A statistical study of the thermal performance of a group of 1478 houses on the Canadian prairies

Hedlin, C. P.; Bantle, M.

Publisher's version / Version de l'éditeur:

ASHRAE Transactions, 90, 1B, pp. 83-93, 1984

National Research Council Canada
Conseil national de recherches Canada

A STATISTICAL STUDY OF THE THERMAL PERFORMANCE OF A GROUP OF 1478 HOUSES ON THE CANADIAN PRAIRIES

by C.P. Hedlin and M. Bantle

Reprinted from
ASHRAE Transactions
Vol. 90, 1984, Part 1B
p. 83 - 93

DBR Paper No. 1253
Division of Building Research

Price $1.00 OTTAWA NRCC 24049

Canada

RÉSUMÉ

On a recueilli des données sur la consommation de gaz naturel et d'électricité, les dimensions, l'âge et le style de 1 478 maisons situées à Régina.

On a également établi pour chaque maison, l'intersection de la pente des deux axes de la consommation de gaz et d'électricité et du nombre de degrés-jours de chauffage.

Des calculs ont été effectués afin de mesurer les écarts de consommation d'énergie pour différentes caractéristiques de maisons. Les variations dans les courbes représentant la consommation de gaz par rapport aux degrés-jours de chauffage ont également été analysées. On a constaté que ces variations étaient fonction de la dimension des maisons et qu'elles se retrouvaient parmi plusieurs groupes de maisons apparemment identiques.

AT-84-02 No. 1

A Statistical Study of the Thermal Performance of a Group of 1478 Houses on the Canadian Prairies

C.P. Hedlin, Ph.D. **M. Bantle**
ASHRAE Member

ABSTRACT

Information about the natural gas and electricity consumption, size, age, and style of construction was obtained for 1,478 houses in the city of Regina.

Slope-intercept relationships between natural gas consumption and electricity consumption versus heating degree-days were determined for each house.

Calculations were made to find the variation of energy consumption with several house characteristics. The variation in the slopes of the natural gas consumption versus heating degree-days was also studied. Variations with house size, and within several groups of nominally identical houses, were found.

INTRODUCTION

For houses on the Canadian prairies, a major part of the purchased energy shows up as space heat that is needed to balance heat loss through walls, windows, roofs, and floors during the heating season. Some of this comes as the by-product of lighting, cooking, domestic water heating, and the use of refrigerators or freezers. A major part of it is provided by the furnace specifically for space heating. In addition to that obtained from purchased energy, heat also comes from occupants and from the sun.

In any given house, such factors as occupancy levels and life-style affect energy consumption for space heating; however, the size of the house and its heat-loss characteristics are the main factors affecting space-heating needs.

Laboratory measurements of the thermal properties of components, combined with calculation procedures, are standard methods of arriving at heat-loss estimates. In some cases, measuring instruments can be employed to gain information. However, the time and effort required limit the number of houses that can be studied.

Information obtained by detailed laboratory and field instrument measurements can be complemented, extended, and, in some cases, its validity tested, simply by using the measured energy consumptions (Mayer and Robinson 1975; Hedlin and Orr 1977; Sonderegger 1977/78; Schrader 1978). These values, as measured by utility companies, may cover all of the purchased energy, unless fireplaces or woodburning stoves are used. The interaction of many factors means that it is difficult to identify some specific effects; the limitations of such

C.P. Hedlin, Head, Prairie Regional Station, Division of Building Research, National Research Council Canada, Saskatoon, Saskatchewan.
M. Bantle, Mechanical Engineer, SED Systems Inc., Saskatoon, Saskatchewan.

analyses must be recognized, and they should not be expected to reveal information about effects that are too heavily masked to be identifiable.

Analyses based on purchased energy might be divided into two categories: those involving individual houses and those involving groups of houses. The present study falls into the latter category. The analyses are statistical and, as a result, the conclusions are drawn for populations of houses and are expressed in terms of probability rather than in the precise numbers often associated with heat balance estimates for individual houses.

This study involves data from houses in which natural gas is used for space heating and, normally, for domestic water heating, and electricity is used for all other energy needs. Natural gas and electrical consumption data were provided by a Saskatchewan utility company for 1,478 homes in the city of Regina within the period 1969-77. Information about the size and shape, and some construction details for these homes, was provided by the City of Regina Assessor's Office.

The year of construction ranges from 1911 to 1973; main floor area (MFA) ranged from about 33 m^2 to 156 m^2, total floor area of the heated space (TFA) from 50 m^2 to 430 m^2, and height from one to two and one-half stories. Most of the houses had full basements, but some had only partial basements or none at all. Those with no basement were built over crawl-spaces or were slab-on-grade homes.

Insulation levels varied. Before 1930 most houses were built with no insulation, although it would have been added to many of them later. Those built between 1945 and 1973 would initially have had no basement insulation; walls would normally have R7 - R10 insulation built into them, and approximately R10 insulation would have been placed in ceilings.

A variety of questions could have been addressed using this body of information; three were selected:

1. The effect of several variables on energy consumption.
2. The nature of the slope of the natural gas consumption versus heating degree-day relationship as a space-heating characteristic for houses.
3. The variation in the natural gas versus heating degree-day slope within groups of nominally identical houses.

