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Potential for Energy Technologies in Residential and Commercial Buildings

November 1979

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Prepared for:
U.S. Department of Energy
Assistant Secretary for Policy and Evaluation
Office of Advanced Technology R&D
Under Contract No. EX-76-C-01-3871

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Contract No. EX-76-C-01-3871

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1. INTRODUCTION

1.1 PURPOSE

In the summer of 1976 Arthur D. Little, Inc., began a project for the Energy Research and Development Administration to evaluate the markets for energy technologies in the Residential/Commercial, Gas Utility, Industrial, and Transportation sectors. The emphasis in these studies was not on an assessment of the expected technical performance of the individual technologies, but on the nature of the markets to which the technologies would be applied. The market analysis of the R/C sector began in July 1976, and subsequent work was focussed on this sector. The project led to the development of a quantitative methodology for predicting the market response of energy technologies in the R/C sector. This report includes a description of the R/C market, the factors influencing this market and the technologies applicable to it.

While the data base, the computer model, the market analysis and the technology descriptions developed by Arthur D. Little, Inc., formed the core of much of the work, the effort was supported by Oak Ridge National Laboratory (fuel share price elasticity analysis), Brookhaven National Laboratory (sensitivity analyses of delivered fuel requirements), Argonne National Laboratory (integrated energy systems), and the Office of Solar, Geothermal, and Advanced Energy Systems of ERDA (geothermal) as well as by numerous other members of the working group who provided insights, support, and direction.

1.2 SCOPE AND APPROACH

The Residential/Commercial sector is defined to include all buildings used for residential or commercial purposes. The residential sector includes all buildings in which people live (single family homes, multi-family buildings [apartments and condominiums], and mobile homes); the commercial sector considers all other structures where services are performed including stores, offices, schools, hospitals, and warehouses, excluding only buildings that are part of industrial facilities.

An analysis was performed which led to an overview of the number of these structures (1975 through 2000), the principal market sectors into which these buildings (over 70 million residential units and 20 billion square feet of commercial space in 1975) might be segmented, the principal decision-makers in each of these sectors, their relative influence in the decision process, and the factors that would influence their decisions on energy technologies.

The individual energy technologies applicable to the R/C sector are numerous. For analytical purposes the technologies were consolidated into ten groupings: electric and gas heat pumps; conservation categories I, II, and III; solar thermal (hot water, heating, and cooling); photovoltaics, and wind systems. These groupings clearly do not allow an assessment of the potential for individual technologies, but they do allow a reasonable comparison of their roles in the R/C sector. Assumptions were made regarding the technical and economic performances of the technologies over the period of the analysis. In addition, the study assessed the non-financial characteristics of the technologies — aesthetics, maintenance complexity, reliability, etc. — that will also influence their market acceptability.

The effect of the technologies in the R/C sector was analyzed quantitatively through the use of a regionalized (four census regions) computer model that calculated the market penetration of each of the technologies, in each of 18 market sectors, for three fuel types (oil, gas, and electricity) through the year 2000. The market penetration is described in terms of residential units or commercial floor space affected and energy savings by fuel type.

The report describes the quantitative methodology that forms the basis for the analysis; the R/C market, the construction process, the participants and their relative influence in the energy technology decision, and the energy-consuming characteristics of the different market sectors; the technical, economic, and other characteristics of the energy technologies that will affect their acceptance by the R/C market; and the results of analyses of energy technologies in the R/C sector.

2. MODEL METHODOLOGY

2.1 INTRODUCTION

The residential-commercial energy technology model was developed by Arthur D. Little, Inc., as a planning tool for policy analysis in the residential and commercial building sectors.* The model and its procedures represent a detailed approach to estimating the future acceptance of energy-using technologies both in new construction and for retrofit into existing buildings. The model organizes into an analytical framework all relevant information and data on building energy technology, building markets, and government policy, and it allows for easy identification of the relative importance of key assumptions. The outputs include estimates of the degree of penetration of the various building energy technologies, the levels of energy use savings associated with them, and their costs — both private and government.

The model was designed to estimate the annual energy savings associated with new technologies compared with continued use of conventional technology at 1975 levels. The amount of energy used under 1975 technology conditions is referred to as the reference case energy use.

In addition to gauging the future effect of normal market forces as reflected in the energy cost savings of the building technologies and the first cost of the technology devices, the Arthur D. Little model considers the effects of government incentives on the penetration of the various technologies.

The model was developed to take into account all the factors that may determine the future market penetration of building energy technologies. These factors include:

- The level and nature of incentives instituted by the federal government.
- The energy and structural characteristics of a particular building type.
- The characteristics of the decision-makers associated with the market class (e.g., developers, owners, financiers, etc.) and their influence on the decision.
- The attitudes of the decision-makers about what is important in the decision on new technologies. These attitudes will be affected by the degree of exposure to the technologies.
- The economics of the new technologies relative to the conventional technologies.
- Competition among the new technologies.
- The economics of new technology choices, e.g., fuel prices; technology system design; conventional or future fuel/firing technologies associated with the buildings; and regional location.

* The Arthur D. Little, Inc. effort required exercising several computer sub-models and developing a number of data bases.

The model accounts for these factors and others related to acceptance of the building energy technologies. The output from the market model includes estimates of the:

- Market penetration of the new technologies during building construction (new) or as a retrofit effort.
- Number of technology units installed over a fixed time (1 to 25 years) and the total square feet of solar collector sold.
- Total investment in energy technologies by the private sector.
- Total government expenditures in financing the various incentives (e.g., tax credits, etc.) and maintaining related activity in new building-energy technology (e.g., research, development, and demonstration projects, educational programs, advertising, government building investment programs, etc.).
- Total "over-the-fence" energy saved by the installed technologies with breakdowns for the amounts of gas, oil, and electricity saved.

A straightforward interactive model was developed as a working tool. A totally comprehensive automated model that would perform all aspects of the analysis was rejected for three reasons. First, such a model would not be flexible enough to perform the range of calculations and approaches needed for energy policy planning in the residential and commercial building sectors. Second, a model that simultaneously considers all markets, regions, and years would exceed the capabilities of available interactive computer systems. Finally, the computer operations costs would be excessively high.

The Arthur D. Little interactive computer model is limited to handling one building "decision cell" at a time. A decision cell consists of one building/market type (e.g., single family homes, speculative developer) for either new construction or retrofit.* Each decision cell considers all the relevant energy technologies. The expected trends for fuel use in conventional systems (assuming no penetration of the new energy technologies) are provided as inputs to the cell logic; these values are referred to as fuel shares.

Fuel shares were assigned by using a residential and commercial energy use model developed at the Oak Ridge National Laboratory. The Arthur D. Little model starts with the fuel shares as inputs and assumes a breakdown of conventional equipment use based on fuel type. The model then considers the replacement of or an addition to a conventional energy system by one or more building energy technology options. The decision to select the building energy technology thus competes against the decision to use a preselected conventional fuel. The implied logic is that the comparative economic performance of new technologies will vary, depending on building type and fuel displaced.

The cell logic considers all conventional fuel shares for a given building and market type. The cells must be individually run for each building market, region, and year. The results of each run are stored in a data base aggregated to give the impact of all new building energy technologies on the total residential/commercial building sector.

* A distinction between speculative or custom development markets is not required for the retrofit markets.

Approximately 150 runs are required to cover all buildings (new and retrofit) in all the regions for one year. Consequently, multi-year analyses require many model runs through manual interaction. To avoid excessive manual input, Arthur D. Little performed single-time analyses that involved a period greater than just one year. In these analyses, parameter values used represented an average value over the period.

2.2 COMPONENTS OF THE MODEL

The Arthur D. Little building model is shown in Figure 2-1. Figure 2-2 is a schematic representation of the model logic. In very general terms, the modeling procedure is as follows.

The fuel shares projected for each particular future market, building type, and region are entered into the model along with such data as:

- Percentage air-conditioning use in non-heat-pump buildings;
- Technology first costs;
- Technology building energy load for heating, cooling, domestic hot water, light and power, and auxiliary energy use;
- Efficiencies of gas, oil, and electrical energy use for conventional and heat pump uses;
- Technology non-financial utility values;
- Percentage of the load saved by each technology for each type of load;
- Choice of first cost and payback penetration curves; and
- Cumulative weight of the non-financial issues in the decision-making process.

These input data are processed and a series of penetration analyses is performed. First, the penetration of electric heat pumps is determined against the buildings that have chosen conventional electric heating. Next, heat pumps using natural gas are evaluated for their penetration in all buildings that have opted for conventional natural gas use.

After the gas and electric heat pump penetrations are estimated, the fuel shares are readjusted to reflect all eight fuel and heating system options, i.e., natural gas, oil, electricity for conventional systems with and without air conditioning, and electric and gas heat pumps with air conditioning (Figure 2-2). For each option the penetration of other building technologies is evaluated sequentially by technology group.

The first new technologies to be evaluated for their penetration are the building conservation options. Three levels of conservation technologies are assembled into a tailored conservation package and evaluated separately. Each level of conservation represents an increment in conservation technology cost, complexity, and energy savings.

The penetrations of solar technologies are then evaluated within the Arthur D. Little model for three solar configurations — hot water only; hot water and heating; and hot water, heating, and cooling. The market penetration of each level of solar technology is estimated for each fuel and heating system option. In addition, the model evaluates the ability of two technologies for producing electricity — wind power and photovoltaic power — to penetrate the various building markets by saving electricity for light and power and other auxiliary uses.

FIGURE 2-1 RESIDENTIAL/COMMERCIAL BUILDING NEW TECHNOLOGY EVALUATION

FIGURE 2-2 ARTHUR D. LITTLE, INC., BUILDING ENERGY TECHNOLOGY MARKET MODEL

The Arthur D. Little model provides a summation of all energy savings that result from adoption of the various technologies. The number of units is provided along with a detailed breakdown on energy savings relative to the reference case. The following sections describe these procedures in more detail and clarify some of the basic assumptions within the model. .

Penetration Curves

At the central core of the model are the market penetration curves. The development of the market penetration curves for the various classes of buildings and markets is the product of extensive experience within all segments of the building industry. The set of penetration curves represents the results of interviews with builders, planners, financiers, home owners, and others in the building sector.

For each building type and market type the Arthur D. Little model uses penetration curves to represent both the near-term (1976-1980) and long-term (1990-2025) behavior of the decision-makers. Generally, the decision-maker will be willing to accept new building technologies on less financially attractive terms in the future because of the familiarity that is gained with the technologies as large numbers of devices are installed and operated.

Two financial variables are deemed influential to the selection of building energy technologies: undiscounted payback period and first cost. Payback is simply the ratio of the technology first cost and its estimated annual energy cost savings. The two financial variables are interrelated because payback includes first cost as its numerator. Figure 2-3 depicts a payback penetration curve. Notice that as payback in years becomes very long (greater than 10 years) the percentage of situations where a technology is selected approaches zero. As payback decreases to a few years, the penetration percentage increases to significant levels. As payback approaches zero (this implies a very high and rapid return on investment), it is assumed that penetration percentage reaches 100%. In the Arthur D. Little model, a first-cost penetration curve is also adopted which is used in conjunction with the payback penetration curve.

The first-cost penetration curve is illustrated in Figure 2-4. Notice that at zero first cost, the penetration is 100%. As first cost increases, the penetration drops, but not nearly as rapidly as for the payback penetration curve. The reason for this behavior is suggested by the fact that certain decision-makers either will not have the opportunity to consider high first-cost technologies or will balk at them. In the near term, the first-cost penetration curve has validity; in the long term, the direct effect of first cost on penetration should diminish and the payback value should be the sole financial criterion.

In both the near and far term, first cost and payback should be able to be traded off against each other. In the near term, a larger-scale (higher first-cost) technology should have a shorter payback than an equally valued technology that is smaller in scale, because of the risk that the technologies may fail to perform as expected. The specter of performance failure raises the concern that a larger investment will incur a larger loss. In the far term, confidence in performance should be greater through greater experience in technology, installation, and operation.

Payback is calculated by the formula:

$$PB = \frac{FC}{OCS} = \frac{\text{Undiscounted}}{\text{Payback}} \quad (1)$$

FIGURE 2-3 PAYBACK PENETRATION CURVE

FIGURE 2-4 FIRST-COST PENETRATION CURVE

where:

FC = first costs of technology

OCS = annual operating costs savings (net fuel cost savings) of the technology.

Payback PB is calculated where appropriate with first cost levels compared with conventional systems. Thus, for heat pumps, FC is replaced by ΔFC , the difference in cost between the conventional natural gas or electric heating system and the heat pump system.

According to the previous discussion, the first cost and payback penetration are multiplicative in the model:

$$P_{TOT}(FC, PB) = P_{FC}(FC) \cdot P_{PB}(PB) \quad (2)$$

where: $P_{TOT}(FC, PB)$ = Total penetration as a function of first cost, FC, and payback, PB

$P_{FC}(FC)$ = Penetration factor for technology first cost alone

$P_{PB}(PB)$ = Penetration factor for technology payback alone.

The penetration curves used are different for each class of building and relevant market. The use of different penetration curves represents the variation in the attitudes of the decision-makers involved in each market and building situation.

The use of undiscounted payback as the primary financial variable has been adopted for two reasons. First, it is believed to be the indicator most used by decision-makers in accepting or rejecting building-related technology or other equipment. Second, although related performance indicators such as life-cycle costs or return on investment provide an identical level of penetration if the appropriate curves are used, most decision-makers can readily identify with undiscounted payback.

Each penetration curve indicates that decision-makers will switch from a given technology to another (or choose an additional technology) on the basis of different financial criteria. The shape of the curve represents the dispersion of the decision-makers' attitudes toward the financial variable. The nature of the decision-maker and his desired rate of return on investment also determine the shape of the penetration curve. A commercial building will generally require a higher rate of return (and thus a shorter payback) on investment than would an institutional building. For this reason the payback penetration curve for the institutional building market is expected to lie to the right of and above the payback penetration curve for the commercial building market.

Non-financial Variables

Although payback (PB) and first cost (FC) are often the most important variables in determining the degree of technology penetration, other non-financial variables will have an important impact upon penetration. Non-financial variables included in the Arthur D. Little model are:

Societal

- Resource Renewability
- Certainty of Fuel Supply
- Ecological Effects
- Aesthetic Impact
- Safety

Technical

- Performance
- Reliability
- Technical Complexity
- Space Requirement
- Maintenance

Industry

- Predictability of Installed Costs
- Designer Familiarity
- Code/Zoning Barriers

Different decision-makers undoubtedly will have different attitudes on the non-financial characteristics of the building technologies, because they will attach different importance to the non-financial characteristics. In addition, the influence exerted by a particular decision-maker will differ according to his position, which could be any of the following:

- (1) Owner
- (2) Developer
- (3) Architect/Engineer
- (4) Financier
- (5) Constructor
- (6) Occupant
- (7) Society

Some non-financial characteristics relate to concerns about such things as reliability, maintenance/complexity, and predictability of installed cost. Others relate to the ability or inability of the devices to fulfill other objectives (e.g., take little space or be aesthetically pleasing).

To see the effect of non-financial attributes on the effective penetration of the new technologies, we must first estimate the relative importance of the decision-makers in each of the markets and then estimate the relative importance of the various non-financial and financial characteristics of the model to the selection of that particular device technology.

Each of the three conservation options, the solar energy devices, the advanced technologies, the electric heat pump, and the gas heat pump are rated with respect to their non-financial characteristics. It is assumed that the ratings will vary over time; for example, a device that gets an early negative rating because of poor reliability could receive a positive rating later if its reliability improves. All ratings are indicated in units from +5 to -5. A rating of 0 implies a neutral attitude toward the device with respect to conventional technology.

The data for the non-financial ratings were developed by Arthur D. Little staff members with an expert knowledge of the various market sectors and of the new technologies. Delphi round scoring techniques were used to produce the actual rating values. The format for showing the rating is depicted in matrix form in Table 2-1. The ratings in row-column form are referred to as matrix T (15 by 10; i.e., 15 rating categories, 10 technologies).

In addition to developing the ratings for each technological device reflected in matrix T, the decision-makers' influence on and interests in the decision must be developed. Again, these weighting estimates were made by a team of Arthur D. Little staff members who have an expert knowledge of the building industry. The results were also adjusted using Delphi interactions among the participants.

Table 2-2 illustrates the format for displaying the relative weightings of the seven classes of decision-makers within the 17 building markets as matrix A (7 by 17). The relative importance of each of the technological device characteristics within the context of device acceptance was developed for each class of decision-maker. The weightings of device characteristics are represented as matrix B (7 by 15), as depicted in Table 2-3.

An additive utility functional form is assumed for the non-financial, aggregate and weighted attractiveness of each technology and each market in order to manipulate the A and B matrices to indicate the influence of the characteristic on the building markets. The two financial attributes PB and FC (payback and first cost) must be eliminated from the computation. Matrices B and T should be replaced by B' and T', which are the same matrices without the financial attributes included (B' is 7 by 13 and T' is 13 by 10). The net result of multiplying A and B' becomes:

$$C' = A B' \quad (3)$$

A matrix of utility ratings (unscaled) is derived by postmultiplying the matrix C' by the matrix T'.

$$U' = C' T' \quad (4)$$

U' is a 17 by 10 matrix which indicates the composite non-financial rating for each of 17 building markets of the 10 technologies. U' must be scaled to produce a rating that varies between ± 1.0 . To scale U', it should be divided by 5.0 to rescale the ± 5.0 technology rating in matrix T and T'.

$$U = \frac{1}{5.0} (A B' T') = \frac{1}{5.0} C' T' \quad (5)$$

The utilities of matrix U' are really decision-makers' weighted value estimates of the technologies in the various building markets. Table 2-4 indicates the format of the U matrix utilities ratings. A non-financial utility value exists for each building market and each technology device at any one given time. The range of the utility value is ± 1.0 . A value of 0.0 implies neutrality of non-financial attitudes with respect to current attitudes on conventional technology. Because the attitudes toward the technologies undoubtedly will change over time, the non-financial utilities have been developed for four time frames: 1977-1980; 1980-1985; 1985-1995; and 1995 and beyond.

