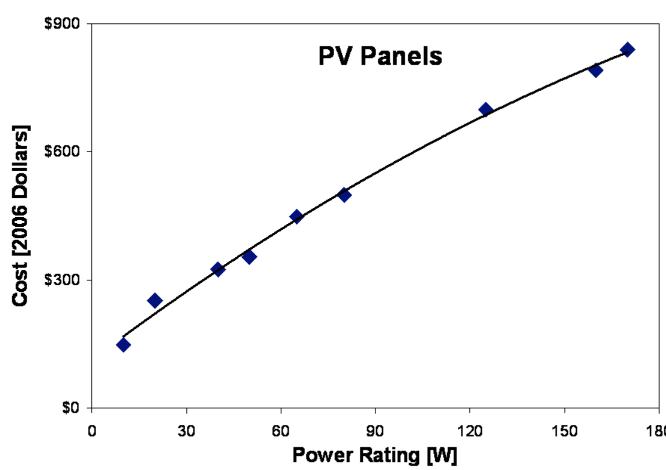


Fig. 9 Cost Correlation for PV Panels

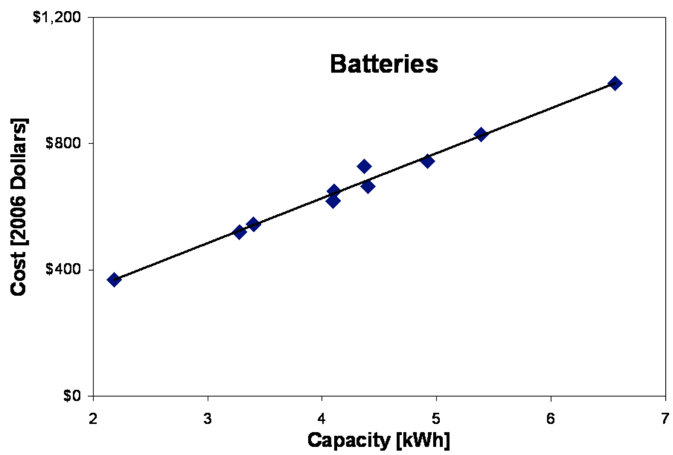


Fig. 10 Cost Correlation for Batteries

3.3 Water Usage Model Results

As shown in Figure 6, a family of four living in an earthship would demand an average of 370 L (98 gallons) of water each day or 135,000 L (35,700 gal) of water each year. Figure 11 shows the amount of water that could be collected off of a 185 m^2 (1990 ft^2) earthship roof in one year based on the U.S. Climate Normals recorded for each city [11].

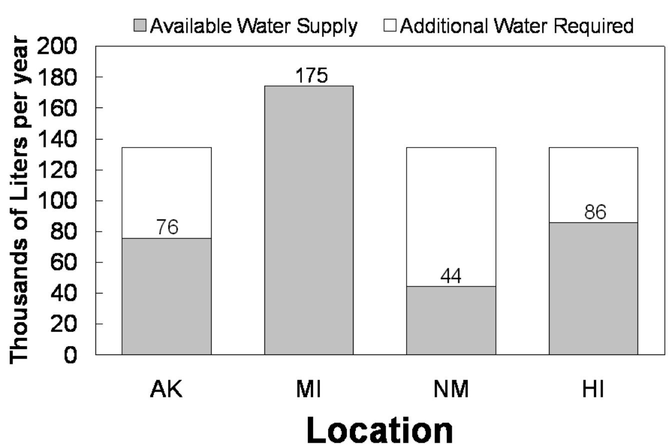


Fig. 11 Collectable precipitation by location

In Honolulu, Albuquerque, and Anchorage there is insufficient precipitation to provide a family living in an earthship with an adequate supply of water. An earthship's catchwater system relies heavily on unpredictable weather conditions. In the event of lower than average rainfall, a back-up supply of potable water must be available to the occupants. In the financial modeling discussed below, the earthships are assumed to supply what catchwater is available at their location, and the remainder of the demand is supplied by local system lines.

