the air a refractive capability that may equal or exceed the curvature of the earth. Manifestations of the arctic mirage, though largely forgotten in modern times, are described in the earliest accounts of North Atlantic discovery.

This interdisciplinary investigation, combining historical induction with scientific observation and analysis, has suggested a new interpretation of historical events. We believe that information gleaned from these mirages was vital to Norse navigation and exploration in the North Atlantic. We further contend that the mirage may furnish a logical basis for the pervasive ancient and medieval concept of the flat or saucer-shaped world.

References and Notes

1. For a detailed discussion of ray propagation through the lower atmosphere, see S. Bertram, *IEEE Spectrum* **8** (No. 3), 58 (1971).
2. B. Rossi, *Optics* (Addison-Wesley, Reading, Mass., 1965).
3. R. K. Moore, *Tropospheric Propagation Effects on Earth-Space Low Elevation Angle Paths* (Engineering Bulletin No. 61, University of Kansas, Lawrence, 1970).
4. At sea or over flat land, the distance to the horizon depends only on the elevation of the observer above the surface. If the light rays are straight, the horizon distance d (in kilometers) is given by $d = 3.58h^{1/2}$, where h is the elevation (in meters). In the normal atmosphere, where the rays have a radius of curvature of 38,000 kilometers, the formula becomes $d = 3.92h^{1/2}$.
5. W. H. Hobbs, *Ann. Assoc. Am. Geogr.* **27** (No. 1), 229 (1937).
6. W. A. Lyons, in *Proceedings of the 13th Conference on Great Lakes Resources* (International Association for Great Lakes Research, University of Michigan, Ann Arbor, 1970), pp. 369–387; see also W. C. Bell, thesis, University of Edinburgh (1974), table 6.20.
7. The underlying physical thesis is treated in detail in W. H. Lehn and H. L. Sawatzky, *Z. Polarforsch.*, in press.
8. T. Storm, *Der Schimmelreiter* (Insel-Verlag, Leipzig, 1968), pp. 113–114.
9. J. B. Tyrrell, Ed., *David Thompson's Narrative of His Explorations in Western America, 1784–1812* (Champlain Society, Toronto, Ont., Canada, 1916).
10. W. H. Hobbs, *Science* **90**, 513 (1939).
11. V. Stefansson, *Ultima Thule* (Macmillan, New York, 1940), p. 51. There is no reasonable room for doubt as to the *Morrissey*'s position. Her three chronometers had been checked daily against the Naval Observatory time signal. The noon observation on 17 July 1939 was, moreover, made under clear skies.
12. F. Nansen, *In Northern Mists*, A. G. Chater, Transl. (Heinemann, London, 1911).
13. A. D. White, *A History of the Warfare of Science with Theology* (Dover, New York, 1960).
14. The authority on which Nansen based his discussion was research carried out by Alf Torp.
15. There is also an ancient lay, the "*Hafgerdingadrápa*," about this phenomenon.
16. Ivar Bárdsson was sent to Greenland in 1341 by Bishop Hákon of Bergen and served at Gardar in the Eastern Settlement (*12*, vol. 2, pp. 107 and 241).
17. This attempt at explaining the legend in terms of the Moskenström appears to have been advanced first by the historian Peter Frederik Suhm (1728–1798) in his *Historie af Danmark* (1790). See also Nansen (*12*, vol. 2, p. 154).
18. J. Jóhannesson, *A History of the Old Icelandic Commonwealth*, H. Bessasson, Transl. (Univ. of Manitoba Press, Winnipeg, 1974). The reason for the small number of voyages to Iceland appears to lie, in part at least, in the fact that the Icelanders themselves (possibly from lack of timber) owned few vessels capable of trading between Iceland and Europe. See also Nansen (*12*, vol. 2, pp. 98–99).
19. ———, "The date of the composition of the saga of the Greenlanders," reprinted from *Saga-Book*, vol. 16, part 1 (University College, London, 1962).
20. On the other hand, there appear to have been occasional protracted periods in winter when the sea between the Faroes and Iceland was calm and permitted of voyages, even in small craft. Calm conditions would indicate the presence of an extensive high-pressure system which would, almost inevitably, be accompanied by the *hillingar* effect.
21. C. O. Sauer, *Northern Mists* (Univ. of California Press, Berkeley, 1968), p. 175.
22. E. Le R. Ladurie, *Times of Feast, Times of Famine* (Allen & Unwin, London, 1966), pp. 259–261. It has been established that the content of the isotope oxygen-18 in rain and snow decreases with decreasing temperature. Analysis of borings taken from the Greenland icecap corroborates the evidence obtained from plant remains in European bogs, namely that there occurred "an intense warming up which lasted from the seventh to the eleventh century" (p. 261).
23. H. H. Lamb, *The Changing Climate* (Methuen, London, 1966).
24. This is because radiation and conduction cooling reach their maximum cumulative level just at sunrise, after which incoming radiation tends to diminish atmospheric stability.
25. Captain Bartlett's observation of the Snaefells Jökull on 17 July 1939 was made with the sun in the southwest, and he consequently had the light over his shoulder also. At noon of that day, and again at 4 p.m., when the sighting of the Snaefells Jökull was made, the ship was in sunshine. By 6 p.m., however, it was rainy, the air having been warm and calm and the sea smooth throughout (*11*).
26. F. Baur, *Meteorologisches Taschenbuch* (Akademische Verlagsgesellschaft, Leipzig, 1970), vol. 2, p. 525.
27. P. Gayet-Tancréde, *Golden Iceland*, M. Magnusson, Transl. (Almenna Bókafélagid, Reykjavik, 1967), p. 63; A. E. Jensen, *Iceland: Old-New Republic* (Exposition Press, New York, 1954), p. 328.
28. V. Stefansson [*Greenland* (Doubleday, New York, 1947), p. 43] matter-of-factly substantiates this legend: ". . . you cannot go far offshore from northwestern Iceland without being able to see both countries. . . . You cannot climb the mountains of northwestern Iceland on many different days without catching a glimpse of the [Greenland] coast. The mountains . . . are of such height that the tops are inter-visible whenever the skies are clear." For this to be so, however, the *hillingar* effect must be present. Under clear skies, indicative of anticyclonic conditions, it almost inevitably occurs.
29. See the account of the voyage of Hrafn-Floki in H. Pálsson and P. Edwards, Transls., *The Book of Settlements* (Univ. of Manitoba Press, Winnipeg, 1972), p. 17.