TABLE 2-1

ILLUSTRATIVE TABLE OF TECHNOLOGY DEVICE RATINGS BY CHARACTERISTIC – MATRIX T

<u>Technology Characteristics</u>	<u>Technology Devices</u>									
	<u>Electric Heat Pump</u>	<u>Gas Heat Pump</u>	<u>Conservation I</u>	<u>Conservation II</u>	<u>Conservation III</u>	<u>Solar Hot Water</u>	<u>Solar Hot Water and Heating</u>	<u>Solar Hot Water Heating and Cooling</u>	<u>Wind Electric</u>	<u>Photovoltaic Electric</u>
<u>Financial</u>										
1. Installed First Cost										
2. Payback Period										
<u>Societal</u>										
3. Non-depleting										
4. Certain Fuel Supply										
5. Ecologically Sound										
6. Aesthetically Pleasing										
7. Safety										
<u>Technical</u>										
8. Performance										
9. Reliability										
10. Technical Complexity										
11. Space Requirements										
12. Maintenance										
<u>Industry</u>										
13. Predictability of Installed Costs										
14. Designer Familiarity										
15. Code/Zoning Barriers										

Format Illustration; values range between ± 5 .

Format Illustration; values range between ± 5 .

TABLE 2-2

ILLUSTRATIVE TABLE OF DECISION-MAKER WEIGHTINGS IN THE BUILDING MARKETS – MATRIX A

		<u>Decision-Makers</u>						
<u>Building Market</u>		<u>Owner</u>	<u>Developer</u>	<u>Architect/Engineer</u>	<u>Financier</u>	<u>Constructor</u>	<u>Occupant</u>	<u>Society</u>
<u>Single-Family</u>								
Custom New								
Spec New								
Retrofit								
<u>Multi-Family</u>								
Rent New								
Condo New								
Rent Retro								
Condo Retro								
<u>Mobile Homes</u>								
New								
Retro								
<u>Commercial</u>								
Owner/Occ. New								
Owner/Leased New								
O/O Retro								
O/L Retro								
<u>Institutional</u>								
Public New								
Private New								
Public Retro								
Private Retro								

Format Illustration, entries range from 0-100%.

TABLE 2-3

ILLUSTRATIVE TABLE OF WEIGHTING OF DEVICE CHARACTERISTICS BY DECISION-MAKER – MATRIX B

<u>Technology Characteristics</u>			
<u>Financial</u>	<u>Societal</u>	<u>Technical</u>	<u>Industry</u>
Installed First-Cost Payback Period	Non-Depleting Certain Fuel Supply Ecological Effects Aesthetic Impacts Safety	Performance Reliability Technical Complexity Space Requirements Maintenance	Predictability of Installed Costs Designer Familiarity Code/Zoning Barriers

Decision-Makers

- 1) Owner
- 2) Developer
- 3) Architect/Engineer
- 4) Financier
- 5) Constructor
- 6) Occupant
- 7) Society

Format Illustration, values range from 0-100%.

TABLE 2-4

**ILLUSTRATIVE TABLE OF AGGREGATE UTILITY RATINGS OF TECHNOLOGY DEVICES
FOR EACH BUILDING MARKET – MATRIX U**

<u>Building Market</u>	<u>Electric Heat Pump</u>	<u>Gas Heat Pump</u>	<u>Conservation I</u>	<u>Conservation II</u>	<u>Conservation III</u>	<u>Solar Hot Water</u>	<u>Solar Hot Water and Heating</u>	<u>Solar Hot Water Heating and Cooling</u>	<u>Wind Electric</u>	<u>Photovoltaic Electric</u>
<u>Single Family</u>										
Custom New										
Spec. New										
Retrofit										
<u>Multi-Family</u>										
Rent New										
Condo New										
Rent Retro										
Condo Retro										
<u>Mobile Homes</u>										
New										
Retro										
<u>Commercial</u>										
Owner/Occ. New										
Owner/Leased New										
O/O Retro										
O/L Retro										
<u>Institutional</u>										
Public New										
Private New										
Public Retro										
Private Retro										

Format Illustration, range is ± 1.0 .

The utility value aggregated over all decision-makers and technology device characteristics is used to adjust the payback penetration levels. Eq. 6 indicates the factor used to adjust penetration on the basis of the aggregate non-financial utility value.

$$F(U_{ij}) = \frac{N}{1-N} \cdot \frac{U_{ij}}{2} + 1 \quad (6)$$

where

- i = building market index $i = 1, \dots, 17$
- j = technology device index $j = 1, \dots, 10$
- N = weighting of the non-financial technology device characteristics
- U_{ij} = utility value for technology device j in building market i .

The total penetration of a particular device in a given market is thus estimated by the product of the two penetration functions and the utility factor:

$$P_{TOT}(FC;PB;U) = P_{FC}(FC) \cdot P_{PB}(PB) \cdot F(U_{ij}) \quad (7)$$

The function $F(U_{ij})$ can modify the total effective penetration by as much as $\pm 50\%$ when $U_{ij} = \pm 1.0$ and $N = 0.5$ (50/50 financial/non-financial weighting). The general effect of the utility aggregation is to average out the ratings and decision-maker preferences. Consequently, the typical aggregate utility will not be rated near ± 1.0 but will tend to reside much closer to 0.0 and thus have only a minor influence on the level of penetration.

Multi-Device Logic

Among the ten technology options (three conservation categories, two heat pumps, three solar systems, photovoltaic, and wind power) considered by the residential and commercial building sectors, some are complementary and some are mutually exclusive. For example, it is possible to choose a conservation technology package and also a solar hot water installation; it is not possible to choose both solar hot water and solar hot water and heating for the same building. The concept of a penetration curve relates to a binary selection between a conventional or base technology and an "advanced" technology. The payback and first cost are estimated, in fact, relative to the level required in the base technology choice. If there are two or more devices, the choice becomes a tertiary or higher dimensional choice and the penetration approach fails.

The best way to address the mutually exclusive technologies is to develop an allocation procedure based upon the performance and penetration characteristics developed with and for the binary penetration curves. The approach taken to the market penetration of mutually exclusive technologies is to consider them sequentially in order of increasing first cost.

The approach uses the concept of marginal or incremental payback — defined as the ratio of the incremental first costs to the incremental annual cost savings. A marginal payback is always defined relative to two specific technologies. The simple payback calculated in Eq. 1 is a marginal payback in its own right, because it represents the ratio of incremental operating cost and additional or incremental installed first costs with respect to the conventional heating and cooling systems. Values of marginal payback exist between any two technologies under joint consideration. Consider the example of three solar energy technologies — 1, 2, and 3 referred to in Table 2-5.

The general formula for marginal payback is:

$$MPB = \frac{\Delta FC}{\Delta OCS} \quad (8)$$

The procedure can be described mathematically as follows. Consider a penetration vector $P = [P_\phi, P_1, P_2, P_3, \dots, P_M]$ where P_ϕ is the "null" or conventional device penetration value — the fraction of those who choose no technology option. For all other i 's, the P_i values represent the penetration for the new technology devices. By definition:

$$\sum_{i=\phi}^M P_i = 1.00$$

where:

- i = technology index
- M = number of mutually exclusive technologies
- ϕ = conventional or "null" technology choice.

The penetration of each of the new technologies is developed by using an allocation method which recognizes that the decision-makers will move to more complex technologies from the simpler ones if the incremental advantages are clearly present. The method outlined in Appendix A uses the device payback values and the between-device marginal payback values. The procedure works in stages or passes and would appear as shown in the example of Table 1 in Appendix A.

Incentives and Policy Options

The Arthur D. Little model was designed to compare the penetration of building technologies with and without various types of federal government financial incentives such as:

- Tax credits on the purchase of conservation or solar equipment.
- A surcharge on the use of oil (or natural gas).

TABLE 2-5

EXAMPLE OF MARGINAL PAYBACK CALCULATIONS

Solar Device	First Cost	Annual Operating Cost Savings	Payback	Marginal Payback	
				1 Step	2 Step
1	$FC_1 = \$1000$	$OCS_1 = \$300$	$PB_1 = \frac{1000}{300} = 3.33$	---	---
2	$FC_2 = \$2000$	$OCS_2 = \$500$	$PB_2 = \frac{2000}{500} = 4.00$	$\frac{FC_2 - FC_1}{OCS_2 - OCS_1} = \frac{1000}{200} = 5.0 = MPB_{2,1}$	---
3	$FC_3 = \$4000$	$OCS_3 = \$800$	$PB_3 = \frac{4000}{8000} = 5.00$	$\frac{FC_3 - FC_2}{OCS_3 - OCS_2} = \frac{2000}{300} = 6.67 = MPB_{3,2}$	$\frac{FC_3 - FC_1}{OCS_3 - OCS_1} = \frac{3000}{500} = 6.0 = MPB_{3,1}$

In addition, the model has investigated such effects and policy options as:

- Improved market response
- Cold weather cycle
- Low natural-gas fuel price
- Mandatory conservation policies.

Implementation of tax credits has been simulated by adjusting installed first costs in the penetration portion of the model. The installed first cost is lowered to the point where it reflects the perceived cost to the decision-maker in light of the available tax credit. From this point of view, a tax credit has a different impact than would a direct subsidy grant.

Surcharges or taxes on fuels have been incorporated into the fuel prices as have scenarios of unexpectedly low fuel prices. Cold weather cycle scenarios have been simulated by increasing the building heating loads for one period and noting the response.

Improved market response has been implemented by replacing the penetration curve with one that has a more favorable payback response. The relationship between improvement in market response and the extent of government actions (education, advertising, etc.) has been quite difficult to assess. Development of a reliable relationship between non-financial government actions and market response is an effort which was deemed to be beyond the capabilities of the model. The cost of government incentives has been determined with the Arthur D. Little model, however. Likewise tax revenues from surcharges on fuels have been estimated.

The last policy options considered were those requiring mandatory use of various technologies. The model considered such policy options; further it estimated the effect that such regulatory actions would have on energy savings, cost, and the adoption of other technologies.

3. RESIDENTIAL/COMMERCIAL MARKET*

3.1 THE BUILDING INDUSTRY

Background

The construction industry is large, diverse, and complex. The total value of construction work put in place in 1976 was \$144.4 billion, and represented 8.5% of the Gross National Product. The industry can be divided into three broad sectors, each with about a third of the industry's total dollar volume. These sectors are residential (homes and apartments), non-residential (commercial and institutional buildings), and non-buildings (roads, dams, sewers and water-works, etc.). The non-building sector is not considered in this study.

The building inventory accounts for about 25% of the total energy consumption in the United States. Changes in building design with the installation of novel energy-related technologies have the potential to affect national energy demand substantially. Subtleties in building design and orientation, the energy use patterns of the individual occupant, broad climate variables, and the type of fuel used all affect energy consumption. Because there are so many variables that affect the way buildings are designed and built and how they use energy, it is quite literally true that the decision to invest in energy-related technology is different for every building.

Building Process and Participants

An understanding of the dynamics of the building process as a whole is essential in determining industry response to new technologies. The range of participants is broad, and the process itself is complicated, with numerous decision points from first perception of need to final use of the product, whether it be a completely new structure or the addition of a new energy system to an existing building. The participants have different roles in both the design/construction process and the decision-making process of the various markets. Some of them may not be directly involved in actual construction, but may nonetheless have a major influence on the application of a new technology.

Every design/construction project, whether the building of a major skyscraper office tower or the remodeling of a modest single-family home in the suburbs, might be viewed as having five discrete stages:

- conceptualization
- design
- approval
- construction
- occupancy

Conceptualization — This is the first stage of a project, during which certain participants conceive of the building or modifications to it, and, by discussion with other industry participants, begin to define the building's characteristics. Conceptualization also includes preliminary

* A more detailed version of this section has been printed separately as *Residential/Commercial Market for Energy Technologies*, August 1979.

information-gathering concerning preliminary design concepts, financial viability, preliminary cost estimates, and applicable zoning and code regulations.

Design — This stage begins with the owner or developer conveying his program or concept to the designer. The designer may need to confer with contractors, cost estimators, and code and/or zoning authorities. For larger projects, interim design review meetings between the client and his designers are common in order to ensure that the project is meeting the client's needs.

Approval — At the final design review meeting the designer presents the plan and the owner or developer accepts. This might involve a formal meeting with drawings, models, and cost estimates that could subsequently be presented to the construction- and long-term lenders for their approval in the form of loan commitments. Similarly, construction permits must be approved by appropriate municipal, state and/or federal authorities.

Construction — This stage begins with the establishment of a contract between the owner or developer and the constructor to perform specific tasks, under specific terms, usually for a specific price. During construction, inspections will be made by the architect and building inspectors, and progress payments will be made by the construction lender as predetermined project milestones are reached.

Occupancy — When the completed project is delivered to the owner, the roles of other participants change or terminate. After the building has passed inspection, the constructor (general contractor or installer) receives a final, previously withheld, payment. After a certain level of occupancy is achieved (or the property is sold to an owner), the construction loan is paid and long-term financing, in the form of a mortgage, is established.

Although the five stages of the prototypical design/construction process are described above as sequential, "feedback loops" make the process more simultaneous than sequential when viewed over time. The concept of the *de facto* simultaneity of inputs by the various decision-makers is a key assumption for the market acceptance model.

Operating across the five stages of the building process are the participants who play six principal roles:

- owner
- developer
- designer
- financier
- constructor
- society

Owner — The owner is the ultimate authority in all retrofit and new construction decisions. The owner is likely to own and operate a building for a long time, and therefore will be concerned with its operating costs and convenience. Reliability, performance, ease of maintenance, and other considerations will be important criteria for decisions related to energy technology. The initial cost of an energy system will be of primary importance, particularly if the owner has poor access to capital.

Developer — The developer has authority in speculative projects, particularly in the conceptualization phase. His decisions are heavily influenced by his perceptions of the ultimate owner's needs. Because the developer uses a great deal of borrowed capital relative to his equity investment, he is very sensitive to any risk that could make his project less marketable and therefore slower to sell. Any modification to a building that increases its selling price, and potentially decreases its marketability, may be rejected solely on the basis of increased capital cost. Because the developer no longer has a financial interest in the building after it has been sold, operating cost savings and convenience seldom influence his decisions.

Designer — Responsibility for all aspects of planning the project falls to the designer. Depending on project size, this could include land-use studies, site planning, architecture, and all structural, mechanical, and electrical engineering requirements. For large projects, many design professionals would be employed, often from several different firms. Unless capital or operating costs are explicitly stated by the client as being important criteria for the project, most designers will place more emphasis on architectural form, interior design, structural integrity, and/or system performance as criteria for design decisions.

Financier — The non-equity capital for each project is provided by the financier, who seeks as high a return on his investment (with as little risk) as the market will allow. Construction lenders provide capital to pay the contractor for labor, management, and materials during the construction phase. After the project is built and perhaps partially sold or leased, the construction loan is repaid with the principal from the long-term lender's mortgage. Capital cost is not an explicit criterion for a financier. Any incremental investment that does not increase total project risk should be acceptable, although reduced marketability of a speculative project or the inability of the borrower to meet his debt service obligations might increase total project risk. Because the financier often places considerable emphasis on the risk of not being able to resell the property if the borrower defaults, he may refuse to loan on energy-saving improvements. Financiers rely on independent appraisers to establish the "market value" of a building, and "the market" has only recently perceived "the value" to the building owner of energy efficiency. With increasing energy costs, energy efficiency is expected to have increased market value.

Constructor — The constructor, usually a general contractor, provides some of the trades necessary to construct the building, but also manages several independent subcontractors who provide special skills. On large, complex projects, the general contractor may devote more effort to project management, cost control, and coordination of his many subcontractors than to supervising the trades he brings to the project. Because most construction work is performed on a fixed-price contract, the constructor will avoid buildings or systems that are unfamiliar, unreliable, or unusually complex, and therefore have unpredictable installed costs. The operating cost of a system or a building is of no concern to a constructor.

Society — Society includes local code and zoning authorities, and state or federal environmental and energy regulatory agencies, whose principal role is to ensure that the building's design and concept are in the public's best interest. By inspecting and approving individual projects, these agencies control the building process within fairly wide boundaries. Because these decision-makers represent society as a whole, their concerns are often different from those of the other five key participants, most of whom have a financial interest in the project under consideration. Societal decision-makers place more emphasis on safety (building codes), land use (zoning), ecology (environmental protection), and energy-related issues. Societal involvement in the building industry is certain to increase in the future.

General Characteristics of the Building Industry

The typical building process and the roles of its principal participants vary widely as a function of market sector. Certain characteristics common to most segments of the building industry, however, affect the applicability of new energy technologies. The most notable of these are:

- Diversity and Fragmentation
- Need for Segmentation
- Conservatism or Inertia

Diversity and Fragmentation — Although the industry is consolidating and maturing, it is doing so at a very slow rate and from an infinitesimally small base. It is unlikely that any industry participant will control as much as 1% of the total building market within the next decade. The implication of this fragmentation is that technologies must be sold to thousands of decision-makers. Since participants have different biases and different criteria for decision-making, promotional and marketing efforts must be broad and flexible.

Market Segmentation — Generalizations that may be appropriate for parts of the industry are rarely applicable to the entire industry. Much has been said about the influence of the trade unions in retarding industry development. Although this may be applicable in some parts of the commercial market, 70% of the labor in the housing sector is non-union. Similarly, it is often stated that the industry uses construction and management techniques of the 1800s. Actually, the construction industry includes many major companies using highly sophisticated management and technical tools. The more the industry is broken down into segments, the more rational it appears to be. Opportunities can be identified and appropriate strategies developed only when the industry is subdivided and analyzed in detail.

Conservatism of the Industry — Practically all markets and all participants in the building industry are conservative, or have a high degree of resistance to change. There are four principal reasons for this conservatism:

Liability — Architects, builders, and sub-contractors are, directly or indirectly, responsible for the work they produce. With existing systems and practices that have withstood the test of time, the contractor has a high degree of confidence that the chances for defective work or serious liability are minimized.

Costs — To use a new material or system requires an investment in learning as well as an investment in detailing and writing specifications. It may also require new equipment and different suppliers. When a contractor has the choice of bidding an established technique or a new one, he usually will bid the established technique, since he will probably then have a lower bid.

