Title
MONITORED SUPERINSUIATED AND SOLAR HOUSES IN NORTH AMERICA: A COMPILATION AND ECONOMIC ANALYSIS

Permalink
https://escholarship.org/uc/item/2mf1m2cn

Authors
Ribot, J.C.
Ingersoll, J.G.
Rosenfeld, A.H.

Publication Date
1982-06-01
To be presented at PASSIVE '82, the National Passive Solar Conference, Knoxville, TN, August 29-September 3, 1982

MONITORED SUPERINSULATED AND SOLAR HOUSES IN NORTH AMERICA: A COMPILATION AND ECONOMIC ANALYSIS

Jesse C. Ribot, John G. Ingersoll, and Arthur H. Rosenfeld

June 1982

TWO-WEEK LOAN COPY
This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098
DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.
Paper to be presented at PASSIVE '82, the National Passive Solar Conference at Knoxville TN, August 29-September 3, 1982.

MONITORED SUPERINSULATED AND SOLAR HOUSES IN NORTH AMERICA: A COMPILATION AND ECONOMIC ANALYSIS

Jesse C. Ribot, John G. Ingersoll, and Arthur H. Rosenfeld

Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

June 1982

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.
ABSTRACT

In our ongoing compilation, BECA-A (Building Energy-Use Compilation and Analysis, Part A, New Homes) we have so far analyzed 97 submetered, energy-efficient homes in North America and Europe. Only 21 have acceptable data on added first cost of conservation measures. Of these, the lowest cost of conserved energy $d$/dE is for the superinsulated category, where $d$/dE is about $7/11Btu. Only 22 homes have submetering adequate to permit correcting space heating loads for variations in occupant behavior (thermostat preference and heat gains from appliances). For these 22, the "standardized" fuel intensity is only 67 kJ/m°DD, compared to U.S. 1979 building practice of 140, or U.S. stock of 260. We solicit (and continue to collect) more data.

1. INTRODUCTION

In our ongoing project, Building Energy-Use Compilation and Analysis (BECA), we are documenting energy conservation in the building sector. We hope to demonstrate the technical and economic potential of conservation techniques and to provide a basis on which policy makers, builders and contractors, commercial building owners, and homeowners can make informed decisions about conservation measures.

In BECA, Part A (BECA-A), we focus on space heating in new residential buildings (by far the largest energy end use in today's houses). We have collected data on 150

low-energy houses throughout North America and Europe, which include active solar, passive solar, superinsulated, and earth sheltered dwellings (and many in combination). The data consist of submetered energy consumption, inside and outside temperatures, number of occupants, and cost of conservation. We perform two levels of analysis: one for all buildings with submetered heating only, and one for those with submetered heating and appliances. In the first analysis we present annual energy use, while in the second we correct the data to reflect "standard" occupancy, internal gains, and inside temperature.

In this paper we present a comparison of the thermal performance and economics of 97 homes (computed June 1982, out of our 150) on the basis of annual heating load and cost of conservation. We discuss the effect of internal gains on performance measures and introduce a method to normalize the heating load to "standard" conditions. We emphasize the importance of normalization to compare building performance accurately, and present the standard heating loads compared with simulation, current building practice, and the national building stock.

2. DEFINITIONS

We have divided the homes into the following five categories: active solar, passive solar, hybrid solar, earth sheltered, and superinsulated. The concepts of active solar and earth sheltering are self-evident, but with superinsulation, passive solar and hybrid solar the definitions become hazy. We have defined superinsulated homes as those in which insulation is a major conservation measure, and have allowed passive solar homes to include those with a majority of the glazing on the south. Hybrid solar is passive solar with fans to distribute the hot air. In practice we find that 31 of our houses do not fit neatly into these categories: 27 are passive/superinsulated, and there is one active/superinsulated, one hybrid/superinsulated, one active/passive/superinsulated, and one earth sheltered/passive/superinsulated home. To circumvent
There are between 4 months and 4 years of energy consumption data per home, with the majority of data in monthly metered periods. When there is less than a full winter's data the annual heating load is derived by extrapolation from the available months. This is done by dividing the actual monthly load \( \text{Q}_n \) by the monthly degree days \( \text{DD}_m \) for each period, and then multiplying this average value, of \( \text{Q}_n/\text{DD}_m \), by the degree days for each unmetered month. The annual heating load is then the sum of the \( \text{Q}_n \) values for an entire heating season.