Discussion of the above topics is preceded by a brief description of heat-balance relationships and the nature of the data used in the analyses.

HEAT BALANCE RELATIONSHIPS

Fuel consumption varies with the weather. In this study, heating degree-days are used to represent the weather variable. In some cases it is expressed in terms of temperature (T):

$$DD/day = 18 - T \ ^\circ C \tag{1}$$

where DD/day is the average number of degree-days/day for the period of observation (one or more days). T is equal to the outdoor temperature (T_a) except for periods that include days having mean temperatures greater than 18°C. For values of T below 15°C, the difference between T and T_a averages less than 0.5°C (figure 1).

The heat equivalent of the fuel consumption (E_G) can be expressed:

$$E_G = I_G + S_G \ (18 - T) \ MJ/day \ . \tag{2}$$

The heat equivalent of the natural gas is assumed to be 37.3 MJ/m^3 (1000 Btu/ft^3). I_G and S_G are the ordinate intercept (MJ/day) and slope (MJ/DD) respectively. The subscript G is used to denote natural gas.

The same form of relationship was used to represent electricity consumption:

$$E_E = I_E + S_E \ (18 - T) \ MJ/day \ . \tag{3}$$

One would not expect as close a relationship between electrical consumption and T; however, since the use of lighting and car block heaters increases in cold weather, E_E is somewhat dependent on T.

Between 20 and 50 values of natural gas consumption were available for each house (and a similar number for electrical consumption). Each natural gas consumption value (which represents, on average, gas use during about a two-month period) was combined with the heating degree-day total for the corresponding period. These data points were used to find slope intercept relationships by least squares analysis for each house. The same procedure was used with electricity data. The results are exemplified in figure 2.

Amount of Variation in Natural Gas Consumption Accounted for by Heating Degree-Days

The reliability of these least squares relationships in describing the fuel consumption of houses depends on how much of the variation in energy consumption is accounted for by the heating degree-day parameter. Measures of this are given by the coefficient of determination (r^2).

Coefficients of determination were calculated for all 1,478 houses (of all styles and ages). It was found that for approximately 33% of the houses, the coefficient of determination exceeded 0.97; for 77% of them, it exceeded 0.90; and for 92%, it exceeded 0.80. This indicates that the relationship explained 80% of the variation in about 90% of the cases, and 90% of the variation in 77% of the cases; the remaining variation presumably would be due to other effects (results are shown in figure 3).

Houses with coefficients of determination of less than 0.80 were excluded from energy analyses. The selection of 0.80 was somewhat arbitrary, but inspection of the data suggested that it would remove anomalous cases. No special effort was made to determine the cause of low correlations. In a few cases the reason was apparent; for example, swimming pools may require a great deal of heat and so distort the energy consumption versus degree-day relationship that it becomes unusable as a measure of house thermal performance.

A general description of the houses was given in the introduction. Figure 4 shows the size - population distribution. The most common size was in the 150 to 200 m^2 range.

The total floor area, used here to express house size, is the sum of the basement area and the areas of above-grade floors. The term 'floor area' is used loosely here; sizes are based on exterior measurements. Thus, occupiable floor area is less than the indicated amount by a quantity approximately equal to the product of the perimeter and the wall thickness. The exterior measurement is used because it is the normal way of expressing house size in this region.

Factors Affecting Energy Consumption

Several sets of variables may affect energy use in houses. In many regions the largest amount of energy is used for space heating (Schrader 1978). Energy consumption for space heating may be related to a number of factors, including size, shape, and style, e.g. single story, two story, or split level. Other factors are orientation, occupancy, and color. Thermal insulation levels and air tightness have a very large effect. In this study the available data do not provide information about all of these factors. However, consumption as a function of size, year of construction, and style could be estimated.

Figure 5 shows the natural gas and electricity consumption as a function of house size. Consumption here represents the average annual consumption for all houses (with $r^2 > 0.80$) in each size range. Quantities for each house were calculated from equations 2 and 3, representing their natural gas and electricity consumption based on 6,000 heating degree-days (°C) (the average for Regina is about 5,900 degree-days/year). Both natural gas and electricity consumption increased with house size. Natural gas consumption ranged from about 150 GJ/year for the smallest houses to about 370 GJ/year for those in the 350-400 m^2 range.

To construct figure 6, natural gas consumptions were calculated for houses built at different times. Houses in the oldest group were built before 1921 and the newest after 1970. Groups containing fewer than five houses were excluded. Small groups containing between five and nine houses are identified by a black dot.

Energy consumption did not vary widely with year of construction, although in the larger sizes, older houses consumed somewhat more energy than newer ones.

Figure 7 gives a breakdown by style and size for houses built after 1944. Again, groups containing fewer than five house are not shown. The total number of houses of each style is shown in brackets. The results do not show marked differences in consumption as a function of style, although duplexes and one-story houses with full basements were somewhat lower than others. Because of the paucity of houses in some groups, it would be inappropriate to conclude too much from them.