Lack of Information — Because the industry is so fragmented, it takes a long time for information about new products to get through the whole system. Communication of new ideas is usually from architect to architect and from builder to builder, based on experience rather than on promotion.

Codes and Unions — The constraint to change created by codes and unions is overstated and is often used as an excuse when product or company deficiencies are the

real cause of failure. Nevertheless, good products must still find their way through a maze of code and union constraints. While there are national code and union groups that may approve new materials or systems, the principal control remains at the local level, where the status quo is often supported because of inexperience or vested interests.

3.2 MARKET SECTORS

Although the residential and commercial (R/C) building markets have a number of characteristics in common, the industry is in fact so diverse that neither a precise image of the decision-making process within it nor an accurate estimate of overall market acceptance of energy technologies can be achieved without some disaggregation. We have adopted the following as primary market sub-sectors:

Residential

- Single family
- Multi family
- Mobile home

Commercial

- Prestige commercial
- Commodity commercial
- Institutional

Some of these sub-categories differentiate on the basis of structural type and others on the basis of building use. Building use will typically be important in a discussion of decision-making processes; building type will be important in discussing energy use patterns.

Residential Market

In 1975, the residential housing inventory of 75 million units was estimated to have accounted for 75% of energy demand for the R/C sector. Although these housing units have similar energy-consuming characteristics (within a region), there are notable differences in their receptivity to new energy technologies.

Single-Family Market

The single-family market is the largest residential sector in terms of number of units produced and value of work performed. It is also the most dispersed, fragmented, and difficult to understand. Furthermore, statistics for single houses include structures (e.g., townhouses and attached single-family houses) that some would perceive to be multi-family but from an ownership, and therefore from a decision-making, basis are in fact single-family residences.

The key to the success of new energy systems in new single-family houses is the builder rather than the consumer, especially in the non-custom sector of this market. In 1976, 59% of the single-family structures were speculative and 41% were custom built. This pattern has not changed significantly in the last 10 years, nor is it expected to do so in the years ahead.

There are four types of builders: the large developer, the medium developer, the small builder, and the do-it-yourselfer.

Large Developer — About 40 developers build more than 1000 houses per year, but they accounted for only 6% of the total single-family houses built in 1976. They will build an increasing number of houses in the next decade (perhaps as many as 15% of the total). The large builders are

well financed, extremely sophisticated and well managed, and are often public companies or divisions of large companies in which earnings are crucial and growth is imperative. Most of the major decisions and most of the problems of the developer are those relating to buying the land, planning the subdivision, getting zoning, etc. The actual construction of the house is the simplest part of the task and the one to which he devotes the least attention. The large builder is totally market-oriented. His crucial task is to put the right house on the land and turn it over quickly. He does not want to experiment with new styles, new designs, or new production methods, and avoids technology that commits the house to a certain style or a certain size, because this inflexibility will cut his marketing opportunities and tie up his investment. Furthermore, because of his financial exposure, the large builder will tend to use systems or devices only after they have been proved, when he is sure that the hardware can be installed easily and will not require correction. The large builder will be a candidate for energy technologies with higher first costs only if they (1) enhance sales opportunities; (2) are acceptable to financial institutions, insurance companies, and code authorities; and (3) are in simple packages, installable by present subcontractors. The builder may experiment with new products, such as energy-conserving systems, as options before they have wide market acceptance. The builder may also be attracted by the potential public relations impact of energy technologies and may install a solar system, for example, in a demonstration home just to get people to come to his development.

Medium Developer — Approximately 400-500 medium tract builders build between 100 and 1000 houses with an average of 350 units per year, producing approximately 10% of the single-family housing. Most of the firms in this category operate within one region, even though they have multiple sites, and are thus sensitive to regional economic conditions. They have less staff in the planning, marketing, and production functions than the large developers, and typically have far fewer financial resources.

Because they are more exposed to the vagaries and cycles of the construction industry, they tend to be followers, rather than leaders and to be more cost-sensitive than the giant builders. On balance, this group is slightly less likely to be interested in new energy technologies than the large developers.

Small builder — The nearly 1000 builders in this category build fewer than 100 units for sale per year, with the average about 25 units. The average is much lower (4-8 per year) for those who do not serve the custom market.

Among this group of builders, those who participate in the speculative segment are least likely to support new products or systems. In any case, they are not attractive candidates from the suppliers' point of view because the number of houses over which each exercises control is small, they are dispersed geographically, and the cost of educating them is great. Some of these builders may actively seek information on new technologies, however, because they are technically curious, socially concerned, or see the products as a gimmick.

The custom builders in this category represent a better target for new systems. Perhaps 20% of the custom houses are relatively expensive, prestigious structures often designed by architects and incorporating the latest amenities. This portion of the custom market accounts for approximately 100,000 units per year. It is an excellent start-up area for new energy technologies and many of these owners are concerned with such causes as energy conservation. Their houses are often prototypes of new construction concepts and the foundation for further market devel-

opment. Successful houses may be widely publicized in the popular press as well as in the trade press. This market does not require a packaged system. An architect can work with the consulting engineer to buy components and put them together on the job.

Do-It-Yourself Builders — The do-it-yourself market, while twice as large as the high-cost portion of the custom market, is less likely to be a candidate for higher-cost energy technologies. Nevertheless, the owner-builders in this category include a number of innovators or experimenters who represent a strong potential market for new products.

Multi-Family Market

The multi-family market includes structures from small, several-unit apartments in suburban areas to very large several-thousand-unit high-rise buildings in urban areas. The multi-family market has fewer active builders and is more consistent than the single-family segment. There is little consistent published information on this market; the Department of Commerce began publishing data for the multi-family market only in 1974. Furthermore, there is statistical confusion about what comprises the multi-family sector. The Bureau of Census considers most row houses as single-family units, but two-family houses with living units on different levels as a multi-family structure.

The definitional problem has been further obscured by the advent of condominiums. Since a condominium is a concept of ownership, rather than a structural type, it can be any type of for-sale housing except a single-family detached unit. Most condominiums, however, are units within buildings of five or more units and thus are classified as part of the multi-family market.

About 15,000 builders are active in the multi-family market, 10% of whom are estimated to build 75% of the total production. The builder is responsible for the specification and purchase of 90-95% of the products used in multi-family structures. The roles of the architect and the subcontractor in the buying and specification process are relatively limited.

Most multi-family developers are not in a position to experiment with new product systems or materials. The focus is on maximizing the rentability or salability of the project at the minimum possible capital cost.

The growth of the large single-family builders has been accompanied by their entry into the low-rise multi-family market. Thus, the major decision makers in the multi-family market will be the same as those in the giant developer category of the single-family market.

Another issue with significance for energy technologies is the ownership of multi-family structures whether the multi-family units are to be condominiums or apartments. The reaction to energy technologies will differ in each case. If the builder intends to retain an apartment property for rental he is likely to pay more attention to the impact of design decision on operating costs. He may have a straightforward financial motivation for considering the installation of energy-conserving systems when he pays the utility costs. Where the developer does not retain ownership, his interest in keeping operating costs low is not a major consideration. In the speculative or contract project, the builder/developer's prime motivation is to keep the total project cost down rather than to achieve a capital/operating cost balance, because his profits will be a function of how well he does so.

The condominium concept has achieved rapid nationwide acceptance in the last several years. Few condominiums were built before 1970, but in many urban areas, condominiums account for over 75% of new multi-family starts. In addition, an unknown number of apartment projects have been converted to condominiums in recent years. This has significant implications for the new energy technologies. Because the eventual occupant of a condominium unit will have to pay the long-term operating costs of his unit, he can be expected to be more sensitive to the advantages of energy-conserving technologies.

Mobile Homes

Mobile homes are a significant part of the residential housing industry, and constitute a far more consistent and homogeneous market segment than any other in the residential sector. The industry has 250-300 producers, compared with more than 150,000 residential builders, though it is likely that there will be fewer than 200 producers by the end of the decade, with the 10 largest producers controlling an ever-increasing proportion of production. In order to maintain growth and profitability, the most successful firms are becoming integrated from the manufacturing level through distribution, retailing, and even land control. In the mobile home sector, the manufacturer is the primary decision maker. Mobile homes are standardized units and the manufacturing process does not allow the same flexibility in design or variety of influence (particularly consumer preference) that characterizes other building sectors.

One of the major selling advantages of mobile homes has been the low initial cost — a 5-10% down payment compared with 20-40% on conventionally financed housing. Operating costs do not show a similar advantage, however. Because most mobile homes are financed through short-term high-interest chattel mortgages, the monthly interest and principal payment on a mobile home may be almost as high as that for a single family house. Furthermore, while the market value of the mobile home can be expected to depreciate sharply over its life, the value of a conventionally built home ordinarily increases. Thus, an immediate incompatibility arises between the application of many new technologies and mobile homes. The manufacturer and purchaser of mobile homes try to minimize capital cost at the expense of monthly costs, whereas many new energy-conserving technologies require a high capital investment with the advantage of lower monthly operating costs. Nevertheless, the mobile home industry has shown a willingness to experiment with new products or systems, if these products do not increase first costs. An energy technology that can be mass-produced in standard sizes with attendant cost economies, and that can develop a market position can theoretically increase its market penetration rapidly.

Commercial Market

The commercial sector includes a wide variety of building uses and construction processes. A prototypical building is seldom representative of a class.

Prestige Commercial

These structures are built for a specific owner who will occupy the building and who, therefore, has a major influence on design and construction. The owner is often a major corporation or bank contracting for its own office building or retail stores. A greater concern for basic amenities than for capital cost lends the name *prestige commercial* to this sector.

Commodity Commercial

Most commercial construction falls into this category of speculatively built structures where the owner's interest is only financial. Because the building is usually basic space for an (often) unknown tenant and the lease rate is a primary consideration, capital cost is an important issue.

Institutional

This sector includes schools, hospitals, and government buildings, which are ordinarily "owned" or financed by public agencies (federal, state, or local) or by nonprofit institutions. This sector has access to relatively low-cost sources of capital and goes through a more formalistic construction process. Within the institutional market the hospital subsector includes not only hospitals — typically four- to six-story structures heavily air conditioned, heated, and with extensive plumbing — but also small nursing homes, which are similar to single-family structures. The hospital category also includes suburban medical centers, which are physically much more like a small office building than a hospital. The same kind of inconsistency between use and characteristics is evident in all of the use markets described above.

Building Process

Three contracting procedures are common for non-residential buildings, with the type employed often dictated by the ownership pattern for the building. The formal contract is usually associated with institutional or public buildings, although some large structures built for occupancy by owners follow the formal bidding procedure. The negotiated contract is common for prestige commercial buildings, while the turnkey process is typical for speculatively built, "commodity commercial" structures.

Formal Contract — In formal contracting the owner enlists an architect to design a building to meet his technical and financial needs. The architect is usually paid a fixed percentage of the value of the job; in turn he pays his consultants, such as the HVAC design engineer, a fixed percentage of the value of his portion of the work. Clearly, the architect and his consultants have little motivation to make detailed studies of all alternative methods of constructing the building. They will tend to use rule-of-thumb guidelines or follow standard techniques they have used before.

In the formal bidding typical of public or institutional construction, the motivation for new energy systems must come from the owner or public agency involved. This market is financed through long-term bonds at low rates that favor capital-intensive energy-conserving systems. In these cases, the awarding agency must instruct the architect to consider or to use the new technologies.

Negotiated Contract — While this process is generally the same as with the formal contract, the relative power and positioning of the participants can be different. The design process also is more iterative; the owner, the architect, and the contractor work together, making compromises among design, appearance, cost, and availability of materials. Usually, the owner and the architect negotiate rather than take the low bidder.

In the negotiated market, the owner or the major corporation may consider a new energy technology for economic or public relations reasons. The architect or contractor

may also bring the possibilities of the technologies to the attention of the owner. Alternative schemes may then be designed and the economics compared. Here new technologies will have a reasonable chance to be considered fairly.

Turnkey — A “turnkey” builder, or joint venture group consisting of architect, engineer, and builder/developer, designs and builds a structure for the owner under a single contract. The turnkey builder bids on a package; when the job is done the builder “turns over the key” and the owner moves in. In this case the architect and consultants are subservient to the builder/developer who may use the cheapest, or at least economical, designs and modest mechanical systems.

In this situation, capital-intensive energy technologies will have the least opportunity, because first costs are crucial to the turnkey developer and he has the least incentive and the most liability in spending money on alternative designs.

Role of the Architect/Engineer

In all market sectors the role of architects and engineers in the acceptance of new energy technologies is one of responsiveness to the desires of the client/owner. While the architect/engineer has the most information on building design technology, the major influence regarding the cost and/or mechanical complexity of a project ultimately rests with the owner.

Architect/engineers can, however, play a more significant role in the selection and cost of building systems. For example, as the building industry becomes more aware of energy cost and availability, the mechanical engineer has been given more responsibility for energy-conserving mechanical systems and schemes. The owner must then make better long-term decisions concerning initial cost/annual savings trade-offs.

In terms of influence, design firms (particularly those with engineering staffs) are generally critical in the selection of energy systems, although in certain types of structures the desires of the owner prevail. Their influence might be summarized according to the following schedule:

Strong Influence:	Typical Process
Multi-Family High-Rise	Turnkey
Office Buildings, Prestige	Negotiated
Schools	Formal
Hospitals	Formal
Government Buildings	Formal
Moderate Influence:	
Shopping Centers	Turnkey
Office Buildings, Commodity	Turnkey
Motels	Negotiated
Occasional Influence:	
Multi-Family, Low-Rise	Turnkey
Industrial Plants	Turnkey

The architect plays only a minor role in the actual design and selection of most energy systems. Introduction of new systems will probably continue to be chiefly the responsibility of the engineer.

The design process by which HVAC systems are selected for large residential and commercial buildings commences with a preliminary estimate of the heating and cooling loads of the building, which are usually based upon some form of architectural schematic. A preliminary HVAC system is then selected based upon the functional, capital cost, and operating cost considerations of each of several alternative systems. If the engineer is to consider a new energy system, it must be during these preliminary steps.

Mechanical and electrical engineers associated with the building industry have a keen interest in strengthening their knowledge of the effectiveness of new energy technologies. The building industry as a whole is aware of the initial cost of HVAC and other mechanical systems, but the operating costs of such systems have been largely overlooked. Owners are beginning to pressure the engineer to reconsider implications of his design for annual energy costs.

A preliminary set of schematics and specifications for the system and its estimated capital and operating costs is compiled prior to a review by the architect and owner. For new energy systems, configurations must be selected and accompanied by supporting information on installed cost and energy consumption effects.

The engineer next works out the final HVAC system design by revising the heating and cooling loads to accommodate architectural developments since the preliminary calculations were made. At this point, some consideration is usually given to identifying the operating costs (i.e., energy consumption) of the particular system selected. The inclusion of a new energy system within a project would probably require a more concerted effort to identify the cost relationships between the new system and the more typical "conventional" system.

Once the system has been designed, the firm produces a set of working drawings accompanied by a set of equipment specifications describing the conceptual configuration and performance requirements of the HVAC equipment. Manufacturers generally provide assistance to the engineer in the form of technical representatives, design catalogues, and various standard engineering details. Initially, manufacturers of new energy systems must make a substantial effort to provide such information.

The final steps in the design process are rather routine, and should not be affected by the introduction of a new system into the project, although the absence of an historic data base on the material and installation costs of new systems components results in a high degree of uncertainty on the part of the bidding contractor. He may therefore be extremely conservative in costing out the installation of new products, with a resulting high overall systems cost. In order to overcome this conservatism, manufacturers at first may have to guarantee their installed cost.

In completing his responsibilities, the engineer reviews the detailed shop drawings submitted by the suppliers, acts as the architect's agent in supervising the actual construction and start-up of the mechanical systems, and recommends the acceptance of the building by the architect/owner. Introduction of new energy systems will be achieved more readily and with greater success if the mechanical design of a given project is managed by engineers with a reputation for inventiveness and capacity to design unique or complex mechanical systems.

The pressures of the energy crisis have fostered a reevaluation of the types of HVAC systems and equipment selected for use in most buildings. Estimates on how much energy could be saved

in heating and cooling and domestic water heating generally ranged between 20-30%, implying that the first step under conditions of constrained energy availability should be to reduce nominal building use. The cut in energy consumption would perhaps alleviate energy pressures without more complicated new energy systems. This attitude, however, assumes that the costs of conventional energy will remain relatively low; a significant rise in these costs presents a strong economic argument for entirely new systems and additional conservation measures.

The reservations of design engineers concerning new energy technologies have been directed toward capital costs and the payback periods associated with them.

3.3. ENERGY CONSUMPTION CHARACTERISTICS OF MODEL BUILDINGS

Estimates of the unit demand for energy by end use (heating, cooling, etc.) have been used as the basis for projections of energy consumption in buildings. Derived "average" values represent a widely diversified data base. "Prototypical" buildings are not representative of all the structures within a particular category, but are useful in determining the key variables that affect energy use.

Residential Demand

Prototypical buildings were defined on the basis of their energy-consuming characteristics and the annual energy consumption of the average unit built in the base year of 1975 was estimated. An analysis of identifiable differences in the design of the typical inventory house (e.g., average area of 1300 square feet for an inventory house vs. 1560 for the new house) enabled us to design prototypes, not only of the new buildings being added to the inventory, but of the units in the inventory in 1975.

Unit demands in each region were established for the following types of living units:

- Single-Family, Detached
- Single-Family, Attached
- Multi-Family, Low-Rise
- Multi-Family, High-Rise
- Mobile Home

Space heating is the largest consumer of energy in the residential sector and its dominance is expected to continue. It is the area in which reductions in unit demand can be most significant on a national basis.

Air conditioning (compared with heating) is a relatively small but highly visible consumer of energy in the residential sector. The use of residential air conditioning has grown rapidly in recent years, with 45% of new single-family homes built with central air conditioning and almost 85% of new multi-family structures having room or central units. The average consumption of electricity for cooling is expected to increase over time, although air conditioner efficiency will continue to improve as a result of industry and government labeling and efficiency regulations.

Unit demands for water heating were based on the requirement of 20 gallons/person/day. Over time the per-unit energy consumption for water heating will be affected by design changes, appliance-generated loads (dishwashers and clothes washers), and family size. These factors are

expected to counterbalance each other, and in the reference case per-unit energy consumption for water heating is assumed to remain constant.