30. The work was supported in part by the Northern Studies Branch, Department of Mines and Natural Resources, Ottawa, Canada, and by the Faculty of Graduate Studies, University of Manitoba.

Energy Conservation in New Housing Design

Jack E. Snell, Paul R. Achenbach, Stephen R. Petersen

The total annual energy use, including space heating and cooling, in a typical detached house built before 1970 in Baltimore, Maryland, with a floor area of 140 m^2, amounts to an average 187 gigajoules (10^9 joules) (*1*) of heating fuels and 44 gigajoules of electrical energy (*2*). At 1975 average prices for natural gas and electricity (*3*), the corresponding annual cost is about \$840. If the house has electric resistance heating, its 1975 annual energy costs could be as much as \$1400. These household expenditures are nearly double the expenditures for the same energy requirements in 1970. Thus a primary incentive for increasing the thermal efficiency design of new housing is the increasing cost of energy. However, this is not the only factor stimulating energy consciousness in housing design. The more or less regular recurrence of brownouts in some large cities since 1970, the subsequent unavailability of natural gas to new residential customers in many parts of the country, and finally, of course, the Arab oil embargo of November 1973 all served to place in focus both the vulnerability of the United States to an energy shortage and changing and uncertain patterns of future fuels availability (*4*). Hence the more efficient use of energy has become an urgent national goal which is providing a further impetus to the consideration of energy conservation design features in housing.

The potential impact of these strong economic and national policy thrusts on both existing and new housing is significant. Existing dwellings that have low thermal efficiency and cannot be improved economically will become increasingly obsolete. This will result in decreased property values (relative to

Dr. Snell is Chief, Office of Energy Conservation, Mr. Achenbach is Chief, Building Environment Division, and Mr. Petersen is a member of the Building Economics Section, Technical Evaluation and Application Division; all of the Center for Building Technology, Institute for Applied Technology, National Bureau of Standards, Washington, D.C. 20234.

more thermally efficient dwellings) and, in some cases, outright abandonment. To a large extent, this obsolescence is due to a general failure to anticipate the dramatic increase in energy costs that has occurred since 1970 and now promises to continue, although at a lesser rate, at least through the end of the century. If such premature obsolescence is to be avoided in new housing, its energy efficiency must be increased substantially over that of most of the existing stock of housing.

In this article, we examine the potential implications of energy cost and availability for new housing design over the rest of the century. Our discussion is based on the premise that the rise in the price of fuels relative to that of labor and materials is focusing the attention of home builders and home buyers on total life-cycle costs. This shift in emphasis from first-cost, short-term, and speculative factors to the energy conservation technologies stimulated by life-cycle cost analyses portends a number of major physical changes in new residences over the next few decades.

This thesis is developed by looking first at the housing market, the historical influences of certain building practices, and fuel price changes in recent years. Attention is directed primarily to single-family detached dwellings including mobile homes, single-family attached homes, townhouses, garden apartments, and low-rise housing units. Next, major design parameters related to energy are examined in the context of a simplified life-cycle cost model, with numerical examples. The constraints imposed by existing technology, building and occupancy practices, and energy costs on total life-cycle costs are examined for their implications to future housing design practices. Then, the technological opportunities for energy conservation as a design consideration are discussed, with an emphasis on identifying the extent to which many design parameters related to energy will change in the next few decades. Finally, we focus on the question of the implications of energy conservation on new housing design, ownership, and operation and on the identification of several specific research and policy issues.

Major Factors of Change

Existing housing and new construction data presented by the Federal Energy Administration (FEA) in its Project Independence report (*5*, table 2.6) show several important trends (Table 1). Without explicit consideration of future energy price increases and anticipated energy conservation measures, FEA predicted major increases in mobile home construction and essentially constant shares of the national housing inventory for single-family detached, low-density, low-rise, and high-rise units over the 1970–1990 time period. Thus, FEA estimated that, even in 1990, 70 percent of all housing would be single-family detached units or mobile homes, 25 percent would be low-density and low-rise units, and only 5 percent would be high-rise units. The FEA also suggests that new mobile home construction in 1990 will nearly equal the 1970 inventory of these units. Our analysis identifies influences that could significantly alter these expectations.

Table 1. Representative housing data for the United States. Data from (*5*).

Year	Number of housing units ($\times 10^6$)					
	Mobile home	Single-family detached	Low density (duplex)	Low-rise, townhouse, garden apartment	High rise	Total
1970	2.1	44.6	11.0	6.5	3.3	67.7
1990	7.4	59.4	14.8	8.8	4.5	94.9
Construction, 1990	1.9	6.6	2.2	1.2	0.6	12.5

Table 2. Price indexes for heating fuels (on the basis of billed costs), construction costs, and consumer prices. Data from (*3, 21–25*).