Active solar buildings have the poorest "thermal integrity" (annual heating load per unit area per heating degree-day), averaging 78 kJ/(m²·°C-day) [3.8 Btu/(ft²·°F-day)], and buildings that include superinsulation perform the best, averaging 45 [2.2]. Passive solar in combination with superinsulation or earth-sheltering also performs well, averaging 46 [2.3].

Fig. 2 shows thermal integrity, versus cost of conservation for the 21 homes for which we have cost data. The sloping reference lines represent the boundary of cost effectiveness against typical residential energy prices, i.e. electricity at 6.2¢/kWh, gas at 30¢ per therm, and oil at $1.30 per gallon. Since conservation investments for new residential buildings are typically "one-time," the future stream of energy purchases...
this problem we include combined building types in each of the categories that apply. The cost of conservation is defined as the cost above conventional construction for conservation or solar measures. The figures we present were derived by the researchers from whom we received data by summing up the added costs incurred (i.e., extra insulation, alternative framing, or solar collectors) and subtracting avoided costs (as in downsizing the furnace).

3. BASIC SHELL PERFORMANCE

Our goal is to evaluate the quality of the building's thermal envelope. First we are interested in deriving the annual heating load, which is the annual thermal energy delivered to the house by the heating system. To accomplish this we have obtained for each building: submetered heating-system energy use, degree days (base 18.3°C [65°F]) during each metered period, a building description (including floor area, R-values, and conservation measures), and cost data.

The thermal energy delivered to the house, \( Q_H \), is obtained by multiplying the heating energy delivered to the heating system, \( E_H \), by the heating system efficiency, \( \eta_H \) (or \( \epsilon_{hp} \) as in the case of a heat pump).

\[
Q_H = \eta_H E_H \tag{1}
\]

In the cases of hybrid solar and active solar collectors, we count the parasitic losses (operating electricity for pumps and fans) as equivalent to electric resistance heaters (\( \eta = 1.0 \)). The solar contribution from passive and active solar homes is not counted in Equation 1, since it will be reflected in a reduced \( \eta_H \) (see Equation 2). In treating solar gains this way we are in effect considering the ability of the house to use solar energy as part of the shell performance. We excluded all buildings heated with wood due to large uncertainties in stove and fireplace efficiencies, energy content of wood and amount of wood burned.

---

**Fig. 1.** Scatter plot of annual heating load vs. climate for 97 submetered energy-efficient new homes. The solid curve is NAHB's 1979 survey of U.S. building practice, taken from Fig. 3.
for 30 years (the assumed life of a house) are converted to a single present value assuming a 6% real discount rate. The conservation measure is cost effective if the data point lies below the purchased energy line. Homes in the superinsulated category have the lowest cost of conserved energy, $\Delta E/\Delta t$, ranging between $\$4$ and $\$10$/MBtu. In this analysis superinsulation is the only measure which is cost effective. (In the construction of building 17, the builder offset the extra cost of insulation by savings on the heating system. The net cost of conservation was $\$0$ in this particular house, since the load was so small that the builder replaced the central furnace with small resistance heaters.)

4. INTERNAL GAINS

Comparison of homes on the basis of measured annual heating load gives only a first approximation of shell performance. To obtain a closer approximation it is necessary to account for both internal gains and indoor temperature. Heating-energy consumption for a building may be described with the following basic heat-balance equation:

$$ E_H \eta_H = Q_H = (Q_T - Q_I - Q_S) \tag{1} $$

where

- $E_H$ = energy delivered to heating system,
- $\eta_H$ = heating system efficiency or COP,
- $Q_H$ = thermal energy delivered to the house from the heating system (furnace output),
- $Q_T$ = total thermal energy losses from building shell (conduction and infiltration),
- $Q_I$ = internal gains from people and appliances, and hot water, and
- $Q_S$ = solar gains.

Solar gains, $Q_S$, which are a function of building shell design (or heating system in the case of active solar), are roughly constant from year to year. Thus, the main variables from house to house are $Q_T$ and $Q_I$.

The homes surveyed show internal gains ranging from 23 to 64 MGJ/year [22 - 61 MBtu/year]. During a heating season (5 months) these gains range from 10 to 27 MGJ [9.5 to 25.5 MBtu], and average 16 MGJ [15 MBtu], compared to an average annual heating load of 15 MGJ [14 MBtu]. Homes with identical shells and furnaces may have different annual heating loads due to such different internal gains. Since internal gains can be as large as 100 - 150% of the furnace input, considerable error will result if internal gains are not properly included. For example, it is not surprising that for house 16, with an annual heating load of only 0.5 MGJ [0.5 MBtu], $Q_I$ equals 27 MGJ/season [25.5 MBtu/season]: the lowest annual heating load and the highest internal gains.