The Slope of the Natural Gas versus Heating Degree-Day Relationship as a Measure of Space Heating Requirements

In the preceding discussion, total natural gas consumption data have been presented. Most of that energy is used for space heating; some of it is also used to heat water for domestic purposes and much of that energy is lost and does not contribute to space-heating needs. Since the use of natural gas for water heating is not measured separately, these data do not give explicit information about space heating requirements. However, S_G in equation 2 represents the change in fuel consumption with the outdoor temperature (T) and, with some qualifications, constitutes a measure of the space heating requirement for the house system. The value of S_G will be influenced by the slope of the electricity consumption (S_E), and by seasonal variations in solar gain and hot water use. Nevertheless, for these houses, variations in S_G will be preponderantly dependent on space-heating requirements and it is used here as a 'space heating coefficient.'*

In the following treatment, five different house styles are studied: split level, two story, one and one-half story, one story full basement and one-story houses with no basement.

Values of S_G for two-story, full basement houses are plotted against total floor area (figure 8). Values for houses of the same model were averaged to produce a single point. Thus each point represents one or more houses of a given model. In spite of the scatter, the plot demonstrates an upward trend with increasing size. To reduce the scatter, five or more points were averaged to produce a single value, and these average values are also shown in figure 8.

This averaging was also done for the other styles of houses listed above. The combined results are shown in figure 9. This gives a curvilinear plot with values that vary from about 21 MJ/DD for houses with a total floor area of 50 m^2 to 50 MJ/DD at 350 m^2.

Data were available for other groups of houses, which were not used in preparing figure 9 but were superimposed on it. These include houses built before 1945 and duplexes. All had full basements. Consumptions per degree-day for duplexes were substantially less than the average for other houses of corresponding size.

The curve through the points in figure 9 was used to prepare a second curve (S_G/A, scale on right side of figure). This gives the space-heating coefficient per unit area, degree-day versus area. This shows values falling sharply from about 0.42 $MJ/m^2 \cdot DD$ for 50 m^2 to 0.15 $MJ/m^2 \cdot DD$ for houses 200 m^2 or larger. Figure 10 shows S_G as a function of house style in size increments of 50 m^2. The pattern is similar to that in figure 7, where the ordinate variable was natural gas consumption.

Variation in S_G for Nominally Identical Houses

The data include values for a number of groups of houses of the same model. These were constructed according to the same plans; nevertheless they would have somewhat different thermal performances due to differences in exposure, orientation, color, quality of construction, owner management and changes made by the owners after purchase, such as finishing the basement and adding additional insulation (Mitalas 1976). It is to be expected that furnace efficiency would also vary from house to house. Statistical uncertainty about the slope introduces another variable. For eleven such groups, of 19 to 58

*Other factors are involved, but space does not allow a complete discussion of the validity of S_G as a device for characterizing energy use for space heating.

houses, the slopes were found for each house and the mean and standard deviation of the slope were computed for each group (table 1).

The sorting process identified a total of 374 houses in the 11 groups. Of these, five were known to have heated swimming pools. These were rejected since the natural gas use is severely distorted by that load; in some cases, S_G was negative.

Six of the houses were questioned because their values of S_G differed substantially from the mean for the group. Their ratios to their respective mean values ranged from 0.4 to 1.7. Also the coefficient of determination for seven houses was less than 0.8. The data are presented in table 1 with and without the questionable houses, under the headings "No Exclusions" and "Exclusions", respectively.

Table 1 shows that when the questionable values are included the standard deviation of the groups ranges from 7.6 to 28.1%. Including the questionable values increased the standard deviation of five groups by up to 75%. When questionable values were excluded, the standard deviation ranged from 6.6 to 28.1%.

Finally, in order to estimate the scatter of the houses as a single group, the slope for each house (S_G) was found as a fraction of the mean slope for its group ($\bar{x}$). These fractions were used to prepare figure 11. The numbers of houses falling in each increment of .04 in $S_G/\bar{x}$ ($S_G/\bar{x}$ from .94 to .98, .98 to 1.02 etc.) are plotted in histogram form for all 369 houses.

For the 369 houses as a group, the standard deviation was 14.7% of the mean value. If the 13 questionable houses were deleted, the standard deviation was 12%. Further, if the first group, which had an exceptionally large standard deviation, was excluded, the standard deviation for the remaining 334 houses was 10.2% of the mean.

Studies were also made on the standard deviations of energy consumption for the same houses. They were slightly smaller than the corresponding values for S_G: for natural gas consumption the standard deviation for the 369 houses was 13.9% of the mean; for natural gas plus electricity consumption, the standard deviation was 13.0% (compared to 14.7% for S_G). When the questionable values were excluded, the standard deviations were 12.1 for natural gas consumption, 11.2 for natural gas plus electricity consumption, and 12.0 for S_G.