Year	Natural gas	Fuel oil	Electricity* (1 January)	Residential construction	Consumer price index
1950	69.9	72.6	97.5	63.0	72.1
1955	82.9	86.0	99.3	72.5	80.2
1960	100.1	89.0	102.4	81.8	88.7
1965	99.9	94.4	102.9	90.4	94.5
1970	107.4	109.3	99.7	122.4	116.3
1975	182.1	230.6	187.0	184.3	162.3

*On the basis of 20,000 kwh annual usage in cities of more than 50,000 (1975 index extrapolated from 1974 index on the basis of 12,000 kwh annual usage rates; 1950–1960 indexes extrapolated on the basis of 6,000 kwh annual usage rates).

About 60 percent of all the energy used in a typical house is devoted to environmental conditioning and the remaining 40 percent of use is directly related to the activities of the occupants, such as water heating, cooking, lighting, laundry, food preservation, dishwashing, waste disposal, personal hygiene, entertainment, and communication (*5*, figure 1.2). These occupant services are provided by a wide variety of appliances, most of which use electricity. In the 1960's, energy use in housing was increasing at an annual rate of 4 to 6 percent, largely due to the ingenuity of industry in providing a large variety of attractive and convenient appliances for the home (*2*, p. II-1). This proliferation of appliances was viewed as an increase in the standard of living, and their energy use was of little concern prior to 1970 because energy was considered relatively plentiful and inexpensive.

The growth in energy consumption per capita was altered significantly with the oil embargo of 1973. The immediate response was to institute austerity in living habits to reduce the demand for foreign oil. Austerity took the form of lowered house temperature, reduced use of appliances, lowered lighting levels, decreased mobility in transportation, and similar measures for conserving energy. It was demonstrated that the energy use of almost any building can be reduced by 20 percent by more careful operational practices and by maintaining a consciousness of energy conservation (*6*). Some homeowners also made improvements in the thermal properties of their homes by the use of insulation, storm windows, and caulking. Both austerity and building improvement practices have continued since the oil embargo ended, partly because of dedication to the national goal of self-sufficiency, but mostly because of the very sharp rise in the price of all forms of energy since 1973.

Few, if any, of the gains made in the environmental quality of housing over the last few decades need to be sacrificed in order to reach the desired goal of energy self-sufficiency in this country. Improved design of housing, increased efficiency in equipment and appliances, and better control and operation of equipment and systems can reduce the energy requirements of new housing from 30 to 50 percent as compared to practices prevailing before 1970 (*6*). One answer to the question of what influences there are to motivate home buyers or builders to seek these changes can be found in examining the economic factors facing these decision-makers. The extent to which energy conservation features can best be utilized in new housing can be determined objectively in a life-cycle cost context where both first costs and recurring costs are considered.

While life-cycle cost analysis has been a valid means of investment analysis for many years, it has only recently been used explicitly as an aid to energy conservation in the design of buildings (*7, 8*). Historically, the construction cost or sales price of housing has dominated investment decisions in the housing market. As a result, energy conservation features that were incorporated into the building design were often based on comfort considerations or on a reduction in the costs of heating and cooling equipment rather than on a reduction of long-term operational costs.

An examination of U.S. prices related to energy and construction between 1950 and 1970 (Table 2) will help to explain this first-cost syndrome. During this period, natural gas and fuel oil prices rose at an annual rate of 2 percent in current dollars and actually declined in real terms. During the same time period, the price per kilowatt-hour of electricity (at given usage levels) showed almost no increase in current dollars and, in fact, declined substantially in real terms. At the same time, construction costs increased at an annual rate of approximately 3.5 percent in current dollars and increased in real terms as well, while mortgage interest rates more than doubled. Anticipation of higher inflation rates at the end of this period also resulted in higher discount rates for the evaluation of future energy savings. Thus, while first costs and mortgage costs were increasing at a relatively rapid rate, energy costs appeared to be becoming less and less significant, even in a life-cycle cost context.

Since 1970, however, this situation has reversed. Energy costs have increased dramatically. Not only have they outpaced construction cost increases, they have, more importantly, reversed direction from declining real costs to increasing real costs. While it is unlikely that the sharp rate of growth in energy costs experienced between 1970 and 1975 will continue through the end of the 20th century, homebuyers' expectations as to the rate of future energy price increases must be considerably higher than just a few years ago.

Table 3. Space heating and cooling equipment installed in new single-family housing (percent). Data from (*26*).

Year	Gas	Oil	Electric	Central air conditioning
1965	64	13	20	25
1970	62	8	28	34
1975*	35	9	55	48

*Extrapolated from 1974 data.

Moreover, two important factors are occurring that greatly influence life-cycle heating and cooling costs. (i) There has been an accelerating switch from less expensive natural gas and fuel oil to more expensive electric heat, especially of the resistance type. (ii) The percentage of new residences with central air conditioning has nearly doubled since 1966 (Table 3).

Table 4 shows the effective cost per gigajoule of space heating output (adjusted for equipment conversion efficiency), based on average billed energy prices between 1950 and 1975. The present value of the annual cost to provide a gigajoule of heat to the conditioned space of a residence over its expected lifetime, N, can be calculated in a straightforward fashion with the use of the present worth factor (PWF). The PWF is calculated with the use of N, the annual discount rate, and the expected annual rate of increase in unit energy costs (*9*).