5. STANDARDIZED PERFORMANCE

An important aspect of our work is to generate a basis on which to compare buildings with each other, with simulations, and with mass-metered building stock data. To compare buildings it is imperative to normalize internal gains and indoor temperature, $T_i$, to standard conditions. We selected $T_i = 20^\circ C$ [68° F], and standard internal gain, $Q_{IS} = 32$ MGJ/year [30 MBtu/year] as standard conditions.

In our normalization procedure we begin by obtaining the total thermal energy produced inside the building envelope, $Q_{TI}$. To do this we must know the number of occupants and submetered heating, appliance, and hot-water energy consumption.

$$ Q_{TI} = Q_H + Q_I - Q_A + Q_{W} + Q_p \tag{3} $$

where

- $Q_A$ = appliance energy (less dryer energy)
- $Q_I$ = gains from water heater: standby losses (as a function of location and insulation) plus 5% of the remaining hot-water energy use, and
- $Q_p$ = gains from people: (no. of people) x (7.64 MGJ/person-day) [7.2 MBtu/person-day].

- Annual variation in solar radiation typically varies less than 10% (private communication with Frank Quinlin, NOAA, 1982).
- Dryer energy use is never considered a gain, because 80% of it is latent heat. Even if the dryer is vented inside the house the latent gains will be only temporary, and soon offset by evaporation into dry infiltrating air.
For a subset of 22 homes we have submetered data on heating, hot-water, and appliance energy use, and number of occupants. To correct $Q_{TI}$ to an inside temperature of 20°C we multiply $Q_{TI}$ by the fraction $(20°C - T_i)/(T_i - T_o)$ where $T_i$ and $T_o$ are average inside and outside temperatures respectively. We thereby replace the actual inside temperature with the standard, and the result is $Q_{TS}$. From here it is simple to obtain the standard heating energy, $Q_{HS}$:

$$Q_{HS} = Q_{TS} - Q_{IS}. \quad [4]$$

The standard annual heating load is the sum of the $Q_{HS}$ values for one year.

6. BUILDINGS IN CONTEXT

In Fig. 3 homes are compared under "standard conditions," free of variation in occupant effects. In presenting our standardized data we make two changes from the format in Fig. 1. In Fig. 3 we compare our homes with the new residential Building Energy Performance Guidelines (BEPS, 1981) [developed at LBL as an extension of the research on the federal Building Energy Performance Standards (BEPS, 1979)], new building practice (NAHB, 1979), and the national building stock (RECS, 1980). The BEPG curves were generated with internal gains equal to $Q_{IS}$, and it is assumed that these numbers are

$\text{Heating degree days (Base = 65°F)}$

<table>
<thead>
<tr>
<th>AVG = Average for a group of buildings</th>
<th>BEST = Best of group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single family dwelling</td>
<td>Passive solar</td>
</tr>
<tr>
<td>Multi-family dwelling</td>
<td>Active solar</td>
</tr>
<tr>
<td>US Building stock (RECS, 1979)</td>
<td>Earth sheltered</td>
</tr>
<tr>
<td>A - Active solar</td>
<td>Hybrid solar</td>
</tr>
<tr>
<td>E - Earth sheltered</td>
<td>Insulation (super-insulation)</td>
</tr>
<tr>
<td>H - Hybrid solar</td>
<td>P - Passive solar</td>
</tr>
</tbody>
</table>