Studies have been done by others on energy consumption and its house-to-house variation (Mayer and Robinson 1975; Sonderegger 1977/78). One report concluded that a significant part of the variation could be attributed to occupant-related factors (Sonderegger 1977/78). In that study the standard deviation was 22% of the mean - more than the standard deviation for the combined groups in the present study but less than the deviation for the most scattered group. Our report does not include information on the effect of occupant behavior or other causes of the wide group-to-group variation in standard deviation (which ranged from 7.8 to 26.4% for the combined group of 369 houses based on natural gas consumption, and from 7.6 to 28.1% based on S_G). This large difference suggests that significant modifications were made to some of the houses and/or that construction quality differed widely from group to group. It seems unlikely that occupant behavioral patterns for the different groups of houses would vary that much. This view is supported by the fact that S_G varies as much as energy consumption and (theoretically at least) S_G should represent the performance of the system. Ideally it should reduce or nullify the effect of occupant preference for a high or low interior temperature and the effect of the amount of hot water consumed. If interior temperature and hot water consumption do not vary during the heating season, the fact that they are high or low should have little effect on S_G.

SUMMARY

1. Studies using records of consumption for natural gas and electricity were carried out on 1,478 houses of all styles, ranging in size from about 45 to 400 m^2 total floor area. Slope intercept relationships between electricity and natural gas consumption and heating degree-days were found for each house.

2. The relationship between the energy equivalent of natural gas consumption and heating degree-days is expressed here as $E_G = I_G + S_G (18 - T)$, where 18 - T is simply another expression for the number of heating degree-days/day. The constants I_G and S_G were found for each house in the group by using fuel meter readings and heating degree-days for the corresponding periods. Similarly I_E and S_E were found from electricity consumption data.

3. Total consumption of natural gas varied from about 150 GJ/year for houses with total floor areas in the 50-100 m^2 range to 370 GJ/year for houses of 350 to 400 m^2. Corresponding electricity consumption varied from 14 to 50 GJ/year.

4. Natural gas consumption was not markedly different for old houses than for newer ones, and these data did not show a large difference due to style of houses.

5. In the relationship $E_G = I_G + S_G (18 - T)$, S_G (referred to here as the 'space heating coefficient') is characteristic of the house to which the equation applies. It represents approximately the rate of change in fuel consumption with change in the outdoor temperature (T).

6. S_G increases with increasing house size in a non-linear fashion, ranging from about 21 MJ/DD for houses with a total floor area of 50 m^2, to 50 MJ/DD for houses with a total floor area of 350 m^2.

7. For groups of nominally identical houses, the standard deviations for S_G (and average daily consumption of natural gas and electricity) were approximately 10% of the mean values for the groups. These would appear to provide a measure of the combined effects of such factors as exposure, occupant management, furnace efficiency, color, and orientation, as well as variations in quality of house construction and changes made after construction, on the thermal performance of the house.

8. The information gained from this study provides a useful set of reference values. Fuel consumption in low energy houses can be compared to these values in order to evaluate the success of energy conserving measures. Studies designed to identify causes of variation in fuel consumption may benefit from analysis of the total variation that was found here for nominally identical houses.

REFERENCES

Hedlin, C.P. and Orr, H.W., 1977. "A study of the use of natural gas and electricity in Saskatchewan homes", SHELTER, Proceedings of the Technical Program of the 91st Annual EIC Meeting, Jasper, Alberta, May 1977, pp. 123-131, NRCC 16898.

Mayer, L.S. and Robinson, J.A., 1975. "A statistical analysis of the monthly consumption of gas and electricity in the home", Center for Environmental Studies Report No. 18. Princeton University, NJ.

Mitalas, G.P., 1976. "Net annual heat loss factor method for estimating heat requirements in buildings", Building Research Note 117, Division of Building Research, National Research Council Canada, Ottawa.

Schrader, T.F., 1978. "A two-parameter model for assessing the determinants of residential space heating". M.S. thesis, Princeton University, NJ.

Sonderegger, R.C., 1977/78. "Movers and stayers: The resident's contribution to variation across houses in energy consumption for space heating". Energy and Buildings 1 (1977/78) pp. 313-324.

ACKNOWLEDGEMENT

The authors wish to express their appreciation to the Saskatchewan Power Corporation for providing the energy consumption data and to the City of Regina Assessor's Office for providing size and other information about these houses. Without their assistance and cooperation, the study could not have been carried out. We also wish to thank H.W. Orr and S.S. Tao for their advice and assistance and T.B. Remple for his work in carrying out the analyses. This paper is a contribution from the Division of Building Research, National Research Council Canada, and is published with the approval of the Director of the Division.