In a typical house built in 1970, natural gas was used as a heating fuel (Table 4) at an average cost of \$1.41 per gigajoule of output, with an expected price increase (calculated on the basis of historical experience) of about 2 percent. A discount rate based on a 1970 mortgage interest rate of 9 percent and a conservative lifetime of 30 years results in a present-value life-cycle cost of \$17.70 per gigajoule of output. The typical house built in 1975 uses electric resistance heat at \$6.94 per gigajoule of output. Assuming that an expected annual price increase of at least 5 percent is reasonable, and again using a 9 percent discount rate, we calculate the present-value cost of gigajoule output annually for 30 years as \$121.31, nearly seven times greater than that for a gas-heated house in 1970. Moreover, if air conditioning is added, the total expected present value of providing heating and cooling requirements over a 30-year period rises even further relative to the expected cost, just 5 years ago, of gas heating alone.

Decision Model for Optimization of New Housing Design

Energy conservation features offer little appeal when their only visible impact is either increased first cost or substitution for convenience or esthetic design features. The picture changes dramatically when life-cycle costs are considered. These costs can be computed on the basis of annual costs over the useful life of the building or the present value of all such costs. If properly considered, each of these approaches gives identical results. The first, often referred to as "Pity-em" in the trade, or *P*rincipal-*I*nterest, *T*axes, *E*nergy, and *M*aintenance, provides a convenient assessment of the relative affordability of various housing types compared to the householder's salary or take-home pay. The second approach is more closely related to standard financial analysis procedures and is therefore used in the following examples.

Since space heating accounts for the principal share of residential energy use, a simplified model of how these parame-

Table 4. The U.S. average cost per 10^9 joule output to conditioned space by fuel type (on the basis of billed rates). Data from (*3, 21, 22*). The assumed seasonal conversion factors are as follows: oil and gas, 0.6; electric resistance, 1.0; and heat pump, 1.7.

Year	Cost (dollars)						
	Natural gas		Fuel oil		Electricity (1 January)		
	Per therm	Per 10^9 joule	Per gallon	Per 10^9 joule	Per kwh*	Per 10^9 joule: Resistance	Per 10^9 joule: Heat pump
1950	0.058	0.92	0.123	1.39	0.013	3.61	2.12
1955	0.069	1.09	0.145	1.64	0.013	3.61	2.12
1960	0.083	1.31	0.150	1.69	0.014	3.89	2.29
1965	0.083	1.31	0.160	1.81	0.014	3.89	2.29
1970	0.089	1.41	0.185	2.09	0.013	3.61	2.12
1975	0.151	2.39	0.390	4.40	0.025	6.94	4.08

*On the basis of the billed cost of annual consumption in the 15,000- to 20,000-kwh range.

Table 5. Representative housing data: Parameters of prototype designs in northeastern United States (5, figure 1.2).

Parameter	Mobile home	Single-family detached	Low density (duplex)	Low-rise, townhouse, garden apartment
Dwellings per building	1	1	1	20
Floor area (m^2)	68	150	100	85
Total floor area (m^2)	68	150	200	1,700
Plan area (m^2)	4 × 17	10 × 15	13.3 × 15	15 × 56.6
Building height (m)	2.2	3	3	5
Shell area (m^2)	160	270	344	1,690
Shell area per dwelling (m^2)	160	270	172	85
Degree days (K)		2,900		
Summer design temperature (°C)		30.5 db/ 24.4 wb		
Glass (percent)		15		15
Wall, U_0 (watt/m^2K)		1.36		1.93
Roof, U_0 (watt/m^2K)		0.42		0.40
Annual electricity consumption (kwh)		18,600		404,564
Oil (liter)		5,980		85,500
Lighting (watt/m^2)		11		11
Infiltration (air changes per hour)		1.0		0.5
Cost (construction) ($)	9,000*	33,500	50,000*	351,000
Mechanical, electrical systems ($)	2,000*	7,000	12,000*	80,700

*Estimates of values not found in the cited references.

ters affecting this energy use contribute to life-cycle cost is examined. The analysis may be readily extended to space cooling, lighting, and other energy uses. In this context, the major elements of the life-cycle cost of a house are the first costs of the building shell and the heating system, and the present value of heating system operations over the useful life of the building.

The first cost of the building shell is directly related to its surface area, A, and its overall thermal resistance, R_0 (expressed as reciprocal watts per square meter per degree Kelvin), by the expression $(a_1 + p_1R_0)A$. The parameters a_1 and p_1 represent costs per unit area and, in general, may take on different values for increasing ranges of values of R_0 to account for piecewise linear shell costs. The first cost of the heating system is directly related to its design capacity, $(\Delta t\ A)R_0$ (where Δt is the design temperature differential between indoors and outdoors), with a fixed cost a_2 and a unit capacity cost, p_2. Then

$$\text{First cost} = (a_1 + p_1R_0)A + a_2 + p_2(\Delta t\, A)/R_0 \quad (1)$$

Recurring annual energy costs related to heat transmission through the building shell are a function of the average annual climatic heating load relative to occupant indoor comfort requirements, H (often represented by heating degree days × 24 hours per day); the heating equipment conversion efficiency, η; the cost per gigajoule of energy used for heating, p_3; and A and R_0. Present-value life-cycle energy costs (2) can be found by applying the PWF to the average annual energy costs at current energy prices, as follows:

$$\text{Present-value energy costs} = (p_3H/\eta) \times (A/R_0) \times \text{PWF} \quad (2)$$

so that the simplified, life-cycle cost of space heating for a house is obtained by combining Eqs. 1 and 2

$$\text{Life-cycle cost} = (a_1 + p_1R_0)A + a_2 + [p_2\Delta t + p_3(H/\eta) \times \text{PWF}](A/R_0) \quad (3)$$