$\text{Heating degree days (Base = 18.3 °C)}$

<table>
<thead>
<tr>
<th>0</th>
<th>1,000</th>
<th>2,000</th>
<th>3,000</th>
<th>4,000</th>
<th>5,000</th>
<th>6,000</th>
<th>7,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10.5</td>
<td>21.0</td>
<td>31.5</td>
<td>42.0</td>
<td>52.5</td>
<td>63.0</td>
<td>73.5</td>
</tr>
<tr>
<td>10</td>
<td>19.5</td>
<td>39.0</td>
<td>58.5</td>
<td>78.0</td>
<td>97.5</td>
<td>117</td>
<td>136</td>
</tr>
<tr>
<td>20</td>
<td>28.5</td>
<td>48.0</td>
<td>67.5</td>
<td>87.0</td>
<td>106.5</td>
<td>126</td>
<td>145</td>
</tr>
<tr>
<td>30</td>
<td>37.5</td>
<td>57.0</td>
<td>76.5</td>
<td>96.0</td>
<td>115.5</td>
<td>135</td>
<td>154</td>
</tr>
<tr>
<td>40</td>
<td>46.5</td>
<td>66.0</td>
<td>85.5</td>
<td>105.0</td>
<td>124.5</td>
<td>144</td>
<td>163</td>
</tr>
<tr>
<td>50</td>
<td>55.5</td>
<td>75.0</td>
<td>94.5</td>
<td>114.0</td>
<td>133.5</td>
<td>153</td>
<td>172</td>
</tr>
<tr>
<td>60</td>
<td>64.5</td>
<td>84.0</td>
<td>103.5</td>
<td>123.0</td>
<td>142.5</td>
<td>162</td>
<td>181</td>
</tr>
<tr>
<td>70</td>
<td>73.5</td>
<td>93.0</td>
<td>112.5</td>
<td>132.0</td>
<td>151.5</td>
<td>171</td>
<td>190</td>
</tr>
<tr>
<td>80</td>
<td>82.5</td>
<td>102.0</td>
<td>121.5</td>
<td>141.0</td>
<td>160.5</td>
<td>180</td>
<td>200</td>
</tr>
<tr>
<td>90</td>
<td>91.5</td>
<td>111.0</td>
<td>130.5</td>
<td>150.0</td>
<td>169.5</td>
<td>189</td>
<td>209</td>
</tr>
<tr>
<td>100</td>
<td>100.5</td>
<td>120.0</td>
<td>139.5</td>
<td>159.0</td>
<td>178.5</td>
<td>198</td>
<td>218</td>
</tr>
</tbody>
</table>

**Fig. 3.** Twenty-two-home scatter plot of "standardized" heating fuel intensity vs. climate. Instead of the heating loads of Fig. 1, we have plotted the fuel use per unit floor area (standard thermal intensity divided by 0.7). The various comparison curves are defined in the text. The average fuel intensity per degree-day for our 22 homes is 67 kJ/(m²·°C-day), or half of the current building practice line.
close to those of the national building stock. Since the RECS data are measured fuel consumption we present the BEPC and NAHB data in fuel-equivalent units by dividing each point by $\eta = 0.7$ (an average furnace efficiency), and present our 22 homes in the same units.

The most salient feature of Fig. 3 is not the relationship between the types of homes but the demonstration of such a tremendous potential for conservation. Dividing each point by its degree-days, we find the mean standard fuel integrity of our energy-efficient homes is 67 kJ/(m$^2$·°C·day) [3.3 Btu/(ft$^2$·°F·day)] compared with 260 [12.8] for the national building stock and 140 [6.9] for current building practice. Our best building consumes only 14 [0.7], less than one-twentieth of the U.S. average, and one-tenth of current building practice.

7. CONCLUSION

We have assembled data for 150 houses and entered 97 of these into our data base. Of these 97 buildings only 21 had data on additional first cost, and 22 were monitored in enough detail to standardize. We invite other researchers to contribute their data to further this research.

We have compared the 97 buildings by building type, heating performance, and added cost for conservation and solar measures. We found that active solar buildings used the most heating energy, 78 kJ/(m$^2$·°C·day) [3.8 Btu/(ft$^2$·°F·day)] and that those with passive solar and superinsulation consumed considerably less, 46 [2.3] and 45 [2.2] respectively. We also observed that the superinsulated homes had the lowest cost of conserved energy, ranging between $4 and $10/MBtu.

We have introduced a method to correct for occupant effects on heating energy performance measurements by substituting a standard internal gain and indoor temperature. We compare our standardized buildings with the BEPC, current building practice, and with U.S. building stock data. On a scale where U.S. building stock averages 260 kJ/(m$^2$·°C·day) [13 Btu/(ft$^2$·°F·day)], current practice is 140 [6.9], and BEPC are 106 [5.2] (high infiltration) and 82 [4.0] (low infiltration), solar and conservation homes average 67 [3.3] (ranging from 14 [0.7] to 194 [9.5]).

8. ACKNOWLEDGEMENT

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Systems, Buildings Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We would also like to thank Jeffrey Harris, Wolfgang Luhrsren, Françoise Flouquet, Virginia Magnus, and John Flaherty for their assistance.
This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.