TABLE 1
Mean and Standard Deviation of S_G for Groups of Nominally Identical Houses

			No Exclusions*			Exclusions+		
Construction date	Main floor area (m^2) (ft^2)	Total floor area (m^2)	No. in group	Mean slope (S_G) (MJ/DD)	Standard deviation (% of mean)	No. in group	Mean slope (S_G) (MJ/DD)	Standard deviation (% of mean)
Single-Story, no basement								
1946	58 (625)	58	22	25.2	28.1	22	25.2	28.1
1957-60	88 (950)	88	19	21.8	11.7	18	21.9	11.6(c)
1960-61	89 (960)	89	23	26.3	17.0	22	25.7	12.7(c)
Single-Story, full basement								
1952	89 (960)	178	51	29.5	15.0	50	29.1	11.0(d)
1965-67	96 (1030)	191	37	27.3	7.7	37	27.3	7.7
1957-65	97 (1040)	193	58	29.9	15.1	56	29.3	10.9(c)
1965-68	97 (1041)	193	46	27.9	18.3	43	28.1	10.5(d)
1965	106 (1144)	213	19	29.3	10.9	19	29.3	10.9
1965-68	107 (1147)	213	32	28.2	7.6	31	28.3	7.1(c)
1957-66	109 (1176)	219	30	33.3	12.3	27	32.5	6.6(c,d)
Four-Level Split								
1963-71	130 (1394)	259	32	39.6	12.6	31	39.6	12.7(c)

*Except for houses with heated swimming pools.
+Excluded because of low coefficient of determination (c), large difference from the mean (d).

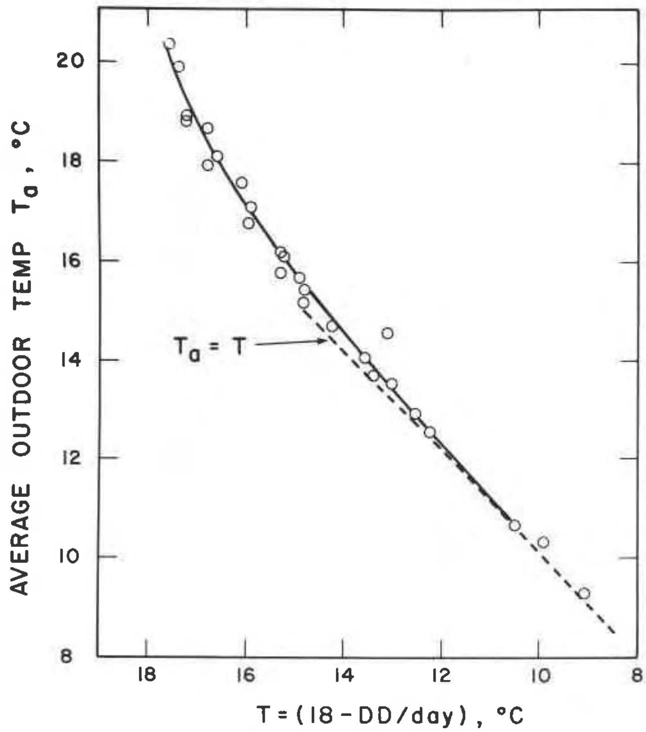

Figure 1. *Outdoor temperature T_a versus T. T is based on monthly averages of DD/day. The dotted line corresponds to T_a=T.*

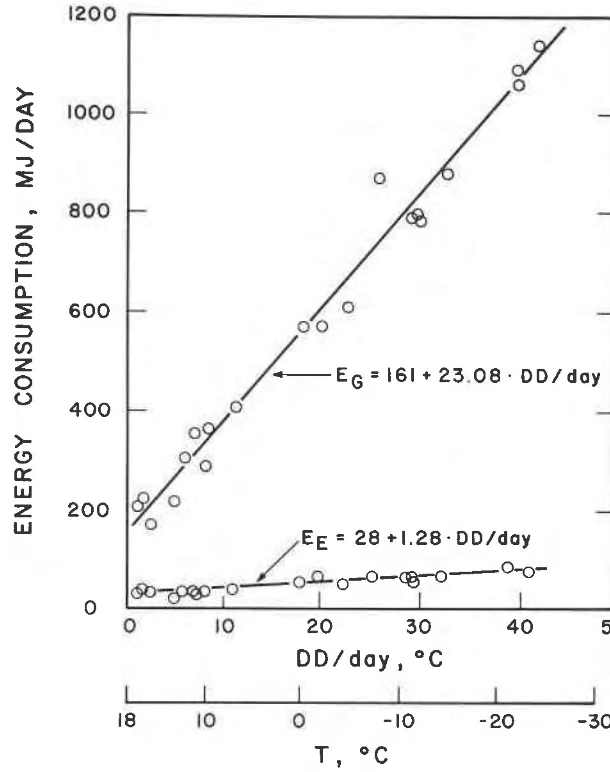

Figure 2. *Average daily consumption of natural gas (E_G) and electricity (E_E) (MJ/day) for a typical house from study. Abscissa scale shown both for degree-days/day and corresponding temperature (T).*

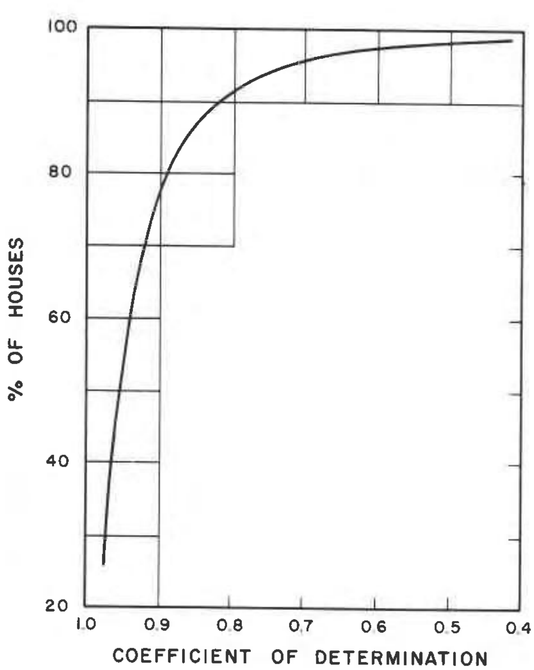

Figure 3. *Frequency versus coefficient of determination for least squares fits of natural gas consumption - heating degree - day data for 1478 houses.*