This is obviously an oversimplified equation. It does not explicitly account for a number of factors—such as wind speed, solar insolation, landscaping, building and window orientation, architectural treatment, air infiltration or controlled ventilation, occupant behavior, and the like—each of which, in many cases, could significantly influence actual residential energy use. However, this equation does identify the major determinants of life-cycle energy costs in housing design—that is, size, thermal resistance, climatic location, energy prices, PWF, and equipment efficiency. The optimal value of thermal resistance R_0* is that which minimizes life-cycle space heating costs (Eq. 3). In the simplest case, where a_1 and p_1 are constant, R_0* is obtained by differentiating Eq. 3 with respect to R_0

$$R_0^* = \left[\frac{p_2\Delta t + p_3\dfrac{H}{\eta} \times \text{PWF}}{p_1}\right]^{1/2} \quad (4)$$

Equation 4 is generally valid for R_0* in cases where insulation can be increased with no structural modification to the building shell. Otherwise, a_1 and p_1 may take on different values for different intervals of R_0. In such cases, the optimal value of thermal resistance is obtained by selecting, from those values of R_0 which define intervals of p_1 and the values of R_0* defined by Eq. 4, the one for which Eq. 3 is minimized. R_0* is primarily a function of incremental heating system capacity costs, energy prices, the incremental cost of thermal resistance, equipment efficiency, climate factors, and the PWF. However, R_0* is unrelated to the total area of the building shell.

Equations 3 and 4 can be used in the context of an example to analyze the potential design implications of various energy conservation measures that influence life-cycle cost. For this purpose, consider a hypothetical single-family residence in New York City, drawn from a recent study (10). The major design parameters of this and similar dwellings are given in Table 5.

A 150-m^2, one-floor residence is typical of much recent U.S. construction. The major elements of first and operating costs are shown in Table 6. The major energy-related components (shell and heating and cooling system) account for 30 percent of the first cost. Annual energy costs (fuel oil at 10 cents per liter and electricity at 4 cents per kilowatt-hour) are $1342. Space heating accounts for 77 percent of the total energy used but less than half the annual energy costs, which consist primarily of lighting, hot water, and appliances. Since cooling makes up such a small portion of the energy load in this example, it is excluded from the following calculations.

Optimal shell resistance. Equation 4 can be solved for the optimal value of attic resistance, on the basis of current insulation costs, a New York climate, a discount rate of 9 percent, a fuel price increase of 5 percent, and a lifetime of 40 years (11). Such a solution gives R_0* values of 5.3 for oil heat, 8.3 for electric resistance heating, and 6.3 for electric heat pump operation. From Table 5, for the roof, a design U_0 of 0.42 ($R_0 = 1/U_0 = 2.4$) is considered typical in much existing housing. These R_0* values are two to three times greater than conventional usage of residential attic insulation provides. Likewise, although a U_0 of 0.57 ($R_0 = 1.75$) is considered typical for opaque wall areas in existing housing, an R_0 of 3.2 to 4 has been shown to be economically feasible in most new housing (9). Multiple glazing and significant increases in floor insulation are also called for in many cases. As a result, heating (and cooling) energy requirements related to the shell of a house can be halved in comparison to past construction practices by increasing the overall thermal resistance to a more economical level.

Energy price increase. If energy prices were assumed to increase at an annual rate of 10 percent, R_0* in attics would increase from 5.3 to 7.9 in the above example for oil heat. Not only is optimal design highly sensitive to energy price, but uncertainty about future energy prices can lead to major diseconomies in residential operations. The net effect of this on economic useful life is difficult to estimate. Even now it is usually impractical to retrofit existing housing with enough wall insulation to meet presently optimal insulation levels for new housing. If energy prices do continue to increase significantly there is a possibility of rapidly accelerating economic obsolescence in a significant fraction of existing, particularly single-family detached, housing.

Housing type and size. Shell area (A) is a major parameter of both housing design and energy usage, as shown by Eq. 3. Comparison of a single-family detached unit, for which shell area is 270 m^2 (not including floor), with a similarly insulated, two-story, inside townhouse unit of the same floor area but a shell area of only 135 m^2 reveals that heating and cooling expenditures are approximately halved, in addition to a significant reduction in construction costs. Further reductions in unit shell area are found in mid- and high-rise residential complexes. The opposite is true for mobile homes, which have the highest surface-to-volume ratio of the types of dwellings considered here. A mobile home may have as little as half the floor area of a small detached house but its unit energy use is greater than half of that for the single-family house.

Equipment efficiency. As heating system efficiency increases, the cost per gigajoule output from the system to the conditioned space decreases, reducing both life-cycle energy expenditures and the optimal R_0. Heat pumps, which may be 50 to 100 percent more efficient than electric resistance heating equipment, can have a substantial impact on optimal house design and total life-cycle costs where electricity is the most practical heating source. In large building complexes, total energy systems (such as the Modular Integrated Utility System) may provide greater efficiencies and use lower cost fuels than systems available for use in low-density communities.