Appliances account for approximately 10-12% of total residential energy consumption, with increased market penetration of such major appliances as ranges, television, refrigerators, and dishwashers and proliferation of such minor convenience items as electric can openers, toothbrushes, and carving knives. These minor appliances account for less than 1% of total residential energy consumption. Dramatic reductions can come only from design improvements to increase the efficiency of the major appliances.

Commercial Demand

As in the residential sector, commercial energy demand is defined by comfort conditioning. Estimates in this sector, however, are far less firm than in the residential sector, where selection of the model structures was the critical variable in determining unit demands. In the commercial sector there is a wide variance not only among building types within a particular category, but also among HVAC systems.

Unit demands were established for each of the following types of buildings:

Office Buildings: General office space, public and administration buildings, etc.

Retail Establishments: Urban and suburban commercial stores, and other merchandising activities.

Schools: Classrooms, laboratories, libraries, and related institutions on all levels.

Hospitals: Hospitals, clinics, and other intensive medical care facilities.

A fifth category (Other Buildings) includes hotels, motels and dormitories, amusement and recreational facilities, and religious buildings. It has been assumed that this category is equivalent to retail establishments in terms of energy consumption.

Space heating requirements were calculated, taking into account the high internal loads common to commercial buildings. A reduction in heating requirements was accounted for by crediting 40-60% of the emitted heat from the lighting fixtures to the heating of the perimeter zones, (20-60% of the total floor area of the building) over the heating season.

Unit demands for cooling were based upon an accepted, but approximate, procedure by which the unit area per ton of air conditioning is estimated from field data for a particular building type. This information is published by manufacturers of air conditioning equipment, and once the connected kilowatt load per square foot is derived, it is multiplied by the equivalent full-load operating hours to determine unit demand.

Water heating is assumed to be a minor requirement in all buildings but hospitals. Restaurants use moderate amounts of water but represent a small proportion of retail stores. Daily per-capita demand was assumed to be 0.5, 2, 5, and 60 gallons, respectively, for retail establishments, office buildings, schools, and hospitals. The unusually high hot water demand for hospitals includes domestic washing, food service, laundry, and sterilization.

Lighting levels within commercial buildings are typically designed according to recommendations of the Illuminating Engineering Society (IES). The connected electrical loads required to support these levels are a function primarily of the type of lighting selected for the space; for example, incandescent lights are less efficient (in lumens per watt) than are fluorescent lamps. Thus, the annual power demand for lighting is the product of the connected load times the building's annual operating hours.

Appliance loads (exclusive of computers and major refrigeration equipment) were assumed to be 25% of the lighting load in office buildings and retail establishments, 20% in schools, and 40% in hospitals, where intensive use of monitoring, signaling, and life-support systems accounts for the higher load.

Only data processing and refrigeration and freezing related to food and beverage distribution were analyzed separately. Minor refrigeration equipment used in motels, schools, hospitals, and other retail establishments was included in the appliance load calculations. Appliances, refrigeration, and data processing equipment are included in the light and power category.

Besides the unit energy requirements for heating and cooling, energy is needed to power the HVAC system auxiliary equipment, i.e., pumps, cooling tower fans, distribution fans, etc. Of all the energy uses within commercial buildings, probably least is known about this auxiliary equipment. Computer models have provided designers and engineers with a stronger tool for examining auxiliary equipment, and published results indicate that it constitutes major demand.

Inasmuch as the approaches taken in the commercial sector to estimate unit demand yielded "prototypical" values, it was necessary to validate these estimates. Approximately 520 buildings were identified from the literature, and reliable end-use unit demand data was available for about 200 of them. In comparing model with field data, it is apparent that:

- Actual unit demands vary considerably, sometimes as much as 400% within the same building types.
- There is no apparent economy of scale to be gained by larger buildings over smaller structures in terms of their annual energy consumption.
- Non-residential space heating accounts for slightly less energy per square foot than the average residence.
- Oil- and gas-fired systems are relatively similar, varying between 10 and 20 Btu/sq. ft/year/degree day. Electric heating is shown to be most efficient when expressed as a site demand, and is a consequence of an abnormally high site efficiency (all the inefficiency is at the point of power generation), and a standard of construction usually superior to that for buildings utilizing fossil fuel systems.
- Energy consciousness is a recent phenomenon and buildings in the inventory, most of which were built in the last two decades, tend to consume 10-20% more energy than buildings designed for today's standards.

3.4. BUILDING INDUSTRY FORECASTS

Residential Sector

The response of the building industry to new technologies must be measured against the size of the industry. Residential construction is highly cyclical, responding to such factors as cost and availability of capital and mortgage money, consumer income, inventory turnover, etc. Government housing programs contribute to the cyclical nature of the industry, particularly since government involvement has been erratic in recent years. Housing starts under government programs have ranged from 225,000 units in 1974 (13% of total starts) to 763,000 units in 1971 (30% of total starts). Longer-term demographic trends, including age distribution of the population, regional shifts in population and economic growth, and changes in consumer preferences for housing types and styles also play a role in residential construction patterns.

Another dimension of housing activity is its regional character. The Northeast region has shown a steady decline in its share of new housing activity in recent years, attributable primarily to shifts in population, reflecting stagnant employment growth in this region. The South rapidly increased its share of new housing from 1960 to 1972, then experienced a dramatic decline from 1972 through 1976. The decline can be attributed to significant overbuilding in many of the Southern markets, especially multi-family units in Florida. In the West and North Central regions, the trends are much less discernible, although the West has shown strong steady growth since 1972, which probably can be explained by the South's decline.

National Forecasts

1976-1980 — We predict that conventional housing starts will average 1.86 million units annually in this period. Housing starts may be close to 2 million in 1977, but are expected to decline in 1978 and 1979 in response to a slowdown in economic activity. Capacity limits, inflation, rising mortgage rates, and weakness in demand in many sectors will support only limited growth through 1980.

1981-1985 — We expect housing activity to be somewhat stronger than during 1976-1980. Taking into consideration such long-term uncertainties as the political situation both here and abroad, energy prices and availability, demographic changes affecting consumer demand, and timing of future economic cycles, a slight slowdown in economic growth is expected to follow the election year's economic stimulation. However, demographic changes and increased economic stability should make the 1981-85 period stronger than the 1976-80 period.

1985-2000 — Household growth is expected to decelerate to 1.2% annually from 1985 to 2000 (from 1.6% for 1980-1985 and 1.8% for 1975-1980). This slowing is partly attributable to the fall in the birth rate that will mean fewer people in the household-forming age group in 1985-2000. Assuming a 1.2% rate of growth, there will be an average of 1.13 million new households annually. Housing forecasts for 1986-2000 show an average of 1.7 million new units per year to accommodate the new households and replace an aging housing stock.

Projections by Building Type — Single-family detached units will retain their dominant share of new housing activity, accounting for 58% of new units constructed over the 1976-1980 period, 51% during 1981-1985, and 49% during 1986-2000. Single-family attached housing is expected to increase slightly in percentage terms, with units in buildings of 2-4 units accounting

for 5% of conventional housing starts. Townhouse units, on the other hand, should take an increasing share of the single-family market, because of smaller households and rapidly increasing prices of land, energy, and housing space.

In the early 1980's multi-family starts will recover from the weakness they have shown since 1973. They are expected to increase their share of new construction activity from 17% in 1976-1980, to 24% in 1981-1985, then decrease slightly to 21% during the 1986-2000 period.

Mobile homes are expected to grow only in specialized markets, with restrictive zoning practices and unfavorable financing terms limiting growth potential. For 1976-1980 we expect mobile home shipments to average 280,000 units per year. Improvement in the economic and housing environment will support shipments of 300,000 units annually from 1981-1985, but 280,000 will be the average in the 1986-2000 period.

Commercial Sector

Commercial construction typically lags residential activity by about one year and follows general trends in economic growth. When real GNP declines, for example, commercial construction on a square footage basis may decline dramatically — the result of cautious business attitudes toward large, costly construction projects in a period of economic uncertainty.

The segments within the commercial sector respond to different variables. Construction of educational buildings is approximately 90% publicly funded so construction activity depends upon the budgetary stances of state and local governments as well as the school age population. Hospital construction, which is twice as expensive per square foot as total commercial construction, is dependent upon government programs for funding assistance.

The highest levels of new commercial construction are expected to take place in the 1986-2000 period. Office and bank construction should pick up in the early 1980's as the inventory of vacant office space created in the early 1970's is absorbed, the economy progresses at a steadier pace, and businesses are less cautious about investing capital in new construction. From 1981-1985 office and bank construction may increase to 180 million square feet annually, then level off at 200 million over the 1986-2000 period. We expect the construction of retail and other commercial buildings to follow the same general growth pattern, with 477 million square feet annually for 1976-1980. This total may increase to 517 million over the 1981-1985 period, and to 590 million in 1986-2000.

New educational construction has been declining steadily since the peak of 245 million square feet in 1966, and this trend is expected to continue through 1985. From 1976-1980, we expect educational construction to decline to an average of 115 million square feet per year, and in 1981-1985 to 110 million. In the 1986-2000 period, however, the children of people born during the post-World War II baby boom will be reaching school age, and school construction should increase to an average of 120 million square feet per year.

Growth in new hospital construction is expected to average 2% annually over the forecast period. This will bring annual construction to 107 million square feet over the 1986-2000 period, from 78 million during 1976-1980. Demand for health facilities will increase as the population in the older age brackets increases, as more emphasis is placed on preventive medicine and early diagnosis, and as many hospitals become obsolete.

The forecasts of new commercial construction were regionalized by using the same assumptions as in the residential sector. As in the residential sector, the South and West are expected to increase their shares of new commercial construction at the expense of the Northeast and North Central regions.

Forecasting removals from the commercial building inventory is difficult because there is little information on current or historical removals. Therefore, we formulated our own assumptions on removals of commercial space in relation to residential units. We projected that 13% of the 1975 housing stock would be removed during the 1976-2000 period. Commercial removals should be slightly higher because the building inventory is slightly older; a greater proportion is located in center cities, where more demolition takes place; and some commercial buildings have cheaper, less solid construction than residential. Therefore, we estimated that commercial removals would be five percentage points higher than residential. This means that 18% of the 1975 commercial building stock would be removed over the 1976-2000 period or an average of 0.7% per year. These removals were assumed to be at the same rate for all building types, but were varied by region to reflect the same trends as discussed in the residential sector.

By adding the new-construction forecasts to the 1975 commercial inventory and subtracting the removals, we calculated the 2000 inventory by region and building type. These forecasts show the commercial building stock growing at a rate of 2.4% annually over the 1975 to 2000 period, with highest growth in the West (2.5%) and lowest in the Northeast (2.3%). The commercial building inventory is therefore expected to increase by 20 billion square feet to 44 billion over the 25-year period.

3.5. PARTICIPANTS, MARKETS, AND DECISION CRITERIA

Influence of Decision-Makers in Market Sectors

Each of the decision-makers in the building process influences decisions affecting energy technologies. The relative influence of each of these participants was determined through interviews with a broad range of participants, then through a modified Delphi technique, by a survey of a group of experts (Arthur D. Little, Inc., professionals and others) who had extensive experience in the building industry and who were exposed to the information developed in the participant interviews.

Decision Criteria

Financial

Financial characteristics are perceived to be the competitive driving force in most markets. Installed first cost is clearly a concern of most participants, particularly builder/developers. They feel that only if this cost falls within given bounds would a new technology be considered further. First cost is relative; \$1,000 for a heat pump may be significant in a home but an insignificant cost increment in a commercial building.

Payback reflects the ratio of first cost to annual operating savings and is the primary economic performance measure used by most decision-makers. Although some form of life-cycle cost is acknowledged by most sophisticated participants to be a more appropriate method for determining the economic performance of a technology, it is not commonly used in making the

purchase decision. Payback may be less important than first cost to a decision-maker who will not be responsible for the operating costs. The knowledgeable energy technology "user," who pays the operating bills, frequently considers payback to be the primary criterion.

Technical

Technical criteria related to the physical operating characteristics of the technologies are also important. Performance, or general perception of the overall character of a given technology, concerns market reaction to the state of the technology. Performance might be considered the measure of the reputation of the technology. It is important for designers, but is less of an issue for contractors or financial institutions.

Reliability concerns how effectively the technology is expected to operate over time, and may be a particular concern for new technologies and/or active systems. Reliability is a concern for those decision-makers who are responsible for the design of a system and the users who will have to deal with the operating problems.

Technical complexity may be important in some market sectors. A system perceived to be highly complex will not be acceptable in much of the single-family market but will encounter significantly less resistance in large institutional structures where sophisticated designers and operators are not intimidated by complexity.

Maintenance complexity/difficulty is another criterion that relates especially to the sophistication of the market sector. An energy technology that requires frequent maintenance by skilled personnel may have limited applicability. Furthermore, complex systems tend to increase operating costs, or at least create concern about the operating cost implications.

Space requirements will also influence market penetration. Incorporating an energy system into a structure efficiently is a primary concern for designers. Minimizing the size of components or simplifying their integration into the structure is an important objective. The large area required for solar collectors restricts their applicability on high-rise structures (unless effective curtain-wall collector systems are developed) and the space needed for windmills limits their use.

Social

Social criteria relate to the broader concerns of society that have become increasingly important. They provide the impetus for increased market penetration for socially-favored technologies and create pressure for supportive government policy.

Aesthetics may be important for such highly visible technologies as solar energy systems or windmills. The aesthetic rating of a technology may change over time or may differ between and even within market sectors. For some purchasers, a highly visible new energy technology may indicate a commitment to renewable resources.

Safety is a necessary prerequisite to the introduction of a new technology. It is often perceived to be the responsibility of public regulatory authorities. Nevertheless, decision-makers in the R/C sector may be concerned about the safety of energy technologies. In some areas, natural gas still has an image problem because of the danger of explosion; flammability has affected the acceptance of some insulation materials; there are fears about the high temperatures developed in solar systems, etc.

Certainty of fuel supply has been a real issue for many industrial and commercial consumers of energy for some time, and this concern has recently been extended to the residential sector. Although many industry participants do not know how to respond to the issue it does appear to be a criterion in the energy selection process.

The use of less scarce or renewable resources is the criterion in the social category discussed most extensively; it relates in particular to the conservation and solar technologies. Although many of the decision-makers may not have a direct economic incentive to support such technologies, they do respond to consumer/users by offering them as options or incorporating them into their buildings.

Ecological soundness supports the use of less polluting energy technologies, but the R/C sector is for the most part at some distance from the pollution that may be associated with energy technologies. Relatively few consumers appear to relate their decision to use electricity for heating and air conditioning to their other concerns, such as the dangers from nuclear power plants, off-shore oil spills, or strip mining of coal. Consumers concerned about ecology appear to support technologies based on natural gas as well as those based on non-polluting renewable resources and energy conservation.

Institutional

Institutional criteria are concerns that are to some extent outside of the technology itself, but they must be addressed if any new technology is to achieve the market acceptance that its supporters desire.

The predictability of installed costs will affect the acceptability of a technology. Because financing is based on cost estimates, uncertainty about the cost of a technology that is unfamiliar, or for which the costs may depend on uncontrollable factors, may lead decision-makers to select a system with known, even if possibly higher, costs. Costs tend to become more predictable with experience, although experience in other markets or regions, or with other participants, may not always be applicable. The need for extensive field work in installation may always lend an element of unpredictability. A packaged or systems approach minimizes the uncertainty of field installation costs by transferring much of the assembly function to the manufacturing plant. Unpredictability of installed costs is particularly notable in the retrofit market where all the problems of interconnection to an existing structure or system are impossible to anticipate.

Designer familiarity is similar to cost predictability in that market penetration will be slow at first and will depend on experience and complexity. Designers have neither the time nor the economic incentive to consider unfamiliar technologies and will tend to choose established systems over an unfamiliar technology with claimed economic or performance advantages.

Codes or zoning barriers may represent particularly acute problems for some new technologies, especially when they are competing with a well established product or system. It is not in the direct interest of most participants in the construction process to address these constraints, nor in the interest of regulatory authorities to change. Therefore, impetus for dealing with these issues must come from the suppliers of technologies and/or the public agencies that may support the benefits provided by the technologies.

Decision Criteria by Market Sector

The relative influence of the decision-makers by market and their criteria for making decisions are combined to indicate market response to new energy technologies. For example, the primary concerns of the developer are financial, especially first cost, and the markets in which the developer is the most influential participant (the speculative single-family market) would be expected to have high sensitivity to first costs. However, the strong influence of the developer is tempered significantly by the concerns of the other participants. If the developer were the only participant considered in the speculative single-family market, the first cost would have a rating of 50% rather than 30%.

Non-financial criteria are actually important in the decision process in all market sectors. In fact, financial concerns do not exceed 50% in any market sector. Although no single social, technical, or institutional criterion is as significant as the financial criteria, the large number of these criteria leads to some dilution of their individual values.

4. TECHNOLOGIES IN THE RESIDENTIAL/COMMERCIAL SECTOR

4.1 INTRODUCTION

This section provides an overview of the salient features of each of the technologies considered in this project; an economic analysis of the technologies, which represents data inputs to the analytical model; and a derivation of the non-economic factors used in the model. The technology overviews include more than simple projections of cost and performance because it is our contention that the structure of the supplying industries, the stage of development, the degree of market experience, and the non-economic characteristics will be strong influences on market acceptance.

Although the economic competitiveness with other alternatives (measured by capital cost and undiscounted payback) may be the primary determinant of the market acceptance of a technology, the rate of acceptance will be influenced strongly by other factors. The ratings are developed with a time function and thus reflect the developing life cycles of the different technologies. For example, in the early years of a technology, not only is it likely that its technical performance will be less favorable because production volume is lower (and thus more costly) and technical improvements have yet to be made, but its non-economic ratings are also likely to be less attractive because of the lack of market experience. The unfavorable experience with heat pumps in the early 1960's continues to represent a barrier to their market acceptance; the aesthetic objection to solar collectors in some quarters may be an obstacle today, but is not likely to affect market acceptance in 20 years after solar systems have become common. (In fact, the visibility of solar systems may become a market advantage.)