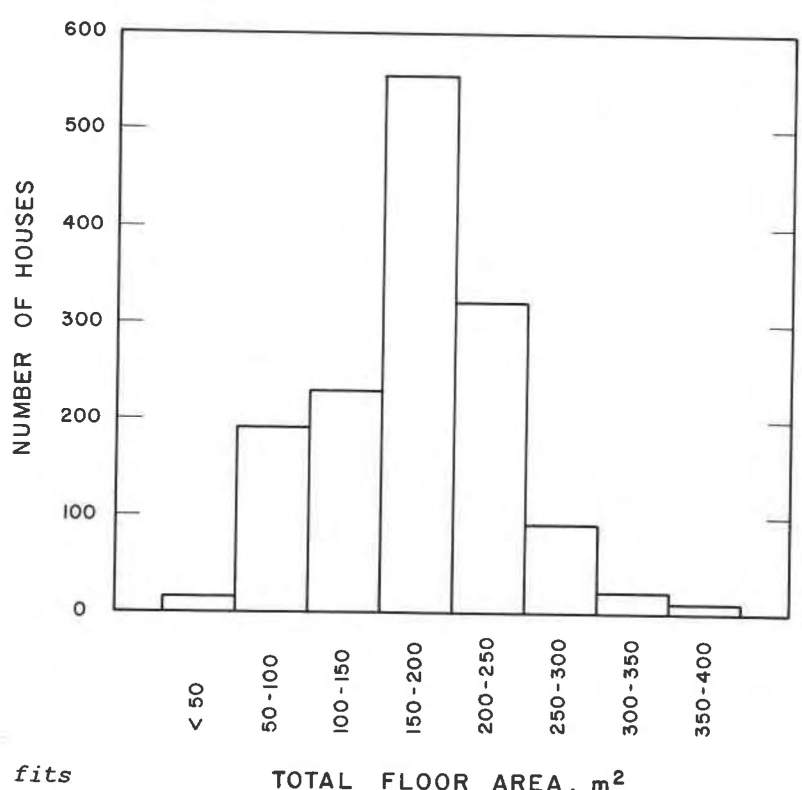

Figure 4. *Size-frequency distribution of houses in study.*

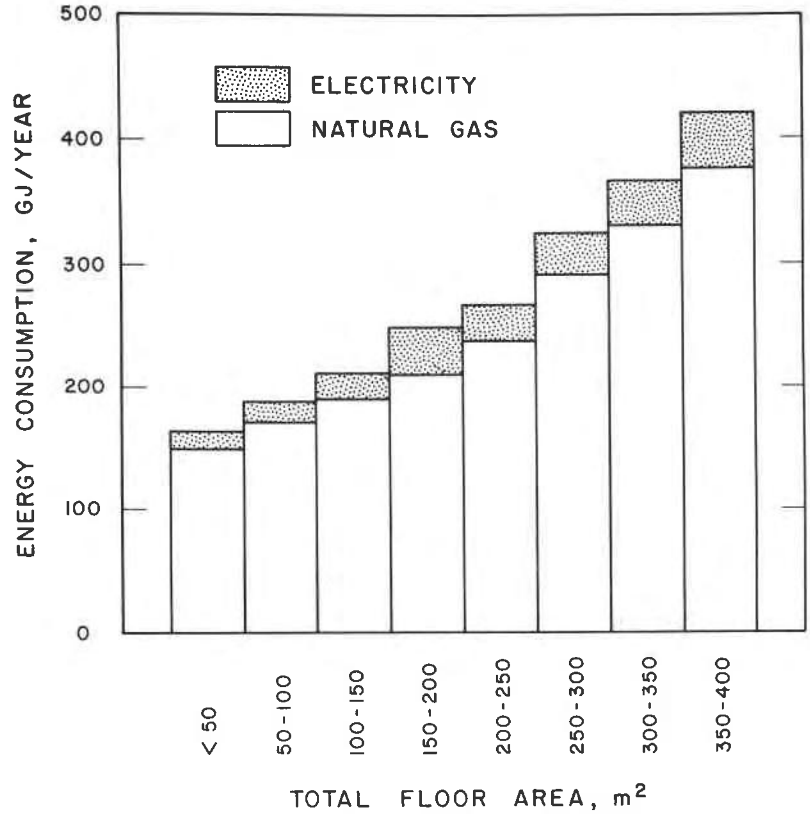

Figure 5. Electricity and natural gas consumption as a function of house size. Each value represents consumption based on average for all houses in the size range.