Climate. Another major factor influencing life-cycle energy cost is climate. This factor directly influences the operating cost portion of life-cycle cost and has a somewhat smaller impact on optimal design resistance, as reflected by the square-root relationship of Eq. 4. Life-cycle cost economy may require highly differentiated building practices in various sections of the country in order to fully reflect heating and cooling load differentials as well as regional differences in energy and construction costs.

Other parameters. This life-cycle cost model and optimization process can be expanded to include other variables related to design. First costs can reflect changes in infiltration characteristics, the installation of cooling equipment, increased heating and cooling equipment efficiencies, solar shading coefficients, window size, and other design characteristics related to energy use. Annual operating costs can be expanded to include the reduced energy requirements and possible increased maintenance costs associated with these improvements. As a result, optimal values of R_0, infiltration rates, size and efficiency of heating, ventilating, and air-conditioning (HVAC) systems, shading coefficients, and other design parameters related to energy can be determined simultaneously.

Energy Conservation as a Design Parameter for Housing

Having established, on the basis of life-cycle cost, a solid rationale for major energy-related changes in future housing design, we can discuss the technological realities relative to such change. In the decades preceding 1970, the building construction industry, architects, engineers, and manufacturers of building materials and equipment invested a great deal of research and development effort to make housing more responsive to the users' needs and to improve the livability of houses. The environmental characteristics of houses that received a great deal of attention in these developments were: (i) efficient use of enclosed space; (ii) quality of the thermal environment (temperature, humidity, air circulation); (iii) indoor air quality (control of solid, liquid, and gaseous contaminants); (iv) use of daylight and sunlight; (v) effective visual communication with the out-of-doors; (vi) acoustical privacy; and (vii) indoor and outdoor esthetics and landscaping. In addition to providing a satisfactory level of each of these environmental characteristics, it was also necessary to provide adjustability of many of them in response to variations in weather, time of day, or activities of the occupants.

Attention among researchers in the building community is directed now toward various means of responding to the influences of fuel price increases and national energy conservation policies. There is considerable optimism that major energy savings are attainable without a deterioration in essential performance. In fact, there is good reason to believe that a more careful study of user needs in illumination, thermal environment, ventilation air, and equipment control may yield information leading to both energy

Table 6. Example of a single-family detached house in New York City (*5*, figure 1.2).

Item	Dollars	Percent
First cost		
Energy related		
Shell	6,464	19.3
Heating and cooling system	3,520	10.5
Lighting	672	2.0
Electrical	784	2.3
Hot water	128	0.4
Appliances	1,000	3.0
Total	12,568	37.5
Other		
Interior finish, plumbing, design, and the like	20,932	62.5
Total first cost	33,500	100.0

Energy source	10^6 joule/ m^2	10^9 joule	Fuel oil (liter)	Electricity (kwh)	Cost (dollars)
*Operating costs**					
Oil for heating	1,555	233.3	5,980		598
Electricity for cooling	41	6.2		1,700	68
for hot water	178	26.7		7,300	292
for lighting and power	233	34.9		9,600	384
	2,007	301.1	5,980	18,600	1,342

*Annual energy use and cost (floor area = 150 m^2).

conservation and improved building. Available options for the housing designers include the following.

1) *Insulation of walls, ceilings, and floors*. A frame wall made of studs 38 by 140 mm spaced 610 mm apart (2- by 6-inch studs on 24-inch centers) has as much strength as the more conventional wall made of 38- by 89-mm studs spaced 406 mm apart; the former uses no more wood than the latter and allows 50 percent more insulation to be used. The use of 38- by 140-mm studs is becoming common practice in some parts of the country (*12*). New truss designs allow insulation up to 305 mm thick to be installed across the entire attic area.

2) *Air infiltration*. Few houses are now built with an air leakage rate of less than one-half building volume per hour (0.5 air change per hour). More typical construction has an air leakage of 1 to 1.5 air changes per hour. Heating the leakage air often accounts for a third or more of all the heating energy requirements of the house. Only 9 to 17 m^3 per hour per person of fresh air is required to meet the oxygen and odor control requirements of people (*13*). Of course, alternative schemes for residential ventilation are available to provide the added fresh air needed during the hour or so of daily cooking time and the occasional periods when groups of people are being entertained. The application of caulking and sealing compounds at all building joints and at all penetrations of the exterior walls during construction is very cost effective and can reduce air leakage to 0.5 change per hour or less in most housing and simultaneously improve building comfort by reducing draft. This is approximately twice the fresh air required for oxygen and odor control. Use of available new compounds, although more expensive in first cost, can eliminate costly periodic replacement.

3) *Windows*. Windows provide daylight in a house and visual communication with the out-of-doors. In addition, when properly designed and located, they can in many cases provide net heating gains from solar energy during the heating season. However, a window not properly exposed to sunshine, even if double-glazed, can lose ten times as much heat as an equal area of well-insulated wall, while 20 times as much heat is lost if it is single-glazed. For this reason, the reduction of window area to the minimum needed for satisfactory daylighting and view to the outside is a wise approach in many situations. Double-glazed windows are cost effective over large areas of the United States; where fuel prices are relatively high and the winter weather is severe, triple-glazing can be cost effective as well.

4) *Landscaping and shading*. Shrubbery planted close to the house and evergreen trees (*14*) located about a building height away from the house on the windward side can significantly reduce the effective wind velocity on the building surfaces. This reduces air leakage and also the transmission loss, especially for windows. Deciduous trees of appreciable height can provide beneficial shade on the house during summer and allow sunshine to impinge on windows and walls in winter.