An important task in this section is to develop technology groupings that encompass the broad variety of technologies applicable to the residential/commercial sector and consider the important differentiations between them, but to avoid creating an unmanageable analytical task. The approach used in this analysis has been to develop ten generic groupings of technologies to include all of the primary technology alternatives that will be available to the primary decision-makers in the R/C sector. Geothermal and integrated energy systems are not included because the analytical approach was designed to consider the market at the building level, and these two systems must be designed at the community level.

Out of a wide variety of possible combinations of technologies, the following groupings were used:

Conservation

Category I

Category II

Category III

Heat Pumps

Electric

Gas

Solar Thermal Systems

- Hot Water

- Hot Water/Heating

- Hot Water/Heating/Cooling

Solar Electricity

- Photovoltaic Conversion Systems

- Wind Power Systems

Each of the technology groupings is designed to match with each of the building/markets in each of the geographic regions so that a specific design is developed for 68 different buildings. The size of the solar heating system, for example, will be optimized to meet the different energy load requirements of the 17 buildings in four climatic areas. Further detailed analyses would be needed to determine applicability in specific cases.

The primary concern in all market penetration analyses is the degree to which the methodology accurately represents the market selection process. The process is difficult enough when the intent is to determine the penetration of a single product into a single well-defined market. The problem is infinitely more complex and the uncertainty much greater when the technologies are numerous, their future performance is highly variable, and their competitive interrelationships difficult to determine, and when the market is as diversified and complex as is the residential/commercial sector.

The need to make the task manageable has led to simplifications that limit the ability to determine the impact of a specific technology. However, we believe that the technology groupings are critical to this analytical process and that determination of the market prospects of a given technology should be the subject of a separate analysis.

Another critical issue in analyses of this type is the way in which the technologies compete with or are combined with one another. Our approach has been to assume that all buildings/markets have the theoretical opportunity to choose from each of the technology groupings, and that the selection process among technology groupings is not mutually exclusive. Thus, the fact that an electric heat pump is chosen does not restrict the decision-maker's choice of conservation, solar thermal, or solar electric options (except to the extent that electricity is used to fuel the electric heat pump, which in turn affects the economic attractiveness of the other technologies). Although capital constraints may apply in the very short term, over the long term they are unlikely to be a significant constraint.

Within the technology groupings where we assume mutual exclusivity (electric heat pumps versus gas heat pumps), experience suggests that investment in energy-conserving technologies becomes synergistic. A purchaser selecting an expensive conservation option appears to be a more likely candidate for solar energy.

4.2 TECHNOLOGY DESCRIPTIONS

Conservation Technologies

Energy conservation techniques used in buildings include both technologies that are "conventional," and those that are "distinct" in either their configuration or their applicability within

the building sector. During the study, it was possible to profile many of the "distinct" technologies according to their performance capabilities and associated economics on an individual basis. However, to do so with each of the numerous conventional conservation techniques would be extremely unwieldy. The approach here was to group various technologies by their applicability, performance, and costs, recognizing that decisions to use them are made on a structure-by-structure basis. These "conventional" technologies modify either the mechanical hardware of the building, its exterior materials, or its operation and maintenance.

Our market-oriented approach to the conventional technologies is based on the following reasoning. Buildings are individual, each with its own energy use pattern and associated potential for energy use reduction. For the most part, annual energy consumption — and potential savings — of an individual building cannot be related to either its HVAC design load or its HVAC equipment capacity; the major determinant is generally building occupancy. Furthermore, most energy use occurs (and can be moderated) during periods of moderate (rather than extreme) outdoor temperatures.

Most energy conservation technologies that are applicable to new and existing buildings are established and understood by the construction industry. These established techniques have the most potential for energy savings.

Few, if any, technologies are both applicable *and* equally effective across all building types and geographical locations. (This characteristic has led to some disagreement within the building design profession about how energy conservation regulations can best be devised or implemented.) Nevertheless, significant conservation may be achieved through the application of more than one technique, and at times, therefore, there is competition among different technologies for application to a particular project.

Although each building is unique in its energy consumption, there are certain similarities in energy conservation potential within generically-similar buildings. For example, office buildings may differ significantly in size, but their fundamental energy usage patterns are similar because of periodic occupancy and high internal lighting loads. However, differences in consumption patterns are noticeable between office buildings and the 24-hour usage and non-shutdown requirements of hospitals.

Those energy conservation technologies that offer the greatest cost benefit are the most likely to be implemented by the building owner or to be recommended by the consulting engineer. This trait is basic to our analysis, and assumes that within a generic building category and location, there is an implied — but not clearly demonstrable — hierarchy of energy conservation technologies.

Table 4-1 lists several examples of conventional technologies and indicates their general effectiveness in new and existing buildings. Although this list is not intended to be exhaustive, it represents those conventional technologies that are often considered or applied to buildings.

Although conservation technologies generally are employed in combination with other technologies, some indication of the relative cost-effectiveness of conventional techniques can be gained by examining the cost-benefit relationship of energy conservation in several actual buildings.

TABLE 4-1

**RELATIVE EFFECTIVENESS OF SELECTED ENERGY CONSERVATION TECHNIQUES
ON NON-RESIDENTIAL COMMERCIAL CONSTRUCTION**

	Relative Effectiveness	
	New	Existing
External and Physical Properties		
Increase in Wall and Roof Insulation	***	*
Reduction in Glass Area	**	
Insulating Glass, Storm Windows	***	
Solar-Reflective Glass	**	*
Improved Sealing and Caulking	*	*
Architectural Shading Schemes	**	
Site Orientation	**	
Internal Loads/Comfort Conditions		
Change in Maintained Temperature Conditions	***	***
Reduction in Lighting Levels	**	**
Reduction in Ventilation Rates	***	**
Zoning of Conditioned Spaces	**	*
Movement of Internally Generated Heat Between Zones	**	
HVAC Systems or Components		
Increased Equipment Efficiency	***	**
Multiple Components	**	
Use of Economizer System	**	**
Incorporation of Heat Recovery Schemes	**	**
Use of Variable-Air-Volume Systems	***	*
Improved Controls, Dual-Set Point Thermostats	**	**
HVAC Systems Operations		
Periodic, Night or Weekend Shutdown	***	***
Automatic Pilot Ignition	*	*
Minimize Partial Load Operation	**	**
Periodic Maintenance Program	**	**
Nighttime Setbacks	***	***
Building Automation	**	**

* Occasionally effective; results vary widely among buildings.

** Usually effective in conserving energy; dependent upon building type, mode of operation, geographical location.

*** Generally effective in conserving energy.

Source: Arthur D. Little, Inc., estimates.

It is impossible to generalize on either additional investment costs or annual energy savings for any one technology but it is often true that each modification represents an incremental reduction in energy costs at some incremental investment cost.

Figure 4-1, based upon a study by Walter F. Spiegel, Inc., represents an existing university-owned athletic facility in the Northeast and is used as an illustration because the facility had not introduced any prior energy conservation schemes. The curve shows the cumulative savings in annual energy costs as a function of the cumulative costs of several conventional energy conservation modifications, which are also expressed as a percent of annual energy costs. Figure 4-1 also shows Spiegel's "educated guess" about the limits of energy savings that might be possible within similar building types in this geographical area.

Evaluation of the data shows the following:

- Many of the initial cost savings possible are both significant *and* relatively inexpensive. For instance, a cumulative expenditure of slightly more than 40% of the annual base-year energy costs results in savings of 40-45%.
- The incremental cost effectiveness of each succeeding modification decreases as the curve flattens out. Thus, those modifications which offer the greatest annual savings at the least incremental cost define that part of the curve where the slope is the greatest. These conventional techniques could be combined to describe successive portions of the curve as a function of its slope.
- There is a point beyond which the slope of the curve is zero, indicating that no future energy savings can be rationally achieved with additional investment. This limit will occur at different points for different buildings, and perhaps encourage the building owner to investigate those energy-reducing technologies available to him which are not necessarily "conventional."

This cost-effectiveness approach can be adapted (Figure 4-2) to obtain curves for other project studies.

Hospital "A"	103,000-sq-ft metropolitan hospital.
Hospital "B"	170,000-sq-ft building addition to a large metropolitan hospital.
Educational "A"	109,000-sq-ft university classroom building.
Educational "B"	92,000-sq-ft combination university classroom and administration building.

Each curve is slightly different, representing both the individual nature of each building and the energy conservation economics associated with each structure. In addition, the changing slope of the curve as investment increases may be used to group different technologies.

Certain types of buildings are generically more suitable for cost-effective energy conservation schemes than others. Curves for the university classroom buildings are similar in shape but distinctly different from those representing the hospitals. University classrooms, which generally operate on less than a 24-hour basis, may achieve significant savings because the HVAC system is shut down when the classrooms are not occupied. Hospitals, on the other hand, are operated

Source: Walter F. Spiegel, Inc., Based Upon a Private Study

FIGURE 4-1 COST EFFECTIVENESS OF VARIOUS ENERGY CONSERVATION MODIFICATIONS FOR UNIVERSITY-OWNED INDOOR ATHLETIC FACILITY

Source: Walter F. Spiegel, Inc. Based on Private Studies

FIGURE 4-2 ENERGY CONSERVATION COST EFFECTIVENESS CURVES FOR SELECTED BUILDINGS

continuously and consume much more energy because of building operations basic to health and safety that are not likely to be terminated or reduced for reasons of energy conservation. Thus hospitals could achieve only minor energy savings relative to the suggested cost of modification, as indicated by the flat curves.

Another observation can be made from Figure 4-2 with regard to the relative position of the two university classroom curves. The data suggest that Educational "A" building has a poorer overall conservation potential (20-25%) than the Educational "B" building (potential savings in excess of 60%). However, Educational "A" had already lowered energy demand by reducing inside air volumes and by shutting down the equipment on weekends. Had these steps not been taken, the curve would approach the shape of the lower curve of Educational "B," where few, if any, energy conservation schemes had been implemented.

On the basis of the cost-effectiveness relationship indicated in the previous two figures, the list of "conventional" technologies was grouped into three categories for each generic building type:

- *Category I* — items that are "quick fix" and require minimal engineering expertise.
- *Category II* — items that are established, basic techniques and have economics found to be acceptable to the industry.
- *Category III* — items that are capital-intensive modifications and require considerable engineering support.

The assumed cost-effectiveness curve for each generic building type can also be divided into three segments, each of which represents a category of conventional technologies. Sealing, caulking, and weatherstripping are very effective in reducing infiltration in a single-family residential construction, but may not be as effective in an office building that uses forced mechanical ventilation. The reverse might be said of architectural shading schemes, which are not as critical in the residential sector as they might be in the office building where large air conditioning requirements could be offset by a reduction in the solar heat gain associated with large areas of glazing.

Nonresidential

On the basis of discussions with engineers involved in energy management consulting, cost-effectiveness curves were constructed for the following buildings:

- Office Building
- Retail Establishment
- School and Educational
- Hospital and Health
- Light Industrial
- High-Rise Apartment

These curves, shown in Figure 4-3, permitted us to estimate the potential energy savings and associated cost of conventional conservation technologies. This estimate was undertaken on a best-efforts basis and may require more analysis before it can be classified as an accurate indicator of potential savings and costs.

FIGURE 4-3 COST-BENEFIT CURVES FOR CONVENTIONAL ENERGY CONSERVATION SCHEMES

Although precise formulas are not appropriate, the results are expressed as the annual savings achieved as a function of the cost of modifying the building. The modification cost is expressed as a percentage of annual energy costs, which, of course, vary by building type. For purposes of this analysis, we estimated the following:

	Annual Energy Costs (\$/SF)	
	Range	Mean
Office Building	0.80-1.30	1.05
Retail Store	0.60-0.90	0.75
Hospitals and Health	2.00-4.00	3.00
Schools	1.50-2.25	1.90
Light Industrial	1.00-3.50	2.25
Low-Rise Apartment	0.50-1.00	0.75

For example, given that Category I, II and III modifications on the office building are, respectively, 6%, 22%, and 46% of annual energy costs, the corresponding modification costs are \$0.06, \$0.23, and \$0.48 per sq. ft., based upon an assumed energy cost of \$1.05 per sq. ft. per year. A summary of the costs is given in Table 4-2.

The modification costs given do not include additional costs for engineering and associated services. In reality, such costs would also be borne by the building owner as part of initial modification costs, and we added \$0.10/sq. ft. to account for this.

For the purposes of this study, it was assumed that the incremental unit cost of applying established conservation technologies will not change over the horizon of the analysis (to the year 2000). Therefore, the costs given in the table are in current dollars. Our reasons are as follows:

- Modification costs are similar across all regions. Cost savings, i.e., the Btu's saved, will vary by region, but the initial cost will not change.
- Most of the technologies are well established within the HVAC industry and are generally understood by most designers and practitioners. As such, they have perhaps reached the flat portion of the economic learning curve and are representative mature products.
- Many of the hardware-oriented and labor-intensive improvements included cannot be leveraged because of changes in either their manufacturing process or their proportion of value added. This is not the case with emerging new technologies such as solar and wind power systems, which in comparison with conventional technologies should be accompanied by estimates that derate the unit cost over time (prior to inflation).
- While future technological changes, i.e., beyond 2000 or so, may make certain technologies more cost-effective, the rough assumptions used in deriving the costs cannot be improved upon easily. Hence, any attempt to increase or decrease the above costs would be fruitless.

TABLE 4-2

ESTIMATED COST AND POTENTIAL ENERGY SAVINGS OF
CONVENTIONAL CONSERVATION SCHEMES

Building Type	Conservation Category	Cost ^a (\$/sq ft)	Regions	Annual Savings (M Btu/sq ft/yr)				
				SH ^b	A/C	AUX	DHW	L/P
Office Building	I	0.06	NE & NC	12	3	2	—	6
	II		S & W	6	8	2	—	6
	II	0.23	NE & NC	16	4	5	—	12
			S & W	10	10	5	—	12
	III	0.48	NE & NC	30	5	5	—	12
			S & W	15	12	5	—	12
Retail Establishments	I	0.06	NE & NC	8	3	3	—	7
			S & W	4	6	3	—	7
	II	0.19	NE & NC	10	7	5	—	15
			S & W	6	11	5	—	15
	III	0.42	NE & NC	12	10	8	—	17
			S & W	8	15	8	—	17
Hospitals and Health	I	0.18	NE & NC	8	3	10	—	4
			S & W	6	6	11	—	4
	II	0.66	NE & NC	13	5	12	—	4
			S & W	10	12	14	—	4
	III	1.20	NE & NC	18	12	16	2	5
			S & W	12	18	20	2	5
Schools and Educational	I	0.13	NE & NC	17	1	4	—	—
			S & W	10	3	4	—	—
	II	0.49	NE & NC	22	2	5	—	8
			S & W	15	4	5	—	8
	III	1.00	NE & NC	25	3	5	—	12
			S & W	20	8	5	—	12
Light Industrial ^c	I	0.20	NE & NC	6	2	2	—	1
			S & W	4	2	2	—	1
	II	0.56	NE & NC	10	4	5	—	2
			S & W	7	5	5	—	2
	III	1.20	NE & NC	21	6	5	1	3
			S & W	12	7	5	1	3
Low-Rise Apartments	I	0.04	NE & NC	13	2	NA	2	—
			S & W	10	6	NA	2	—
	II	0.12	NE & NC	17	2	NA	4	—
			S & W	14	8	NA	4	—
	III	0.26	NE & NC	18	3	NA	4	—
			S & W	15	10	NA	4	—

a. Excludes costs of engineering analysis and associated services. Assume \$0.10/sq ft additional cost for all categories to derive total cost to building owner.

b. Gas fired. To adjust for oil-fired heating, multiply by 1.08; to adjust for electric heating, multiply by 0.3.

c. Used as proxy for "other buildings" category.

In anticipation of future use of the model, it was necessary to build in some flexibility to account for those cases in which regulatory agencies might adopt mandatory energy conservation building codes. Thus, to derive the conventional conservation technology available *after* the implementation of pending mandatory standards in new construction, one need only subtract the savings and cost estimates of Category I — the approximate savings gained from mandatory standards — from those for Category III, i.e., the differential available after Category I modifications have been made.

We estimated within each category where the annual savings might occur as a function of major end use, including:

Space Heating (SH)
Air Conditioning (A/C)
Auxiliary HVAC Equipment (AUX)
Domestic Hot Water (DHW)
Lighting and Power (L/P)

We derived two estimates, one for the winter climates (Northeast and North Central) and one for the summer climates (South and West).

To better define the three major categories, we attempted to classify each of nearly 60 items into one or another of the three categories. (See Tables 4-3, 4-4, and 4-5.) The individual items were grouped according to their applicability in six building types:

- Office buildings, including government administration;
- Retail establishments;
- Schools and educational;
- Hospitals and health care;
- Light industrial; and
- Multi-family high-rise apartments.

(The individual technologies associated with mobile homes and single-family dwellings are relatively simpler in concept, and are discussed separately.)

No effort was made to quantify the relative effectiveness of the individual items within any of the three categories. The effectiveness of a single item vis-à-vis its alternatives depends upon the specific building being investigated, geographical location, usage profile, type of HVAC system, energy type, etc.

Category III (Table 4-5) includes some discrete items that are capital intensive, yet are perhaps independent of conventional technologies. A more rigorous analysis is required to determine their individual cost effectiveness and properly evaluate their position within the marketplace.