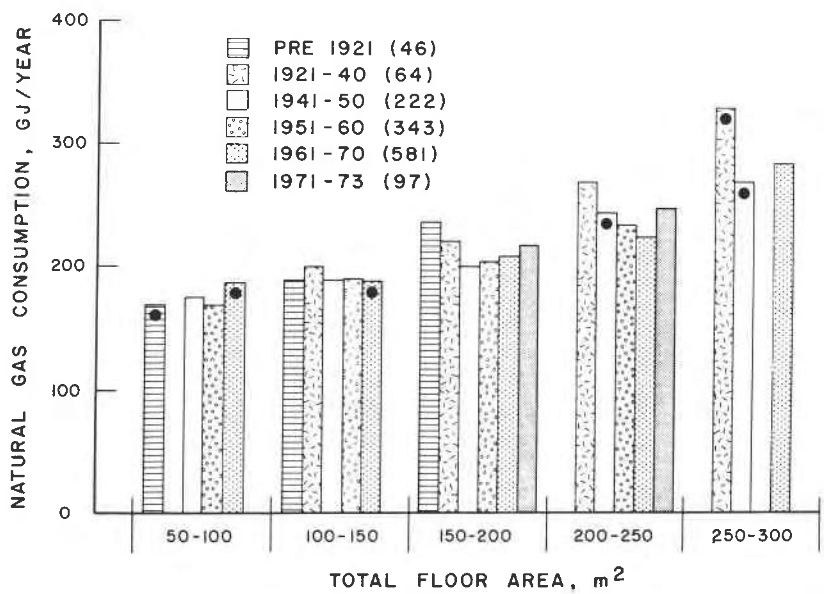

Figure 6. Natural gas consumption versus year of construction and total floor area. Black dots identify groups of only 5 to 9 houses. Numbers in brackets are total houses of that era.

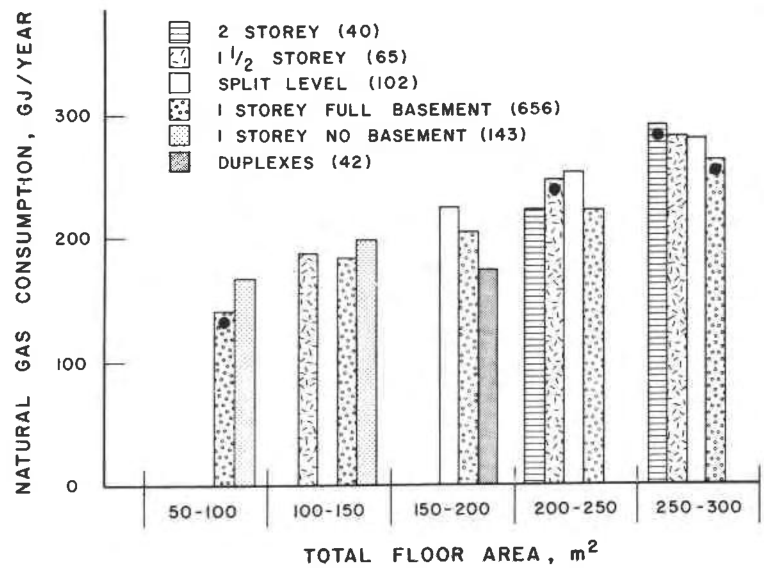

Figure 7. Natural gas consumption versus style of house and total floor area. Black dots indicate groups of 5 to 9 houses. Other groups are larger. Numbers in brackets are total houses of that style.

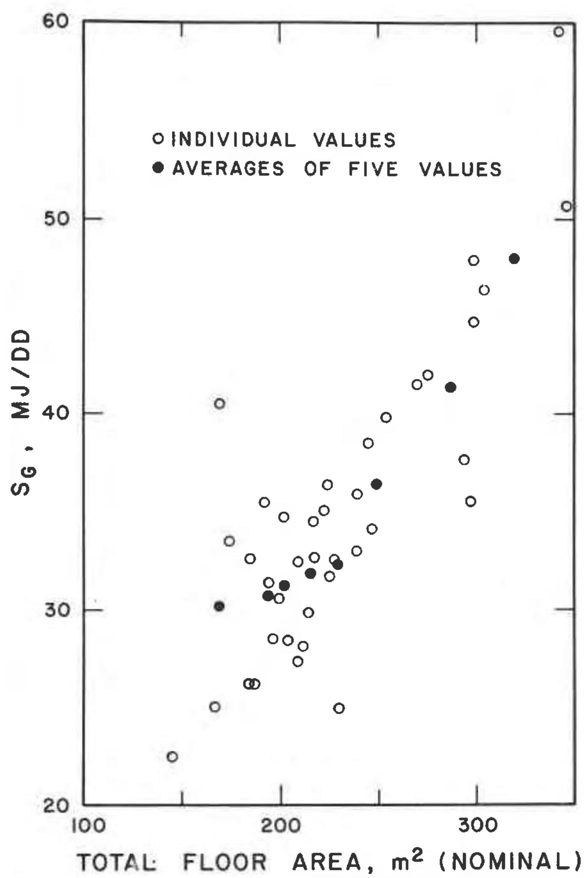

Figure 8. ***Natural gas consumption - degree-day slopes (S_G) versus total nominal floor area for 2-story full basement houses.***