There are a number of opportunities to improve the energy efficiency of the heating and air-conditioning equipment in houses by 5 to 10 percent, and several additional techniques with even greater potential. These are as follows.

1) *Heat pump*. A heat pump for space heating use will result in a seasonal heating efficiency (relative to fossil fuels consumed) about equal to that attained with oil or gas heating equipment, and will save one-third to one-half of the electrical energy that would be required for an electrical resistance heating system. The heat pump is best adapted to the central and south central latitudes of the United States, where the magnitude of the heating requirements is intermediate. The heat pump is less efficient in very cold climates. Also, in the far south, the air-conditioning load predominates, and a system designed only for cooling can be made more efficient than a heat pump.

2) *Solar heating system*. A solar heating system can easily be designed to provide one-half to two-thirds of all the heating energy required in a house. However, the first cost of such systems is sufficiently high that they are now competitive only with electrical resistance heating, and then only in areas where electric energy is relatively expensive (*15*).

3) *Ventilation*. Numerous means are available to provide fresh air in any room in a house when the outdoor air conditions are favorable relative to the indoor conditions. If the occupants are willing to allow the indoor temperatures to fluctuate from 21° to 27°C and to use an attic fan for ventilation of the occupied spaces in lieu of air conditioning whenever the outdoor air is below indoor temperature, a very high saving in electrical energy for air conditioning can be obtained in most sections of the United States. Such a system is usually controlled manually but could be automated. Small exhaust fans, manually operated, are often used to remove odorous or moist air from cooking areas and bathrooms. The same principle could be used in conjunction with solid-state automatic or programmable controls to augment house ventilation during periods of high occupancy, thus eliminating the need for continuous high infiltration of outdoor air into houses.

Options for designs of equipment and appliances that are more conserving of

Table 7. Anticipated impacts of energy conservation on new housing design.

Housing type
Smaller, higher density, fewer detached houses
Increased shift to townhouse and low-rise from single-family detached
Diminished relative attractiveness of mobile homes in life-cycle cost terms
Improved designs with lower unit demands will help keep fossil fuel economically competitive in many areas for years to come
Architectural features
Thicker wall (cavity and sandwich) and roof construction for more insulation
Fewer picture windows, more double- and triple-glazed windows, some specially coated glass
More functional windows—designed as passive solar collectors
Tighter, better sealed joints, higher performance sealants, better workmanship
Better control of moisture to protect insulation
Attention to shape, orientation, landscaping in design
Control of air movement between floors—fewer open stairwells and split-level designs
Insulated foundation walls in cold climates
Greater thermal resistance for more expensive fuels, such as electric heating
Better thermal comfort and greater acoustical privacy
Mechanical systems
Smaller, more efficient HVAC equipment, better load matching
Customized ventilation to provide outdoor air when and where needed
Widespread use of heat pumps in moderate climates—integrated heat pump and solar heating
Solar space heating in selected climates where gas and oil are in short supply
More zoning and multipoint control systems in larger residences
Electrical load management control options for hot water and appliances
Solar water heating in the south
Institutional
Life-cycle cost-based performance standards (voluntary or mandatory) for new housing design
Labeling of houses, equipment, and appliances for energy use, cost, and performance
Householders knowledgeable of how to operate homes efficiently

energy include better matching of demand and capacity, modularization of heating and cooling equipment to increase off-peak efficiency, separate supply of outdoor air for combustion, automatic ignition systems, automatic (failsafe) combustion air dampers, and combustion- and cooling-cycle designs with improved efficiency. Research has provided some quantification of benefits, such as the modularization of heating equipment (*16*), the automatic night setback of thermostats (*17*), the supply of combustion air from outdoors (*18*), the penalties of oversizing heating equipment (*16*), and duct air leakage in attics (*19*). Other options mentioned above require better technical documentation of potential energy savings, and nearly all of the options require economic analysis to correlate cost effectiveness with climate, operational requirements, energy prices, PWF's, and other factors related to life-cycle costs.

It is highly probable that technologies not in significant use now, such as wind power, fuel cells, energy storage systems, and total energy systems, will become candidates for energy conservation in individual houses or communities in the future. The large number of options available for energy conservation in the building envelope and in equipment and appliances indicates that many trade-offs are possible, and that there may be several combinations of options that are substantially equivalent in energy conservation and economic value. Commercially available computer programs make it possible to evaluate many alternatives and, therefore, will undoubtedly find increased use in residential building design.

Implications for Future Housing Design

The preceding analyses demonstrate that rising energy prices and the potentials for increased energy conservation are powerful forces influencing change in housing design practices to follow the dictates of life-cycle performance optimization. The precise nature of these influences is still unclear; present data and analytical capabilities for detailed life-cycle analyses are imperfect. Nonetheless, major influences may be perceived. These are listed in Table 7. All of the indicated changes should improve housing quality while increasing its life-cycle affordability.

Design influences related to energy will, of necessity, stimulate major changes of practice in the building industry that affect architects, engineers, materials and equipment manufacturers, and regulating officials. Two cloudy and potentially troublesome issues are the impacts of energy conservation on mobile home economics and the prospect of accelerated obsolescence of much existing single-family housing that is thermally inefficient.

Private industry and government leaders who believe that new housing should incorporate energy conservation features must consider what the best techniques are for making it happen. Education, persuasion, financial incentives, and regulatory procedures have all been proposed and advocated by various groups for stimulating more energy-efficient housing designs in the near future. There are also significant political, national security, international trade, and foreign policy considerations in adequately motivating a national energy conservation program. A variety of actions has been taken in each of these areas. A few states have adopted energy conservation regulations. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers has developed a voluntary standard (*20*), and several agencies of the federal government have been seeking to develop building performance standards for energy conservation.