In each of the tables, the items were first evaluated in terms of their effectiveness on *existing* construction. Those items that are equally applicable to new construction have been marked with

TABLE 4-3

APPLICABILITY OF CONVENTIONAL ENERGY CONSERVATION TECHNOLOGIES, CATEGORY I^{a, b, c,}

<u>Item Description</u>	<u>Office Buildings^d</u>	<u>Retail Establishments</u>	<u>Schools and Educational</u>	<u>Hospitals and Health</u>	<u>Light Industrial</u>	<u>Multi-Family High-Rise</u>
A. EXTERNAL AND PHYSICAL PROPERTIES						
● Improved Sealing and Caulking	*	*	*	*	*	*
B. INTERNAL LOADS/COMFORT CONDITIONS						
● Reduction in Lighting Intensity	*	*	*	*	*	*
● Change in Maintained Temperature Conditions	*	*	*		*	*
C. HVA/C SYSTEMS AND CONTROLS						
● Insulate Bare, Hot Piping	*	*	*	*	*	*
● Add Timers for Room A/C Units (N)	*		*	*	*	
● Install High Efficiency Lamps (N)	*	*	*	*		
D. OPERATION AND MAINTENANCE						
● Equipment Shutdown	*	*	*	*	*	*
● Repair Steam Leaks	*		*	*	*	*
● Window Shade Control to Meet Existing Conditions	*		*	*		
● Adjust Combustion Equipment	*	*	*	*	*	*
● Replace Defective Steam Traps and Valves	*	*	*	*	*	*
● Reduce Domestic Hot Water Temperature	*	*	*	*	*	*

a. Defined to include those items which are "quick-fix" or "quick-payback" oriented, and require minimal engineering expertise.

b. By definition includes those items applicable to retrofit of existing buildings. Items which are applicable to new construction are designated (N).

c. Excludes items which are specifically intended for new construction under present or pending, voluntary or mandatory energy conservation standards such as ASHRAE Standard 90-75.

d. Includes government administration.

Sources: Walter F. Spiegel, Inc., and Arthur D. Little, Inc., estimates.

TABLE 4-4

APPLICABILITY OF CONVENTIONAL ENERGY CONSERVATION TECHNOLOGIES, CATEGORY II^{a,b,c}

Item Description	Office Buildings ^d	Retail Establishments	Schools and Educational	Hospitals and Health	Light Industrial	Multi-Family High-Rise
A. EXTERNAL AND PHYSICAL PROPERTIES						
• Add Insulation Over Top Floor Ceiling		*	*	*	*	*
B. INTERNAL LOADS/COMFORT CONDITIONS						
• Start-up Ventilation Cycles (N)	*	*	*	*	*	*
• Reduce Ventilation Air	*	*	*		*	
• Reduce Supply Air	*	*	*		*	*
C. HVAC SYSTEMS AND CONTROLS						
• Cycle Control for Steam Cast Iron Radiation Systems	*		*	*		*
• Upgrade Automatic Temperature Control	*	*	*	*	*	*
• Time Clocks and Interlocks for Shutdown (N)	*	*	*	*	*	*
• Cycle Timers for Fans (N)	*	*	*	*	*	*
• Repair Preheater Arrangements	*	*	*	*		
• Efficiency Check and Repair of Chillers	*	*	*	*	*	*
• Electric Demand Control (N)	*	*	*		*	
• Add Flash Tanks for High Pressure Steam System			*	*	*	
• Signal Selectors for Reheat Systems (N)	*	*	*	*	*	*
• Add Enthalpy Control to Economizer Cycles (N)	*	*	*	*	*	*
• Provide Economizer Cycle to Existing Minimum Outside-Air Systems	*		*		*	
• Provide Economizer Cycle by Adding Return-Air to Existing All Outside-Air Systems	*	*	*	*		
• Add Cooling Coil Return-Air Bypass (N)	*	*	*	*	*	
• Modify Double-Duct Distribution	*		*	*		
• Power Factor Correction (N)	*		*	*	*	*
• Air Heat Reclamation			*	*	*	*
• Modify Switching Arrangement for Existing Lighting (N)	*		*	*	*	
• Add Photo-Cell Control to Existing Lighting (N)	*	*	*	*	*	
D. OPERATION AND MAINTENANCE						
• Night Setback	*	*	*	*	*	*
• Improve Combustion Control	*	*	*	*	*	*
• Balance Air Flows	*	*	*	*	*	*
• Secure Idle Elevators (N)	*	*	*	*	*	*

a. Defined to include those items which are established, basic retrofit techniques and which have economics found to be acceptable to the industry.

b. By definition includes those items applicable to retrofit of existing buildings. Items which are applicable to new construction are designated (N).

c. Excludes items which are specifically intended for new construction under present or pending, voluntary or mandatory energy conservation standards such as ASHRAE Standard 90-75.

d. Includes government administration.

Sources: Walter F. Spiegel, Inc., and Arthur D. Little, Inc., estimates.

TABLE 4-5

APPLICABILITY OF CONVENTIONAL ENERGY CONSERVATION TECHNOLOGIES, CATEGORY III^{a, b, c}

<u>Item Description</u>	<u>Office Buildings^d</u>	<u>Retail Establishments</u>	<u>Schools and Educational</u>	<u>Hospitals and Health</u>	<u>Light Industrial</u>	<u>Multi-Family High-Rise</u>
A. EXTERNAL AND PHYSICAL PROPERTIES						
● Add Reflective Film to Windows	*		*	*		*
● Double Glaze	*		*	*		*
● Add Roof Insulation		*	*	*	*	*
● Add Wall Insulation					*	
B. HVAC SYSTEMS AND CONTROLS						
● Add Building Automated Systems (N)	*	*	*	*	*	
● Interconnect Chillers (N)	*		*	*	*	
● Centralize Chilled Water Plant (N)	*		*	*	**	
● Laundry Heat Reclaim (N)				*		
● Wastewater Heat Reclaim (N)				*	*	
● Refuse Heat Reclaim (N)	*		*	*	*	
● Modify All-Air System to Variable-Air Volume	*	*	*	*	*	
● Partial On-Site Energy Generation (N)			*	*	*	*
● Total Energy Systems (N)			*	*	*	
● Upgrade Boiler Controls	*		*	*	*	*
● Convert or Add Heat Pump (N)	*	*	*	*		*
● Return Maximum Steam Condensate			*	*	*	
● Selective Energy Source (N)			*	*	*	*
● Blow-Down Heat Recovery (N)			*	*	*	

a. Defined to include those items which are capital-intensive modifications and require considerable engineering support.

b. By definition includes those items applicable to retrofit of existing buildings. Items which are applicable to new construction are designated (N).

c. Excludes items which are specifically intended for new construction under present or pending; voluntary or mandatory energy conservation standards such as ASHRAE Standard 90-75.

d. Includes government administration.

Sources: Walter F. Spiegel, Inc., and Arthur D. Little, Inc., estimates.

an (N). The tables do not account for those technologies or modifications that will probably be required of mandatory energy conservation standards and are included in pending guidelines such as ASHRAE 90. In essence, the (N)-marked items indicate those technologies which are above and beyond what mandatory energy conservation standards will require.

Finally, the number of items thought to be viable for each specific building type decreases as the conservation technologies proceed from Category I to Category III. To this extent, the steeper slopes of the curves for Categories I and II are not matched by the slope of the curves for Category III.

Residential

In the residential sector, we investigated and categorized individual conservation technologies for mobile homes and detached single-family residences. These are summarized in Tables 4-6 through 4-9 and cover both new and retrofit construction. Specific technologies were also screened by region, and these were classified as applicable to either winter locations (Northeast/North Central), summer locations (South/West), or both.

A cost of \$1 was assigned to Category I technologies for new mobile home construction because HUD standards require a benchmark quality of construction, including specific levels of insulation, that indirectly reduce infiltration. (The \$1 cost represents a computer input, inasmuch as the increased cost of such modifications is not optional to the purchaser of a new mobile home.) The estimated energy reduction may be optimistic, but as yet there has been no conclusive evidence to indicate the actual impact.

In the case of new single-family units, we investigated the technologies applicable to the Northeast and the South, and extrapolated the approximate cost and expected savings which might be appropriate for the North Central and West regions.

We assumed that most low-density residential construction was either duplexes or small three- to four-unit structures, and that the latter represent a small percentage of total residential construction. Thus, we assumed low-density construction in general would achieve energy savings roughly equal to the percentage savings achieved in the single-family units at 75% of the cost determined by the single-family units.

We attempted to account for the technological development of equipment and systems over time using a factor analysis approach. Using ASHRAE 90's requirements, we extrapolated from 1977 and 1980 targets for machine EERs, COPs, efficiencies, and in the case of domestic water heaters, standby losses. A sliding multiplier was derived for both HVAC equipment and domestic hot water equipment and is shown in Figure 4-4. Additional factors were derived and extrapolated for auxiliary HVAC equipment and lighting.

We made the initial assumption that the technological improvement factors were applicable only to new construction and not appropriate for existing construction. Our reasoning was that new equipment is seldom installed in a retrofit situation, efficiencies of existing HVAC components are not susceptible to upgrading, and not all modifications undertaken can use current state-of-the-art technology. However, certain improvements in HVAC system efficiencies can be obtained via modifications, so lower multipliers were assigned for existing construction. Roughly speaking, these multipliers call for an improvement in efficiency in existing construction of 40 to 60% of that achievable in new construction.

TABLE 4-6
CONVENTIONAL CONSERVATION TECHNOLOGIES FOR
NEW MOBILE HOME CONSTRUCTION

Conservation Level	Location	Items
I	NE/NC	Full-Batt Wall Insulation Full-Batt Ceiling Insulation Complete Caulking Certified Windows Improved DHW Heater
	S/W	(Same)
II	NE/NC	Double Glazing Insulate Floor After Tie-Down Dual-Set Thermostat
	S/W	Same, Plus: Window Shading Devices
III	NE/NC	Insulated Rigid Board Sheathing for Walls and Roof Automatic Flue Damper Insulate DHW Piping
	S/W	(Same)

Source: Arthur D. Little Inc., estimates.

TABLE 4-7
CONVENTIONAL CONSERVATION TECHNOLOGIES FOR
EXISTING MOBILE HOME CONSTRUCTION

<u>Conservation Level</u>	<u>Location</u>	<u>Items</u>
I	NE/NC	Improved Caulking and Weather Stripping Insulate Floor Close-Off Crawl Space Install 3-gpm Shower Heads
	S/W	(Same)
II	NE/NC	Storm Windows Dual-Set Thermostat Insulate DHW Piping
	S/W	(Same)
III	NE/NC	Storm Doors Clock Thermostat Automatic Flue Damper
	S/W	Same, Plus: Shading Devices

Source: Arthur D. Little, Inc., estimates.

TABLE 4-8
CONVENTIONAL CONSERVATION TECHNOLOGIES FOR
NEW SINGLE-FAMILY CONSTRUCTION

<u>Conservation Level</u>	<u>Location</u>	<u>Items</u>
I	NE/NC	Full-Batt (R-22) Attic Insulation Full-Batt (R-11) Wall Insulation Insulate Basement Walls (R-3) Improved Caulking and Weather Stripping Improved DHW Heater Improved Appliances
	S/W	Same, except: R-19 Attic Insulation R-11 Wall Insulation 24" Perimeter Insulation for Slab-On-Grade
II	NE/NC	R-30 Attic Insulation R-11 Wall Insulation Rigid Board Polystyrene Sheathing Dual-Set Thermostat Double Glazing
	S/W	Rigid Board Polystyrene Sheathing Dual-Set Thermostat Double Glazing
III	NE/NC	Storm Doors R-7 Basement Wall Insulation 6" Stud Framing With R-19 Insulation Clock Thermostat Insulate DHW Piping
	S/W	Same, But Omit Basement Wall Insulation Add Sun Shades

Source: Arthur D. Little, Inc., estimates.

TABLE 4-9
CONVENTIONAL CONSERVATION TECHNOLOGIES FOR
EXISTING SINGLE-FAMILY CONSTRUCTION

<u>Conservation Level</u>	<u>Location</u>	<u>Items</u>
I	NE/NC	Increase Attic Insulation to R-30 Insulate Basement Walls to R-3 Improved Caulking and Weather Stripping
	S/W	Same, But Omit Basement Wall Insulation
II	NE/NC	Double Glazing Install Automatic Flue Damper Dual-Set Thermostat Storm Doors
	S/W	Same
III	NE/NC	Blow-in Wall Insulation Clock Thermostat Replace Burner Sun Shades Insulate DHW Piping
	S/W	Same

Source: Arthur D. Little, Inc., estimates.

Source: Arthur D. Little, Inc., estimates.

FIGURE 4-4 ASSUMED IMPACT OF TECHNOLOGICAL DEVELOPMENT OVER TIME

We have attempted to identify those factors that would contribute to a change in these estimates. While we are skeptical that such a large variation ($\pm 30\%$) in the possible energy savings could occur by the year 2000, certain issues, if they moved in complete concert, could bring about a major deviation in the estimates of potential reduction in energy consumption. These include the following:

- Marketing and operational effects;
- Economic or technological breakthroughs — Categories I and II;
- Changes in the cost of Category III technologies;
- Adoption of energy conservation standards in new construction;
- Adoption of energy conservation standards for existing construction;
- Increased per capita use of electric appliances;
- Conflicting requirements in energy conservation standards;
- Dissemination of design know-how; and
- Architectural design modifications in new buildings.

Our basic finding is that the potential for energy conservation in both residential and nonresidential buildings, and in both new and existing structures, is high. The energy used in existing buildings can be cost-effectively reduced by approximately 20% and, given some considerations for capital investment, perhaps as much as 40% on average may be saved ultimately. Savings in new construction will probably be on the order of 35% to 40%. The range of potential savings and the range of market acceptance suggest an uncertainty of $\pm 20\%$ around our best estimates.

Conservation technologies include both "hardware" — insulation, improved equipment, etc., — and "software" — reduced temperatures, improved operational techniques, etc., — and it is clear that the adequacy of the technologies (cost and savings potential) is intimately associated with the techniques for developing market acceptance and maintaining energy savings levels. One such marketing approach is common in Europe; in France, for example, companies known as "chauffages" (providers of heat) contract to perform all functions related to the use of energy in a building. Their financial return depends on their success in reducing energy consumption in the building. Section 5.0 discusses the interrelationship between the technologies and the marketing/management approaches in greater detail.

Generally speaking, the technologies involved in Categories I and II are not susceptible to major economic or technological breakthroughs. These technologies have the advantage of years of commercialization, acceptance by designers and building owners, and delivery mechanisms for adequate field servicing.

Perhaps the one exception in which a technological breakthrough might occur is in the efficiency of mechanical compressors. In general, space heating equipment operates by combusting a fuel and then capturing the released heat value for distribution to the occupied space. Equipment for space cooling is based upon compressors, which have undergone significant development. Some of this research has been on alternative systems, such as the rotary and scroll compressors. Most of these alternative cycles are under development in the commercial sector,

and their commercialization would probably result in higher energy-efficiency ratios than those being proposed at the state and federal levels for existing hardware.

On the other hand, some of the systems previously identified as Category III conservation technologies could be upgraded to a Category II ranking with a significant reduction in their costs. Many of these systems are hardware-dependent and the high first cost renders them difficult to sell. Because cost reductions are often critical to success, effective government funding for research and development is most likely to have an effect in this area.

Since 1973, significant strides have been made in certain sectors. One example is building automated systems based on the use of the computer (through mini-computers, "smart boxes," and other microprocessing-oriented hardware). Such systems have been sold to building owners and operators with some success, primarily for larger nonresidential buildings. Costs for such automated buildings are still high, sometimes in excess of \$2.00 per square foot, and rarely less than \$0.40 to \$0.60 per square foot.

Adoption of Standards

The adoption of energy conservation standards for new buildings by state and municipal building regulatory agencies could either accelerate or slow down. In 1975 Arthur D. Little, Inc., estimated that only 50% of new residential construction was being built to an ASHRAE 90 level of quality. Perhaps as much as half of this was new construction built to meet HUD's Minimum Property Standards. We anticipate that the adoption of mandatory standards will increase significantly and that 75-80% of new residential construction will meet improved thermal standards by 1982.

The adoption of standards for new nonresidential buildings has likewise increased in recent years, but remains far below that of the residential sector. We estimate that only 20% of new nonresidential construction meets an ASHRAE 90-level of construction quality, but should increase to 60-70% by 1982.

Considerable pressure has resulted in an accelerated program by ASHRAE, ALA, and IES to make available standards on energy conservation in existing construction. This is a much more difficult task (both professionally and politically) than the ASHRAE 90 effort for new construction. Therefore, it is perhaps doubtful whether these standards will be — and can be — widely incorporated into mandatory building codes within the same time (approximately three years) that it took for new-building energy conservation standards.

Feedback from industry has been insufficient to indicate all of the problems that standards for existing buildings will generate. Support will probably come largely from the professional community and government. Many energy conservation procedures suggested in the emerging standards have already been adopted voluntarily by owners of nonresidential buildings. Given the other factors which could have an impact on the unit energy consumption of existing construction, the availability and enforcement of such standards may be the primary factor in decreasing annual energy consumption in existing buildings.

One factor that may impair the escalating adoption of energy conservation standards deals with possible institutional problems. These consist of, but are not limited to: (1) a reluctance by existing code authorities to change lighting and ventilation standards for hospitals and schools where such standards have been established on health grounds, (2) problems in water vapor control in residential construction because of improper use of insulation, and (3) the threat of over-insulating nonresidential buildings that have high internal heating limits, with the result that additional cooling is required to remove heat from the building. Not all of the anticipated pitfalls have been identified, but it is likely that each problem will be confronted separately, with solutions more a function of timing than of their importance to energy savings.

Historically, the individual designers of buildings have applied established industry practice to a variety of "similar" situations; many of the practicing professionals do not have a working understanding of energy-conserving schemes and hardware. Individual buildings designed with energy conservation in mind have demonstrated that savings can be significant. A broad effort of technology transfer could be successful in bringing the typical practicing professional to a level where he could achieve substantial savings in new construction.

Perhaps the single most important factor that can be identified as affecting future unit energy consumption concerns the application of effective architectural changes. The cost-effectiveness of major architectural modifications in existing buildings is relatively poor compared to the cost-effectiveness of HVAC systems and operating modifications. For this reason, effective architectural modifications are limited largely to new construction.

The architect is the key to significant energy reduction here. Mandatory energy conservation standards, in concert with the sales efforts of various materials equipment suppliers, result in (undefined) lower limits for collective energy savings in new buildings. To go beyond that lower limit requires a competent design professional capable of instituting basic changes in the form of the building itself, including modifications in the building materials used, shading schemes employed, building orientation, location of the building functions, etc. At present, no definitive data exist on the relative effectiveness of architectural design considerations; however, most knowledgeable people agree that they offer a significant — and as yet untapped — advantage.

