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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

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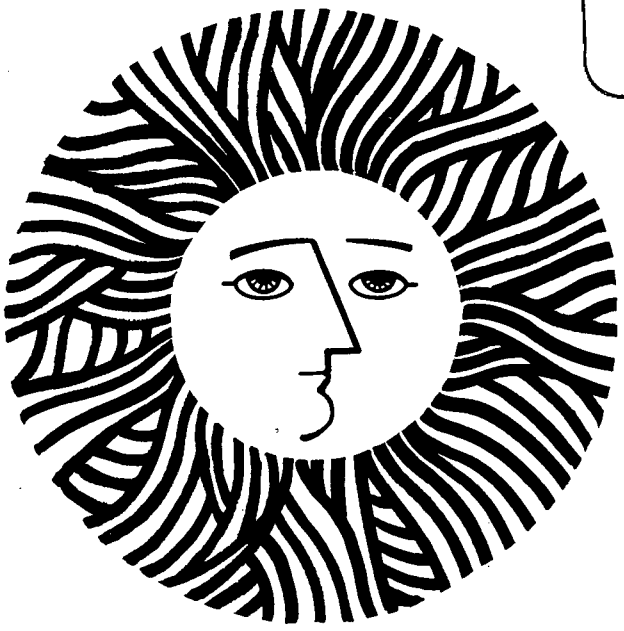

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ABSTRACT

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/MBtu. 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^2-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.[a] 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

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[a] The BECA series is published in Energy and Buildings or is available from the Energy Efficient Buildings program, LBL (Lawrence Berkeley Laboratory), and includes:
Part A = New residential buildings (from which this paper is derived)
Part B = Retrofit residential buildings
Part C = Commercial buildings
Part D = Appliance energy use
Part E = Validation of computer programs

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 (Q_H) by the monthly degree days (DDm) for each period, and then multiplying this average value, of Q_H/DDm, by the degree days for each unmetered month. The annual heating load is then the sum of the Q_H values for an entire heating season. Fig. 1 is a scatter plot of actual thermal intensity (annual heating load per 100 m^2 [1076 ft^2]) versus degree-days. The points are all identified by conservation categories and the identification number for a home or group of n homes. If n is greater than 1, then it is accompanied by the words "Avg.(n)".

Active solar buildings have the poorest "thermal integrity" (annual heating load per unit area per heating degree-day), averaging 78 kJ/(m^2-°C-day) [3.8 Btu/(ft^2-°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 50¢ 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