There is not now a consensus of opinion in the United States on whether measures for stimulating increased energy conservation in buildings should be pressed on a voluntary or mandatory basis. Both processes are being advanced with considerable vigor. The future directions followed in housing design in order to attain a higher level of energy efficiency will probably not differ much under voluntary or mandatory procedures. The rate of progress might be greater and the level of conservation attained might be higher under mandatory procedures, but the directions will be dictated by presently known technologies and those now being researched and developed. When significant advances have been made in improving the efficiency of energy utilization in the residential sector and energy conservation ceases to be a priority national concern, the quality of man's habitat will have been unmistakably improved.

References and Notes

1. 1 Btu = 1055 joules.
2. D. G. Harvey, *Residential Energy Consumption–Phase I* [Department of Housing and Urban Development, Report HAI-1 (Contract H-1654 to Hittman Associates, Columbia, Md., March 1974)].
3. Bureau of Labor Statistics, *Retail Prices and Indexes of Fuels and Utilities* (Department of Labor, Washington, D.C., December 1975), tables 1 and 2.
4. Federal Energy Administration, *Project Independence Report* (Washington, D.C., November 1974).
5. *Final Task Report—Residential and Commercial Energy Use Patterns 1970–1990*, prepared by the Interagency Task Force on Energy Conservation under direction of Council on Environmental Quality (conducted by Arthur D. Little, Inc.), (Federal Energy Administration Project Independence Blueprint, Washington, D.C., November 1974), table 2.6.
6. National Bureau of Standards, *Technical Options for Energy Conservation in Buildings, Technical Note 789* (Department of Commerce, Washington, D.C., 1973); Guidelines for Saving Energy in Existing Buildings, *Building Owners and Operators Manual ECM-1* (Federal Energy Administration, Washington, D.C., 1975).
7. S. R. Peterson, *ASHRAE Trans.*, in press.
8. J. C. Moyers, *The Value of Thermal Insulation on Residential Construction: Economics and the Conservation of Energy* (Atomic Energy Commission, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1971).
9. $$\text{PWF} = \sum_{t=1}^{N} \left(\frac{1+P}{1+D}\right)^t$$
where P is the average annual rate of fuel price increase, D is the discount rate, and N is the building lifetime.
10. Arthur D. Little, Inc., *Report to Federal Energy Administration, An Impact Assessment of ASHRAE Standard 90-75* (Federal Energy Administration contract C-78309, Cambridge, Mass., December 1975), pp. 17, 20, 43, 44, and 77.
11. Parameters assumed for calculation in text; H = (24 hour/day) × (5219 degree days); p_4 = \$0.80/R m²; PWF = 20.4 (N = 40 years; 9 percent discount rate, 5 percent rate of fuel price increase); oil = \$0.10/liter, η = 0.6; electric resistance = \$0.04/kwh, η = 1.0; and the heat pump = \$0.04/kwh, η = 1.7.
12. Owens/Corning Fiberglas, *The Arkansas Story* (Toledo, Ohio, 1975).
13. *The American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 62-73, Natural and Mechanical Ventilation* (United Engineering Center, New York, 1973).
14. G. E. Mattingly and E. F. Peters, *Wind and Trees: Air Infiltration Effects of Energy in Housing* [Center for Environmental Studies Report No. 20 (NSF Undergraduate Research Grant 11237), Princeton University, Princeton, N.J., 1975].
15. J. A. Duffie and W. A. Beckman, *Science* **191**, 143 (1976).
16. G. E. Kelly and D. A. Didion, *Energy Conservation Potential of Modular Gas-Fired Boiler Systems, NBS BSS 79* (Department of Commerce, National Bureau of Standards, Washington, D.C., December 1975).
17. D. A. Pilati, *The Energy Conservation Potential of Winter Thermostat Reductions and Night Setback* (Oak Ridge National Laboratory, ORNL-NSF-EP-80, Oak Ridge, Tenn., February 1975).
18. G. Peoples, Addendum to Proceedings of Conference on Improving Efficiency in HVAC Equipment and Components for Residential and Small Commercial Buildings (Joint sponsors: Federal Energy Administration, American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Department of Commerce, National Bureau of Standards, and Ray W. Herrick Laboratories of Purdue University, Lafayette, Ind., October 1974), p. A66.
19. P. R. Achenbach, C. W. Phillips, W. T. Smith, *ASHRAE Trans.* **70**, 390 (1964).
20. *The American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard 90-75, Energy Conservation in New Building Design* (United Engineering Center, New York, 1975).
21. Federal Power Commission, *Typical Electric Bills 1975* (FPC-86, Washington, D.C., 1975), table 1.
22. Federal Power Commission, *All Electric Homes in the United States* (FPC R-85, Washington, D.C., 1975), table 1.
23. Bureau of Economic Analysis, *Business Statistics* (Department of Commerce, Washington, D.C., 1973), p. 55.
24. Bureau of Economic Analysis, *Survey of Current Business* (Department of Commerce, Washington, D.C., 1975), vol. 55, p. S-8.
25. American Gas Association, *1972 Gas Facts* (Arlington, Va., 1973), table 138.
26. Bureau of the Census, *Construction Reports–Series C25, Characteristics of New One-Family Homes: 1974* (Department of Commerce, Washington, D.C., 1975), table 16.