The discussion above was limited to those uses of energy that are within the direct control of the design architect, engineer, or builder. In the residential sector, significant energy use (13% nationally) is accounted for by electrical appliances, most residential lighting, and miscellaneous effort-saving items. To this extent, the continued penetration of electrical appliances into households may present a unit demand greater than that extrapolated from historic usage. On the other hand, the energy efficiency of electrical components is undergoing federal-and industry-sponsored scrutiny, and in terms of annual energy usage, an increase in saturation may be offset somewhat by increases in efficiency.

Heat Pumps

A heat pump in its most basic form is a cyclic thermomechanical device that absorbs heat from a thermal source and, through a work input to the device, rejects heat to a sink at a higher temperature. The amount of (thermal) energy rejected at the higher temperature sink would then be the sum of that absorbed from the source, plus that (mechanical) energy represented by the work input to the system. The performance of the heat pump is measured by the ratio between the thermal energy put out and the mechanical energy put in. Devices of this type would normally

see application where heat is desired at one temperature — such as inside a residence — but is available at a relatively lower temperature — outdoor winter conditions. Through a work input to the device, the heat at the lower temperature is in effect “pumped” up to the higher temperature where it may be used.

As in a refrigerator, the input heat is absorbed by a working fluid, typically a fluorocarbon compound, that evaporates at a relatively low temperature and pressure. It is then compressed and allowed to condense at the higher pressure, transferring the heat to the sink, whereupon it is returned to the original pressure level for another cycle. Typical source and sink temperatures for space heating might be 45° and 95°F, respectively. The heat pump is most often considered as a device to supply heat, but it may be reversed to operate as a conventional air conditioner in which it simply removes heat from the air in a room and ultimately rejects it to the warmer outdoor air.

The heat pump has been used for residential heating and cooling since the 1950's. Air-to-air* heat pumps dominate the residential market where air conditioning is desired. The relatively small incremental cost between a central air conditioner and a heat pump also makes the heat pump an attractive alternative for cost-effective space heating.

Where an air-to-air heat pump is elected, the system capacity is typically chosen to match the cooling load of the house. In the heating season, however, the system may also provide space heating, at least until the outdoor air temperature falls below the “balance point,” i.e., the temperature at which the heat pump is just meeting the heat loss of the house. At ambient temperatures below the balance point, supplementary heat is needed.

Water-source heat pumps are also commonly referred to as “Florida” and “California” heat pumps because of their widespread use at one time in those two states. Such devices used groundwater and wells as the thermal source (for heating) and sink (for cooling). Because of the concentration of these units, groundwater temperatures were raised to an unacceptably high level and further deployment of water-source units was stopped.

In recent years interest in residential water-source heat pumps has been renewed because of the interest in solar energy. For solar collectors with liquid heat collection loops, the storage tank is not usable for direct space conditioning once the storage temperature has fallen below about 100°F. But when these collectors are used in conjunction with a water source heat pump, much lower storage temperatures suffice. The heat pump simply provides a means of extracting heat from the collector loop and rejecting it to the conditioned space at a temperature high enough to be useful.

Heat pumps may also be used in many ways in commercial applications. One, of course, would be simply a larger version of the residential air-to-air unit. However, the heating and cooling loads of commercial buildings tend to be quite different from those in residences. Whereas the residential demand tends to correlate strongly with outdoor temperatures, commercial demand is often more a function of internal lighting, machinery, and occupancy loads. Furthermore, commercial structures tend to have relatively warmer core areas and cooler perimeters

* Uses ambient air as thermal source and as heat sink.

during the heating season and the opposite during the cooling season. A popular heat pump arrangement in commercial buildings is one in which many small satellite heat pumps operate off a central heat pump to the ambient. The distribution system, typically a water loop, serves to equalize temperatures in the building by taking the heat rejected from heat pumps that cool the building's core and using it as a source for units to heat the building's perimeter.

The heat pump has been undergoing an evolutionary development since the introduction of the air-to-air type in the early 1950's. When first introduced, air-to-air heat pumps were assembled with standard air conditioning components, plus a reversing valve and some additional controls. This new heating device caught on slowly and by the late 1950's perhaps 100,000 or so units had been installed throughout the country. Shortly afterward, heat pumps began having operating problems that were widely publicized; a jarring confirmation came with a Defense Department directive in the early 1960's that removed several thousand heat pumps, which had been purchased in the previous few years and which had proved abysmally unreliable.

At that time, a few of the established suppliers retrenched and began a decade of serious development work in an effort to improve the reliability of the air-to-air heat pump. Most of this work centered around the compressor because it is the heart of the heat pump where the wide variations in operating conditions were felt most severely. Compressor failures were as high as 30% per year during the late 1950's, but had decreased to 8-10% by the late 1960's because of design improvements.

By the early 1970's, the success of the development work was reflected in data collected by electric utilities. Several utilities had assembled a certification listing for manufacturers on whose equipment the utility would grant a customer service contract. The products of several manufacturers have demonstrated a satisfactory and consistently improving reliability. The latest data from those electric utilities who maintain assured service programs for their customers indicate that a compressor failure rate of 4-5% per year might now be expected with equipment that has been properly installed by a dealer within the last eight or nine years and maintained by the utility's personnel.

A far cry from their conventional air conditioning counterparts, current heat pump compressors have larger bearing surfaces, higher operating temperature limits, special lubrication and cooling provisions, and a variety of overload protection measures built into the controls. As a climate control system, the heat pump can be reliable and effective. Properly installed and maintained, it could last as long as 20 years without a major equipment failure. Given the expected level of abuse from defrost cycles, low ambient temperatures, and dirty filters, however, the industry anticipates less than 10 years of reliable service from systems such as those marketed today.

The coefficient of performance (COP) of the air-to-air heat pump will vary with changes in the outdoor temperature. The heating capacity will also vary, and at lower ambient temperatures the heat pump's output will need to be supplemented by electrical resistance heating. To compensate for this temperature dependence, designers commonly use an average COP for the entire heating season. This average, commonly referred to as the "seasonal performance factor" (SPF), is simply the ratio of the total heat furnished by the heat pump during the season to the total electric power input required for both the compressor and the supplementary resistance heaters.

Current air-to-air heat pumps in this country deliver SPF's of 1.5 to 2.5, depending on geographical location. The most common value is around 2.0, indicating that the electricity required by a heat pump is about half that for an electric furnace. As one travels farther north, the SPF decreases because of the greater proportion of resistance heat in the output of the heat pump. There is also a slight effect from the size chosen for the unit. Since a heat pump customarily is sized for the cooling load, unit sizes tend to be smaller in the northern regions, and the portion of the heating load that could be supplied at a COP greater than 1.0 (which corresponds to resistance heating) is limited.

The COPs of the components of air-to-air heat pumps at the rated condition (47% outdoor air temperatures) as well as their overall seasonal performance continue to improve. Some of the newer heat pump compressors are demonstrating COPs greater than 3.0 (up from a typical 2.4) at the rated condition. Furthermore, the compressors are being designed to better maintain their efficiencies (COP) and heating capacities at lower ambient temperatures. Currently, the most credible means of capacity control seems to be the multispeed compressor, which is capable of ensuring higher heat capacity at lower outdoor temperatures. Despite all of these improvements, however, the effect on the seasonal performance factor may not be large. SPF's still will hover about 2.0. Even if a means of capacity control is used, the effect will not be great. A two-speed compressor will elevate an SPF of 2.5 to approximately 2.75, an improvement of 10%.

Sales of unitary heat pumps have increased dramatically in recent years. Total shipments of residential and commercial units in 1976 were up more than 90% from the 1975 total (Figure 4-5). Until very recently, activity in the residential heat pump market has been limited largely to the southern states. The market grew principally at the urging of electric utilities who wished to sell electric heat to customers who relied on other fuels, but still had electrically driven air conditioners. As part of their marketing of electric heat, these utilities developed insulation guidelines and some also provided heat pump service contracts to their customers. In other parts of the country, there are pockets of heat pump activity. Recent fuel shortages and a trend toward central air conditioning in new residences have spurred some new interest in such places as Minneapolis, Chicago, and Portland. However, there is nothing near the widespread popularity seen in the Southeast.

The residential market for the electric heat pump has been well developed for a decade or more. The major manufacturers have dealer organizations throughout the country and some have undertaken aggressive national advertising campaigns. Many electric utilities advertise heat pumps within their service districts and sometimes, through approved lists, recommend to potential buyers manufacturers whose equipment qualifies for a service contract directly from the utility.

The market is segmented somewhat — one of the major manufacturers has come to be identified with the retrofit market; others are popular with tract builders, or with multifamily dwellings; still other manufacturers cater almost exclusively to the commercial sector. There are also geographic areas of market domination by a single manufacturer. Finally, a local "component assembler" often will be able to dominate heat pump sales because of his reputation and potential for more responsive service. Emphasis is often placed more upon the reputation of the dealer himself than on data relating to cumulative reliability of the product he sells. In the last analysis, the talent and responsibility of the workman who installs the heat pump and the care with which he maintains it will ultimately weigh more on the life of the unit than the manufacturer's design.

FIGURE 4-5 ANNUAL SHIPMENTS OF HEAT PUMPS

Three trends since 1970 have influenced heat pump sales:

- (1) An increasing proportion of new construction is centrally air conditioned. From about 11% in 1970, the fraction increased to 43% in 1972 and to more than 50% in 1974.
- (2) All-electric homes represent an increasing fraction of new construction. From about 8% in 1970, it increased to 36% in 1972 and to more than 50% in 1975.
- (3) The regional distribution of new housing starts has increasingly favored the South. For the period 1970-74, about 45% of new housing starts in the country were in the South compared with less than 40% in the 1960's.

As noted earlier, the favorable light in which the heat pump is viewed in the South would tend to make it the choice for a heating system in an all-electric, centrally air conditioned house.

Of the new electrically heated housing units in 1974, only about 8% had heat pumps. Since electric heat is used in more than half of the new housing, heat pumps accounted for only about 4% of the heat systems in new housing. Residential heat pump sales in 1976 accounted for about 16% of new housing starts; it would be reasonable to expect the heat pump to garner its share of 15-20%, at least for the next few years.

Heat pumps are more likely to be installed in new houses than in existing houses. Even those with ducted forced air systems seldom can be considered candidates for retrofit with heat pumps. Those with gas or oil furnaces will not have sufficient duct flow areas to accommodate the heat pump and its lower air delivery temperatures. And those with central air conditioning, although they have ample duct size for the heat pump, may not be immediate candidates until the air conditioner has to be replaced. Of the 75 million residential units occupied at the end of 1976, heat pumps accounted for the heating systems in fewer than 2 million.

Although exact production figures are closely guarded secrets, there are at least 30 supplier/producers of heat pumps. The four largest suppliers account for about 75% of the market, and have consistently the lowest failure rates and maintenance costs. The market dominance is probably due first to the commitment of these manufacturers — particularly General Electric — to improve the heat pump during the 1960's and second to the existence of a national dealer organization for their household appliances and air conditioners.

Below the major manufacturers is a bevy of smaller national firms and many regional suppliers. Many of the regional companies dominate their local market because of favorable prices and a good, if not widespread, reputation. The smaller national firms commonly purchase equipment from the major manufacturers and from each other to "fill out" their product lines.

The high cost of heat pumps clearly affects their use. If central air conditioning is not desired, the incremental cost of a heat pump over that for any alternative heating system, be it fossil-fuel or electric, is sufficiently large to discourage buyers. If central air conditioning is desired, the choice of a heat pump over a competitive system may not be attractive. Where natural gas is still available for residential use, gas furnaces in conjunction with central air conditioners often appear to have lower life cycle costs and higher system reliability than heat

pumps. Even when electric heating is mandatory, there is serious economic competition from electric furnace/central air conditioner and baseboard/room air conditioner combinations. Whenever first cost is the sole acceptance criterion, as it often is with tract builders, the heat pump almost always loses out to a competitive heating and cooling system.

Another issue relates to the *availability and price of various fuels*. Since natural gas is not available for new residential construction in many parts of the country, many builders have been forced to install electric heat. An oil furnace might be another alternative, but its availability tends to be concentrated in a few areas of the country. If the house is to be centrally air conditioned, a heat pump would seem to be a logical choice, particularly in colder areas and where the cost of electric power is high. Since the heat pump may use about half as much electric energy as an electric furnace, the reduced operating costs would help amortize the higher initial investment. But if power is relatively inexpensive or the winters are mild, the higher first cost and maintenance costs of the heat pump may preclude its selection.

All of this rationale presumes the existence of declining block electric rate schedules. Experiments with time-of-day, or demand, metering indicate that the cost of air conditioning will increase, since the utility's desire for peak load reduction would in most cases address a summer air conditioning peak. This may stem the growth of central air conditioning and reduce the heat pump market.

The heat pump is of no more benefit to a utility on a very cold day than on a hot one. Unlike electric furnaces and baseboard heaters, the electrical demand of a heat pump does not increase proportionately as the outdoor temperature falls; rather it increases from perhaps a third of the electric furnace's demand at a 55°F ambient to one almost equal at the "balance point," thus exacerbating the peaking problem. With a sufficient proliferation of electric heat in its service area, an electric utility might be forced to consider demand metering to reduce a growing winter peak. Barring that unlikely event, at least in the near future, the heat pump still will be considered a ripe target for competition from *electric storage heating*. Some of the utilities in this country already have experimental programs under way with ceramic storage heaters manufactured in Britain and West Germany. Night rates, much like those for heating domestic hot water, might easily make these units competitive with the heat pump.

Another trend in new construction that will affect heat pump sales is that of *better thermal performance standards* in new construction. Without too much effort, the annual heating load of a residence can be reduced by one-third to one-half the values resulting from construction practices of even a few years ago. This reduced heating load will result in smaller savings for the heat pump and longer equipment payback periods even for the smaller equipment sizes required.

Solar Thermal Systems

In contrast with other solar energy technologies, heating and cooling systems are simple in concept and well established. The system includes: a solar collector to absorb solar energy, convert it to heat, and transfer the heat to a circulating fluid; a storage system to permit withdrawal of the collected solar heat when needed; an auxiliary energy source to provide heat at night or during extended cloudy periods; a cooling unit to be driven by the collected solar heat; and the controls, piping, valves, pumps, etc. to connect the individual elements.

A wide variety of solar system arrangements is possible. Typical of such system arrangements are the following:

- *Hot Water:* The system arrangement to provide hot water through preheating of the incoming hot water in conjunction with thermal storage (Figure 4-6) utilizes the solar collector efficiently because solar heat collection is independent of demand. The system is particularly useful when climatic conditions are not adequate to heat water to the desired temperatures.
- *Hot Water and Space Heating:* This extends a hot water system to include space heating (Figure 4-7), where the demand can be satisfied either by using thermal storage or by delivering heat from an auxiliary boiler.

The major focus in the development of applications for solar heating and cooling technology has been residential markets and hot water or heating/hot water systems, because such systems are technically simple and economically attractive. As energy costs rise and solar collector costs decline, other applications will be developed, for example, more complex systems for air conditioning and industrial and agricultural heating. Because of the size of the residential market, however, and because of the potential energy savings available, the focus probably will be on residential applications in the near future.

Practical low-technology solar energy systems have been in existence in the United States since the 1930's, and while design concepts may have changed, the basic technology remains the same. Solar research has been under way in this country for years, but until recently the economic and competitive environment for solar energy in heating and cooling applications has not been favorable. The energy environment is now changing, and economic feasibility is bringing solar energy to the point of being competitive with conventional fuels.

Under the constraints of present and near-future technology, typical performance characteristics of solar thermal systems are as follows:

Hot Water — Annual efficiency is essentially independent of building type and location and is directly related to the percentage of hot water load covered by the solar hot water system. Solar systems are typically designed to provide 50% of hot water requirements. Sizing on the basis of solar heat costs yields different results than when life-cycle costs are used to establish system size. The life-cycle approach is geared to optimization of payback, which leads to oversizing of collectors. System efficiencies will therefore be lower, and the larger system, with its associated higher load, may not be economically acceptable. Minimum solar heat costs, throughout the United States, occur at solar load percentages of 40-70%, and a 50% solar load combines acceptable economic performance with reasonable collector sizing. It may be economical to use large solar load percentages when energy costs exceed the minimum solar heat cost. Annual efficiencies of about 35% can be expected with a 50% solar fraction. In the period beyond 1980, some small improvement—up to perhaps 40%—is possible.

Hot Water and Space Heating — Space heating and hot water systems with a substantial space heat component will tend to have lower efficiencies than hot-water-only systems because of the seasonal variation in heating load. Typically, hot water/space heating systems will have an annual efficiency of approximately 35% and will be designed with a solar fraction of 40% (i.e., the

Source: Arthur D. Little, Inc.

FIGURE 4-6 MODEL SYSTEM FOR SOLAR HOT WATER PREHEATING

Source: Arthur D. Little, Inc.

FIGURE 4-7 MODEL SYSTEM FOR SOLAR SPACE AND WATER PREHEATING

solar system assumes 40% of the heating/hot water load). The variables that will affect these figures include building type, region, type of fuel being displaced, new vs. existing construction, etc. As in the case of hot-water-only systems, annual collector efficiencies may improve modestly by 2000.

Hot Water, Space Heat, and Air Conditioning — There is no substantial variation in the performance of this system type by either location or building type (the only exception being commercial buildings with low hot water usage). A solar fraction of 50% is typical because the air conditioning load helps to balance the seasonal space heating load and permit good performance at a higher solar fraction. Annual efficiency is approximately 38%. No significant improvements in performance are anticipated for these systems, because efficiency figures are based on the use of advanced high-temperature collectors.

Collector costs are normally given in "dollars per square foot" — the total cost of a system divided by square feet of collector. As collector area requirements for a system increase (a heating/hot water system will require more collector area than a hot water system, for example), overall system costs will increase. However, costs per square foot of collector will decrease, because the total cost of controls, piping, and storage devices will not increase proportionally with collector area.

Typical new residential hot water solar systems presently cost about \$35 per square foot and require 60 square feet of collector area, thus averaging \$2100 for an installed system. Hot water systems for commercial use are much more variable in size, but would have an average area of 200-800 square feet. Hot water systems are presently the most economical for employment of solar energy because loads are relatively stable throughout the year. In addition, the small size of the systems makes them more readily affordable than systems designed to include space heating and cooling. Residential units are usually installed on an existing pitched roof, while commercial units are typically free-standing collectors on a flat roof and are thus less expensive.