3.4 Financial Model Results

The life time costs of off-grid and grid-tied earthships are compared to the costs of standard wood framed houses in each of the four cities (Fig. 12). Off-grid earthships are modeled with PV systems to supply the electricity demand of the entire house. The battery bank and PV panels for an off-grid earthship must be replaced every 15 and 25 years respectively. The replacement cost produces the sudden steps in the accumulated total cost at 15, 25 and 30 years. These steps are most noticeable for Anchorage, AK; and, because the value of money decreases over time, the lower replacement cost for other locations makes the steps less noticeable. Grid-tied earthships in the financial model purchase all of their electricity from a local power provider. All earthships in the financial model are constructed with auxiliary propane heating, and a catchwater system with a back-up connection to a local water supply.

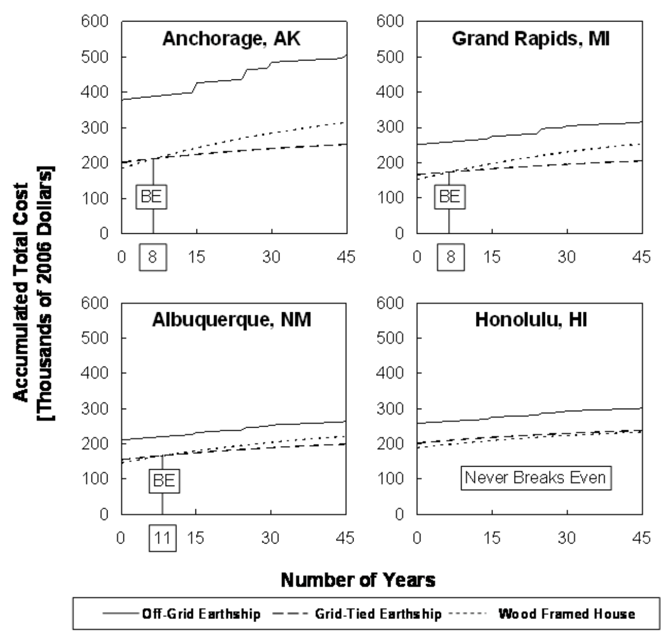


Fig. 12 Accumulated total cost
(break even, "BE", points for grid-tied earthships)

The initial costs of off-grid earthships are far too great for the savings on purchased electricity to pay back the initial price of the PV system. The grid-tied earthships begin with a higher initial price than the standard wood framed houses due mainly to the additional price of the catchwater and gray water system; but in Anchorage, Grand Rapids, and Albuquerque the net present value of the earthships breaks even at 8, 8, and 11 years respectively. The Honolulu earthship does not prove to be a cost effective alternative to a wood framed house.

An alternative way of looking at financial comparisons for the three constructions in each of the four locations is to evaluate monthly payments. Figure 13 shows the monthly mortgage and operation and maintenance payments. The mortgage assumes a 30 year loan covering construction cost of the house and initial PV panel and battery costs. The mortgage does not include property taxes. Operation and maintenance costs include all gas, electricity and water costs as well as PV panel and battery replacements for 30 years. The principal cost of the houses per square foot is shown at the side of each bar.

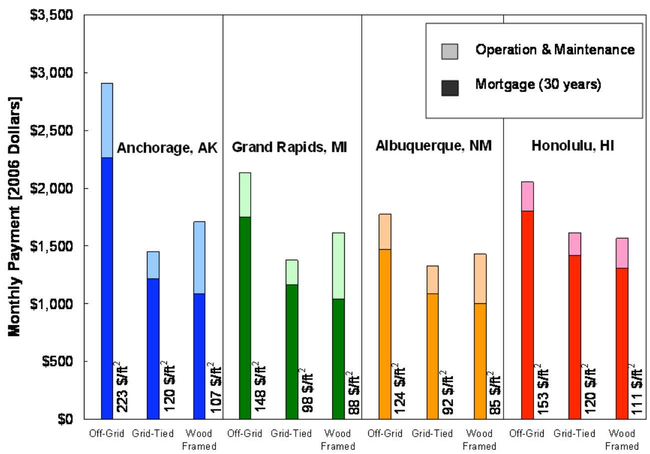


Fig. 13 Monthly payments for mortgage and operation & maintenance (principal cost per square foot shown for each construction)

The thermal envelope of the earthship contributes most to cost and energy savings. Figure 14 shows the annual savings of an earthship on the heating costs and energy relative to the fuel consumption of a standard wood framed house. As would be expected, earthships in locations with the larger heating loads save more, and earthships in Honolulu, where there is no heating load, have no savings.