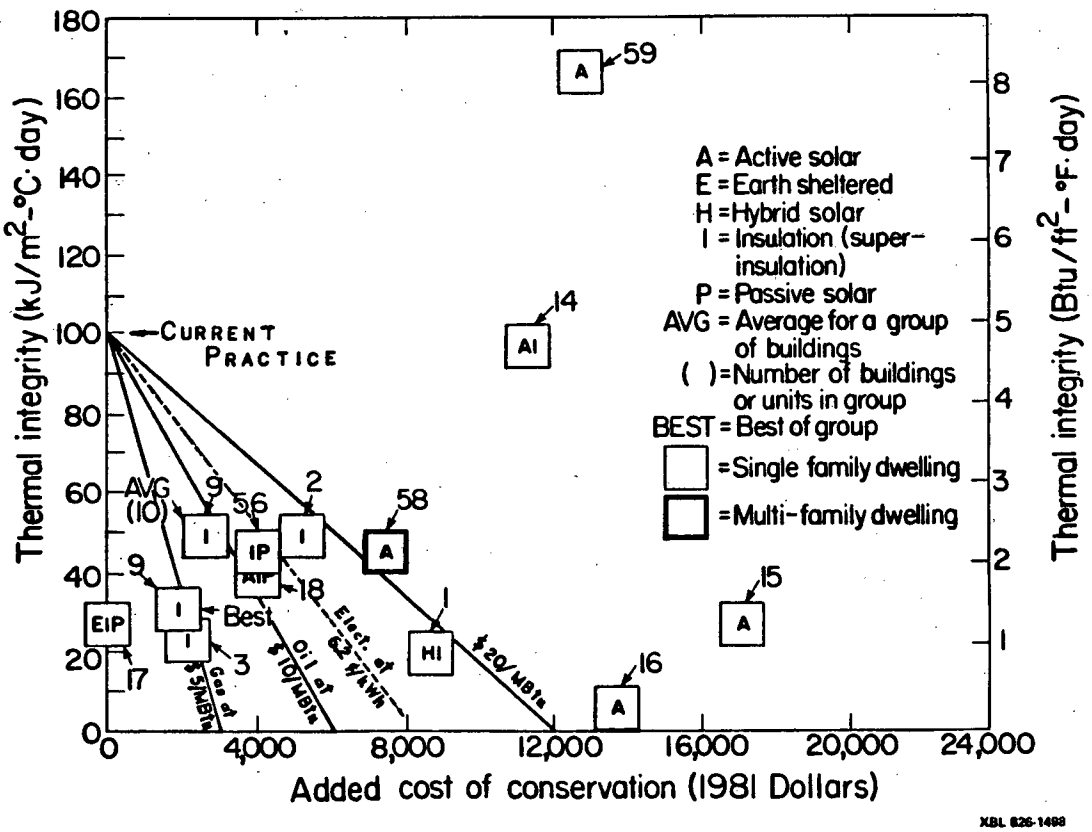

Fig. 2. Twenty-one-home scatter plot of thermal integrity vs. added first cost of conservation-and-solar features. The heating loads of Fig. 1 have been divided by floor area and degree days. The point on the y-axis at 100 kJ/(m^2-°C-day) represents average U.S. current practice (see Fig. 3); the sloping lines descending from it are boundaries of cost effectiveness for typical residential energy prices assuming 70% efficient furnaces for gas and oil, or electric resistance heating. Since conservation investments are typically "one-time," the future stream of energy savings for 30 years are converted to a single present value, assuming a 6% real discount rate (yielding a capital recovery rate of 7.25% per year). The home is cost effective if its point lies below the fuel line in question. Superinsulated homes fall mainly in the fuel price range of $4-to-10 per MBtu for gas, and are excellent compared to 6.2¢/kWh for electricity. Active solar homes are far worse. ($5 per MBtu equals 50¢ a therm for gas and $10 per MBtu equals $1.30 for oil.)

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, η_H (or COP as in the case of a heat pump).

$$Q_H = \eta E_H \qquad [1]$$

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 (η = 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 Q_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.