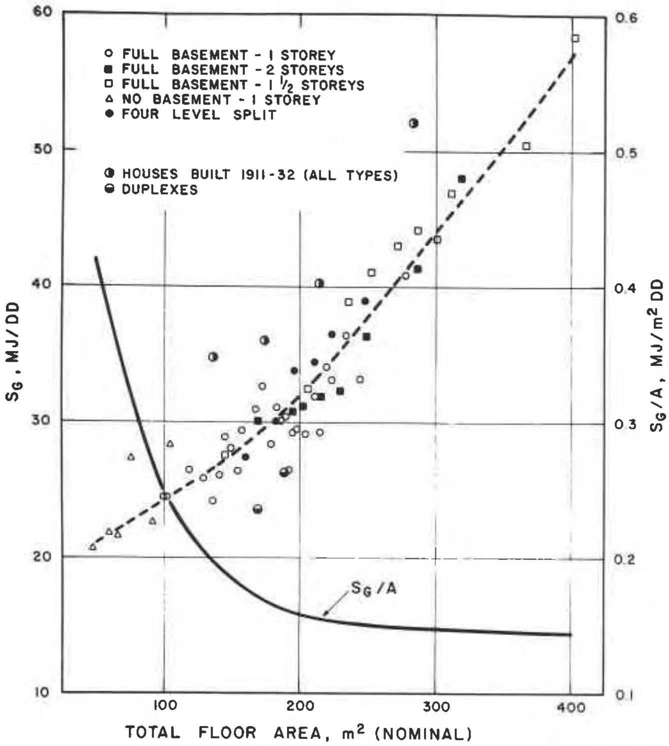

Figure 9. Natural gas consumption - degree-day slopes (S_G) (data points and dotted curve) for houses of different sizes and types. S_G/A MJ/m^2 DD (solid curve).

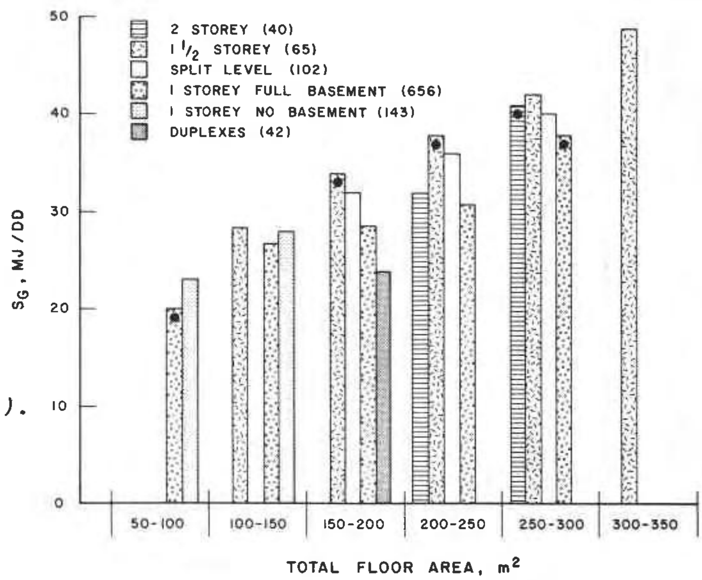

Figure 10. Average values of S_G for different styles of houses as a fraction of size. Black dots identify groups of only 5 to 9 houses. Numbers in brackets are total houses of that style.

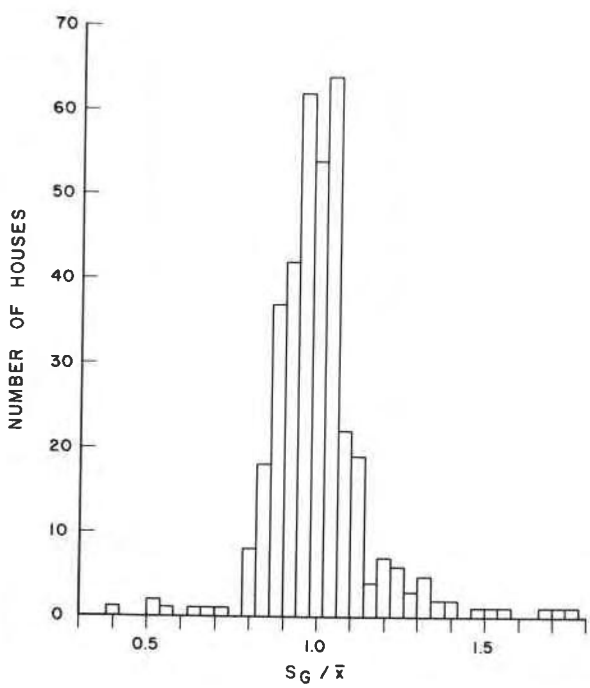

Figure 11. Frequency of occurrance versus $S_G/\bar{x}$ for 369 houses in 11 groups. S_G represents the natural gas slope for a house and x the mean value of S_G for its group.