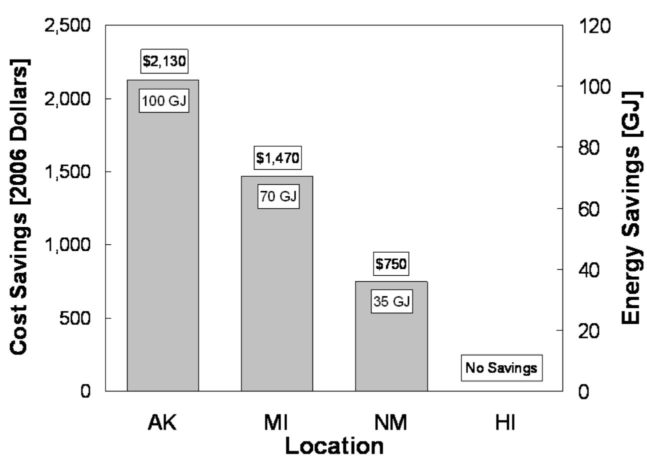


Fig. 14 Annual savings on heating

4. CONCLUSIONS

4.1 Thermal Comfort Conclusions

Although EnergyPlus is tailored to modeling buildings with conventional wall designs, the program can be used to predict the inside temperature of earthships within reasonable accuracy. According to the EnergyPlus thermal model, earthships cannot always provide a comfortable living environment solely through passive solar heating. The inside environment created by earthships may be tolerable from a survivalist point of view, but before earthships can be marketable to the average family they must include centralized mechanical systems to moderate daily temperature fluctuations. Although an earthship may not provide adequate comfort to its occupants the thermal mass in the house significantly decreases the heating load which, in turn, facilitates cost and energy savings that contribute to the homes' sustainability.

In a tropical wet/dry climate, houses do not need such intensive design of the thermal envelope. With annual outside temperatures within the comfortable range, an equally sustainable and comfortable environment can be achieved with less material and a lower cost than the earthship design.

4.2 Electricity Usage Conclusions

As the technology for renewable energy from solar photo-voltaic systems matures, the economic potential for off-grid earthships will increase. However, off-grid PV electricity generation is not yet a financially competitive alternative to purchasing electricity from commercial providers. An exception exists for houses in remote locations where the price of equipment, installation, and maintenance for a PV system are less than the price to extend the lines of the nearest service.

4.3 Water Usage Conclusions

In most climates there is not enough precipitation to supply the entire water demand of a family of four, even with intensive water conservation efforts. The catchwater and gray water systems of an earthship can still be used in conjunction with a back-up connection to local aquifer supplies. Such a design effectively conserves water while ensuring a consistent potable supply.

4.4 Financial Conclusions

Earthships are a financially feasible alternative to wood framed housing in continental sub-arctic, humid continental, and dry/arid climates. Earthships in these climates attain lower operational costs primarily through effective heating of the interior space, thereby accumulating a lower total cost than standard wood framed homes. Because homes in tropical wet/dry climates have no heating requirements, the operation costs of an earthship differ insignificantly from those of a wood framed house. For this reason, earthships in tropical climates have no financial advantage over standard designs.

4.5 Overall Conclusions

Some aspects of Reynolds' earthship concept have not yet emerged as practical alternatives to conventional wood framed housing. To be considered practical, sustainable housing must provide its occupants with standard comfort, electricity supply, water supply; and all for a comparable price. This study has shown that the current earthship concept cannot provide: (a) a consistently comfortable environment solely through passive solar heating, (b) a consistent supply of water solely through a catchwater and gray water system, or (c) an adequate supply of electricity through a PV power generator at a reasonable price. Though aspects of the earthship concept may not be practical; municipal supplements to the utilities, such as auxiliary heating (and cooling) and a back-up water supply, can still be used to improve sustainability in residential living compared to standard, grid-tied wood framed housing.

5. FUTURE WORK

Future work pertaining to earthships may include: (a) evaluating consumer acceptance and marketability of earthships, (b) conducting a longer-term (at least year round) verification of the EnergyPlus thermal model and "ground" boundary assumptions, (c) performing a site specific analysis accounting for wind power potential and obstructions to solar energy, (d) determining the optimal size and arrangement of thermal mass relative to cost and energy savings, (e) adjusting the thermal model to estimate cooling loads and investigating the effectiveness of cooling using earth tubes (underground tubes used to draw air from outside the house, through the cool medium of the ground, and into the house), and (f) modeling a grid-tied earthship which generates power (via PV or wind) and sells electricity back to the grid.

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