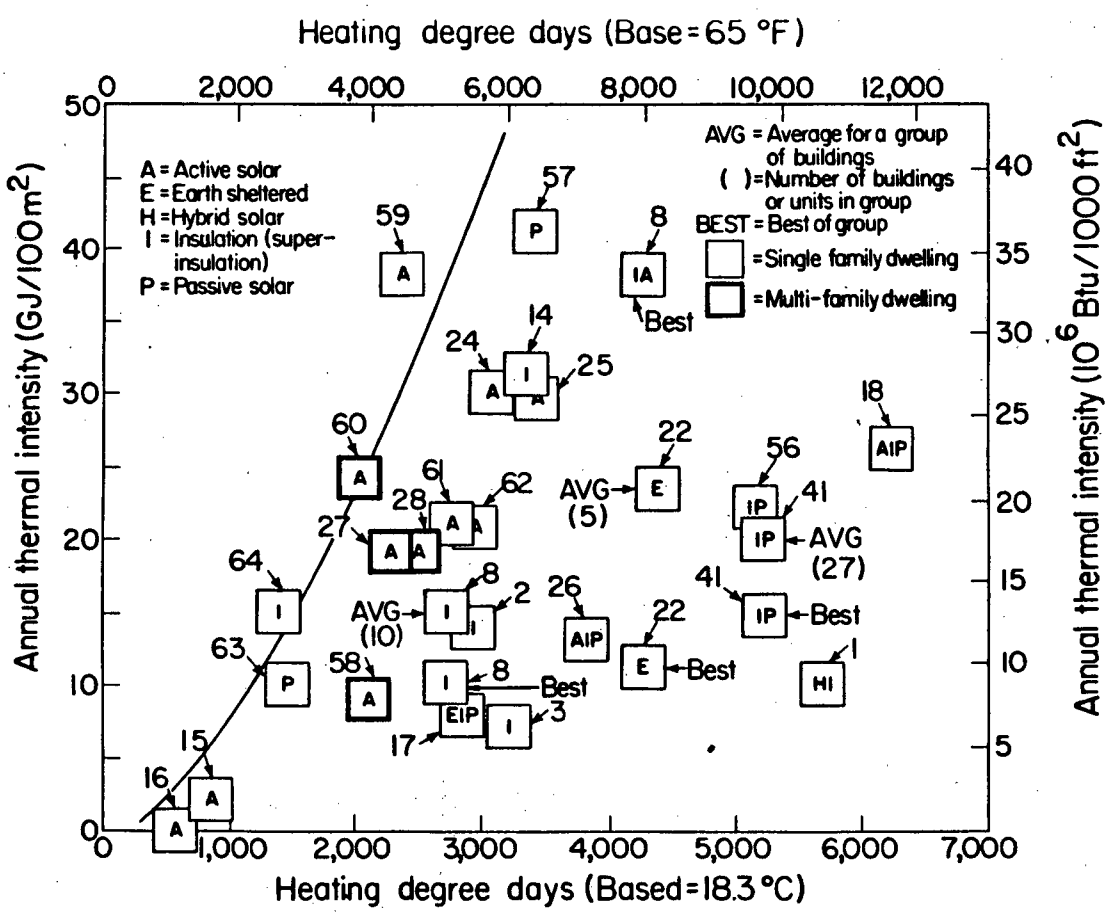

Fig. 1. Scatter plot of annual heating load vs. climate for 97 submetered energy-efficient new homes. The solid curve is NAHB's 1979 survey of U.S. building practice, taken from Fig. 3.

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, d$/dE, 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:

$$E_H \eta_H = Q_H = (Q_T - Q_I - Q_S) \qquad [2]$$

where

- E_H = energy delivered to heating system,
- η_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.[b] 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 GJ/year [22 - 61 MBtu/year]. During a heating season (5 months) these gains range from 10 to 27 GJ [9.5 to 25.5 MBtu], and average 16 GJ [15 MBtu], compared to an average annual heating load of 15 GJ [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 GJ [0.5 MBtu], Q_I equals 27 GJ/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°C [68° F], and standard internal gain, Q_{IS} = 32 GJ/year[c] [30 M Btu/year] as standard conditions.[d]

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.

$$Q_{TI} = Q_H + Q_I = Q_H + Q_A + Q_W + Q_P \qquad [3]$$

where

- Q_A = appliance energy (less dryer energy)[e]
- Q_W = 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 (7.6 MJ/person-day) [7.2 KBtu/person-day].

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[b] Annual variation in solar radiation typically varies less than 10% (private communication with Frank Quinlin, NOAA, 1982).

[c] This figure is in common use among researchers as the U.S. average. California Energy Commission, "Staff Presentation Outline for Committee Proposed Standards," April 1981; Oak Ridge National Laboratory, "ACES: Final Performance Report," December 1978 through September 1980," April 1981.

[d] The complete data base and the standardization procedure (its assumptions and boundary conditions) are presented in "Building Energy-Use Compilation and Analysis (BECA): An International Comparison and Critical Review. Part A: New Residential Buildings;" Proceedings of ACEEE 1982 Summer Study, Santa Cruz, California, August 1982 (Care of EEB Program, LBL).

[e] 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 $(20°C - T_o)/(T_i - T_o)$ 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}:

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

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 (BEPG, 1981) [developed at LBL as an extension of the research on the federal Building Energy Performance Standards (BEPS, 1979)],[f] new building practice (NAHB, 1979),[g] 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

[f] John Ingersoll et al., "Methodology and Assumptions for the Evaluation of the Heating and Cooling Energy Requirements in New Residential Buildings," LBL Report 13767, Berkeley, CA, 1981.

[g] Derived by simulation on DOE 2.1 from "Single Family Construction Practices," NAHB Research Foundation, Inc., Rockville, MD, 1979.

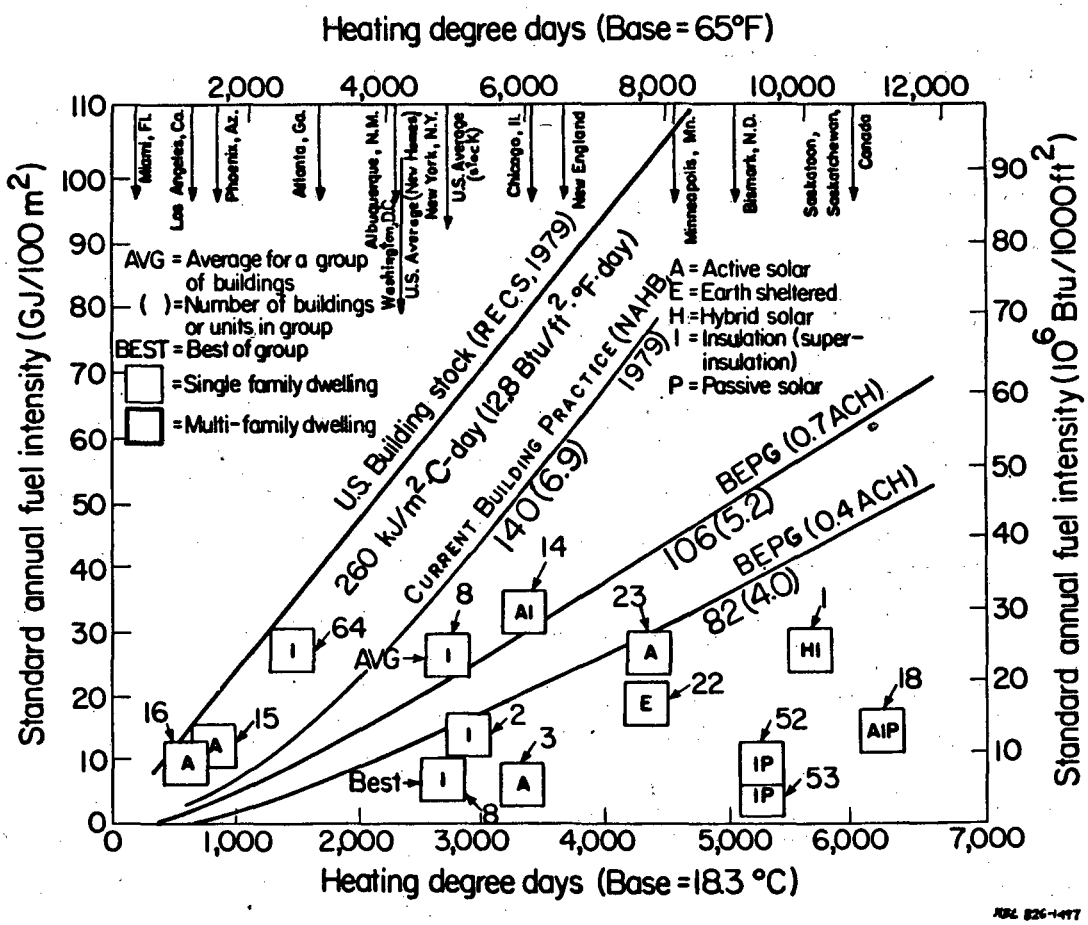

Fig. 3. Twenty-two-home scatter plot of "standardized" heating fuel intensity vs. climate. Instead of the heating loads of Fig. 1, we have plotted the fuel use per unit floor area (standard thermal intensity divided by 0.7). The various comparison curves are defined in the text. The average fuel intensity 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-^oC-day) [3.3 Btu/(ft^2-^oF-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-^oC-day) [3.8 Btu/(ft^2-^oF-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-^oC-day) [13 kJ/(ft^2-^oF-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

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