Cost estimates have been based on the incorporation of solar systems and designs into new construction. Retrofit costs will be about 15% higher for hot water systems and 25% higher for space heating and cooling systems. The distribution and installation process for the retrofit market typically has higher costs and markups than when similar systems are sold to the new construction market. While penalties for retrofit applications will vary widely, depending upon building type, home location, etc., the figures given above are representative of nationwide experience.

Major technological changes in system configuration are not expected in the solar thermal area in the foreseeable future. While considerable government-supported and privately funded technical developments are under way, it is unlikely that any radically new concept will dramatically improve the performance or reduce the cost of such systems. Significant cost and performance improvements are likely but are expected to be the result of incremental engineering and manufacturing developments. To the extent that efficiency is improved and to the extent that the size of the required collector array can be reduced, system costs will, of course, decline. And the relative costs of solar systems will drop as alternative fuels become more expensive.

In 1973, sales of solar equipment used for heating and cooling totalled less than \$1 million; sales exceeded \$140 million in 1977. The allocations of this total by system type and building market are as follows:

Solar System Market — 1977

Sales Volume	\$145 million
Market Segment:	
residential	82%
non-residential	18%
	<hr/> 100%
System type:	
hot water only	61%
heating and hot water	38%
heating, hot water and cooling	1%
	<hr/> 100%

Most of the experience and exposure gained in the design, production, and marketing of hot water systems will be applicable to the heating system market as it begins to develop. The cooling market is likely to develop more slowly, primarily because it depends on the development of economical and efficient high-performance solar collectors and heat-actuated cooling equipment.

Market emphasis on hot water systems also suggests an initial market concentration in residential rather than non-residential buildings. A much higher percentage of the energy load of the average residential building is devoted to hot water than is the case for any other building category, except for laundries, restaurants, and certain industrial uses. In addition, residential construction is a large market that is likely to receive strong government support for the installation of solar heating systems.

In the early years, solar applications in new buildings will be less extensive than systems installed in existing buildings. The sheer size of the retrofit market suggests its greater potential: present building inventory is approximately 75 million residential units and 20 billion square feet of non-residential space, and only 2 million new buildings are constructed annually. The economics of retrofit use of solar are not as attractive as for new buildings, however. (Installation is more difficult and expensive, and distribution more costly.) It is expected that retrofit activity will remain strong during the years of federal financial incentives, but as the most receptive retrofit markets become saturated, new buildings will take increasing market shares in terms of solar applications. The development of solar use in new buildings will depend heavily on builders and their willingness to include solar energy as part of building design. It is expected that solar installations will become a recognized marketing advantage, particularly as experience with solar expands.

The solar energy industry is in the early stages of its development. It can best be described as a collection of relatively small entrepreneurial, opportunistic firms — many of them inexperienced, and most lacking the financial resources and management capability to survive or become significant in the industry in the long run.

The Federal Energy Administration's quarterly survey of solar collector manufacturing activity indicates that roughly 195 companies were engaged in the manufacture of solar collectors in late 1977. The Solar Energy Industry Association, which is concerned with developing broad public credibility and promoting the use of solar systems, had a membership of 231 product and

service companies in early 1977. Figures such as these cannot be interpreted as definitive, however. Participants can be expected to enter and leave the industry in significant numbers over the next several years, and the exact nature of and participation in the industry cannot be predicted accurately.

Many solar firms are local or regional concerns performing almost all of the functions from manufacturing through distribution, marketing, installation, and servicing. These small firms will have a role in the expansion of the industry, but it is likely that their primary functions increasingly will center on distribution and installation rather than on the manufacture of solar equipment. As consolidation and rationalization occur, the major HVAC and materials companies will begin to capitalize on their established strengths in manufacturing and distribution, and the number of large companies participating in the industry will increase.

The participants in the infrastructure of the solar industry include designers and architects, materials suppliers, equipment manufacturers and distributors, builders and contractors, financial institutions, and the ultimate consumer. The government (federal, state and local) participates to the extent that incentives and demonstration programs are used and in the development and administration of regulations, codes and standards. Coordination of efforts to develop solar energy may pose problems because few people are yet capable of assessing the cost/benefit implications of solar use.

The purpose of financial incentive legislation is to accelerate rapidly the development of the industry. The industry has not reached the stage of maturity where reliable and cost-effective products are being accepted by a knowledgeable market. Further modifications are required in the design and installation of systems to improve both their performance and their reliability. Systems costs are relatively high because there are limited economies of scale from manufacturing, distribution, and installation, and because many of the participants are inexperienced. Consumer knowledge is relatively undeveloped; most consumers demonstrate either limited understanding of solar energy or unrealistically high expectations about the potential of solar systems.

There are no major technological barriers to the commercialization of solar heating and cooling systems. The foremost barrier is economic. Solar systems require a high initial capital investment but have relatively low annual operating costs. Conventional systems, on the other hand, have lower initial capital costs, but high annual operating costs for fuel. On the basis of most generally accepted measures of economic evaluation (first costs, payback period, life cycle costing) solar systems have not yet proved economically competitive with conventional systems, and the potential purchaser of solar equipment does not find the high initial cost justified by savings in operating expense.

Solar heating and cooling systems can be expected to become competitive only as costs of conventional fuel rise, as solar technology improves, and as solar equipment costs decline. In the short term, consumer acceptance of solar can be accelerated through federal financial incentives designed to improve comparative economics, and through consumer education programs.

The development of solar energy markets may also be hampered by institutional constraints, although the significance of such constraints is difficult to project. Activities of the building and financial communities, utility companies, insurance companies, and local governments are potential areas of concern. The utility companies could develop a strong anti-solar

bias, for example, if the development of solar energy leads to significant changes in peak load demand or loss of revenue. Changes in insurance rate structures to cover solar installations could contribute to consumer resistance; obstacles in the financing of solar purchases could dampen consumer enthusiasm, etc. The relative importance of such constraints will become apparent as solar energy markets expand.

Most of the uncertainties regarding the commercialization of solar heating and cooling systems bear on the speed, and not the direction, of the development of the solar industry. The energy issue has become a national priority. The variable and uncertain aspects of the emerging conservation ethic include the availability and price of all energy forms, market share of major fuel types, and government regulation of price and use. The development of solar markets will also depend on cost and performance of solar systems and the extent of industry commitment and market response.

Industry delivery of reliable and durable solar systems is mandatory. Faulty installation and/or poor design can lead to consumer backlash — as can overly optimistic expectations about the capabilities of solar equipment — with the potential for undermining many of the positive aspects of the conservation concept. In the long run, the solar industry itself will determine how successfully the market for solar energy systems will be developed. This effort will take place via self-policing activities of industry participants in response to government standards for consumer protection, patterns of trade, etc.

In the short run, solar development will depend on government action. On one side, energy policy will determine the energy framework within which solar must compete, and on the other, the granting of government incentives to dilute the first-cost barriers of solar investment will determine the specific competitiveness of solar energy systems.

The benefits of solar commercialization will accrue to the individual consumer via reduced energy bills and reduced dependence on other fuels. The nation as a whole will benefit as solar acceptance is accelerated and as national demand for conventional fuels is mitigated. The use of solar systems to provide basic energy has the environmental benefit of being pollution-free and virtually noiseless, and the development of an expansive and sophisticated solar industry will mean new business opportunities.

Unique among heating and cooling fuels, solar is a visible energy source — the collector arrays typically being installed on south-facing roofs. Solar installations may therefore have the spillover benefit of advertising active concern for conservation and energy awareness. In addition, the potential purchaser will be able to see that solar is gaining acceptance.

Photovoltaic Conversion Systems

Present photovoltaic conversion technology is dominated by the single-crystal, silicon solar cell developed in 1954 at Bell Laboratories and applied to meet military and space systems requirements. Individual solar cells are thin wafers sliced from single silicon crystals to which dopants are added to create p- and n-type materials to form a junction. When the region of the silicon adjacent to the pn junction is illuminated, photons cause electrons to move across the junction to produce the photovoltaic conversion effect. A grid of narrow metal contact strips

applied on the surface of the cell collects the current, which then flows through an external circuit to the load. Under peak sunlight conditions, about 0.015 volt DC can be generated by a typical solar cell.

The solar cells are coated with thin layers of transparent dielectric materials to reduce reflection of the incident radiation, are mounted and interconnected in series-parallel arrangements into arrays, and are encapsulated to protect against atmospheric contaminants. The solar cell arrays can be interconnected to meet specified electric power requirements.

Most photovoltaic conversion systems need a means of storing the electric power generated for use during night and cloudy daytime conditions. Storage batteries are usually supplied along with a power conditioning system that includes a voltage regulator, blocking diodes, controls, and inverters to convert DC into AC.

Terrestrial application of photovoltaic systems is presently confined to unattended power supplies for use in remote areas, where conventional portable engines or generators may not be feasible, and where electric power transmission lines cannot be installed economically. Even at the current high prices for silicon solar-cell arrays, \$15 to \$25/Wp,* photovoltaic systems are being developed for such terrestrial applications as:

- Microwave repeater stations
- Communications equipment
- Television stations and TV receivers
- Water pumps for irrigation
- Navigation aids (buoys, platforms, drilling rigs)
- Railroad grade crossing signals
- Battery chargers
- Lighting of highways and airport runways
- Cathodic corrosion protection of pipelines, underground equipment and bridges
- Systems to monitor weather, air pollution, etc.
- Military range instrumentation
- Consumer products such as calculators, watches and toys
- Commercial and residential buildings for pilot tests and demonstrations
- Production of fresh water from brackish or salt water.

Silicon solar-cell arrays are being produced with efficiencies (based on total area) of about 12% for circular cells and up to 15% for rectangular cells. The present silicon solar cells are produced using techniques developed by the electronics industry.

A typical photovoltaic conversion system consists of an array of solar cells that may be either flat arrays or solar cells combined with solar concentrators, mounted to face the sun. The mount may either be stationary or may follow the sun. Solar-cell arrays in series-parallel arrangements will achieve a required output voltage; a controller will maintain the required voltage and a uniform flow of power to the load, a battery will store power for future use, and an inverter will convert the DC output of the solar cell array and/or the battery storage into AC power compatible with load requirements.

*Wp (peak watts) is the power produced at noon.

The DC output from the solar-cell array can either be used to charge the battery or be transmitted directly through the inverter to the load. There is an advantage in going directly through the inverter to the load to avoid charge-discharge losses (up to 30% of the solar cell array output) in the storage battery.

Dramatic improvements in the cost and performance of photovoltaic conversion systems are expected if development is continued and the milestones outlined by DOE are met. The photovoltaic industry expresses confidence that it can achieve the goals of the program, provided that substantial government funding of R&D and demonstration programs continues.

Under present market conditions typical costs of a present photovoltaic conversion system, exclusive of solar cells, are as follows:

- *Structural Supports* — The installed cost of structures required to support solar cell arrays in a fixed position is \$2.00-4.00 per square foot of array, with the cost shared evenly between materials and installation labor.
- *Batteries* — Over the near term, the cost of high-quality lead-acid batteries capable of efficient operation under the high-duty cycle conditions is projected to be \$40-60 per kWh of capacity. For most applications where storage is required only on a daily cycle, 2-4 kWh of storage battery capacity are required per peak kW of solar-cell capacity. The cost of switching-type, solid-state inverters, similar to those required, varies widely with power level and design, but typically ranges from \$300-800 per kW at the 2.5-kW power level to \$100-400 per kW for larger units (500 kW). These costs could be reduced substantially with quantity production.
- *Wiring* — The power output of individual solar cell arrays will be at low voltage and high current. Solar-cell arrays can be arranged to achieve the required voltage through series-parallel connections. The cost of the wiring is projected to be about \$1-2 per square foot of solar-cell array.

The present cost indicated above for array installations, energy storage, and inverters amounts to \$0.4-0.8/Wp of solar cells. Over the near term, the solar-cell array represents the major portion of the system costs. However, as the cost of solar cells decreases to \$2/Wp and lower, the cost of other components will assume increasing importance. Therefore, they will have to be developed in parallel with efforts to develop more reliable and low-cost solar-cell arrays. Programs are now underway to establish performance criteria and the environmental requirements of photovoltaic systems.

Photovoltaic conversion systems are now used primarily for special applications where their cost has only a limited influence. The FEA estimates the current U.S. market for photovoltaic systems to be between 250 and 300 kW. The present government market is about 25% of this total and depends mainly on space vehicle requirements, demonstration programs, and communications. Commercial and industrial applications for unattended power supplies constitute the majority of the remaining market. The market for major applications — markings and warning devices, corrosion protection, monitoring and sensing devices, communications, consumer products, and general power sources — is expected to increase to 25,000-50,000 kW annually by 1986, according to BDM Corporation.

The cost reduction projections for silicon solar cells are based on extrapolation of past experience in achieving production volumes. Expected commercialization of the technologies is expected to lead to further market growth, increased industry volume, and additional cost reductions. The cost projections do not apply if major cost elements are determined by patent monopolies, material resource restrictions, or government regulations. These constraints are unlikely to apply to silicon solar cells, but cadmium sulfide and gallium arsenide solar cells introduce uncertainties in the availability of the required minerals, particularly at greatly increased volume.

The industry is now a conglomerate of organizations including:

- Electronics and manufacturing companies
- Energy development and distribution companies
- High-technology and aerospace companies
- Non-profit organizations
- Universities
- Consulting firms
- Government laboratories and project management groups.

No single force dominates the industry and no one organization has the ability to assemble a complete system from its own components and materials. Only Texas Instruments and Motorola are vertically integrated in the solar cell business, but even they are not yet automated because they produce integrated circuits. Irrespective of future actions by large companies, small suppliers probably will co-exist successfully with larger companies until a mass market has been created.

The large electronics, high-technology, and energy companies, which have acquired or developed photovoltaic technology subsidiaries or divisions, are planning to expand their photovoltaic business and if market conditions are favorable, are prepared to invest substantially in new ventures. These companies also have the capability to supply systems to the large utilities or sell photovoltaic systems to industrial customers at the megawatt level for commercial uses. Market opportunities may also be associated with solar power satellite developments if this large-scale option for power generation is demonstrated to be competitive with large, central-baseload, power-generation plants that use conventional fuels.

Many companies in this field, including some large semiconductor manufacturers, prefer to seek government support during the market start-up stage. The semiconductor industry is aware that the major energy companies (i.e., Exxon, Mobil, Shell, Atlantic Richfield) have moved into the photovoltaics field through acquisition and hiring of key personnel, and that they could use their powerful and widespread distribution and service facilities to become major suppliers to the emerging photovoltaic market.

Market projections for photovoltaic systems based on achieving a \$0.50/Wp cost goal have been interpreted to mean that photovoltaic systems could be cost-effective vs. conventional power generation. Only through a *long-term commitment by the government* to test and demonstrate programs are such market projections likely to be achieved. Producers of photovoltaic systems, especially those in the semiconductor industry, find that investments required to meet

projected cost goals are too great for the private sector to accommodate and that the government must be counted upon to underwrite the development of the industry during the initial period of market growth.

A major educational campaign is needed to acquaint potential users with technical specifications and applications information concerning photovoltaics. Even at the present high cost for solar cells, more photovoltaic systems would be installed if potential users were better informed.

Attitudes of electric utilities will be crucial to the development of photovoltaic system markets. An understanding of the effects of photovoltaic systems on utility operations and definition of utility interfaces will be essential for developing strong and mutually profitable relationships with utilities.

Technical advances are likely to occur in the photovoltaic field over the next 20 years because the projected market growth provides substantial incentives for aggressive manufacturers. For example, amorphous semiconductor materials might revolutionize the photovoltaic industry. Likewise, major and unexpected advances in the techniques for storing electric energy would further increase market penetration.

The emergence of a thriving photovoltaics industry, with the ability to supply many cost-competitive systems, could provide important benefits to the economy. In addition to the primary benefits of reducing dependence on fossil fuels and the direct economic benefits of a new industry, a number of other advantages should be considered:

- The semiconductor industry, outside the solar cell field, would have access to much improved and less costly silicon processes.
- Storage battery advances could support the use of electrically powered vehicles. The high cost of battery storage is also a major cost in wind power; a reduction in storage battery costs would enhance the economic competitiveness of wind power. Residential use would provide the individual control over power supply which is inherent in the "Small is Beautiful" ideology.
- The integration of distributed photovoltaic systems with utility operations, although complex, could reduce the use of fossil fuels and improve load management.
- Power produced for remote village applications, such as to power irrigation pumps, could be competitive with diesel produced power and have a significant impact on socioeconomic conditions in developing countries. Photovoltaic systems will begin to compete with diesel powered pumps and diesel generators at a level of \$2/Wp because of lower maintenance costs and less need for skilled labor in installing and servicing.

Wind Power Systems

Wind power plants for generating electricity or for mechanical pumping have been used for some time in remote areas where power from the utility grid is not available and operation of engine generators is impractical.

Most of the commercially available wind generators have rated outputs of 0.1-15 kW. The upper end of this range may be applicable to residential on-site power units in the United States. The present worldwide market for small wind generators, only about \$3-6 million, is expected to grow substantially as the costs of conventional energy sources increase and the technical/economic performance of wind turbine systems is improved.

Several programs are under way to develop larger wind power units with output capabilities of 100-1500 kW. These units, several of which are in the preliminary testing stage, would be applicable to various on-site applications for residential units, commercial buildings, and small industrial operations.

Figure 4-8 shows how typical installed costs of complete wind generators vary with system output. The present commercial units, under 15 kW, have installed costs of \$1800-\$3000 per kW at rated wind speeds (battery storage not included). The DOE goal is the cost projected for large units (200-1500 kW) once they are fully developed and in production. The larger units may be applicable for some on-site applications involving apartments, commercial buildings, and industrial plants.

The cost breakdown of a typical commercial wind turbine unit using battery storage is shown in Table 4-10. The cost of the wind plant and the tower is over 80% of the system cost, with batteries and the inverter accounting for the other 20%. The costs associated with storage are, therefore, not presently a critical factor in determining the economics of smaller wind power systems. This situation could change, however, if the cost of the wind plants can be reduced significantly. Many of the commercially available wind turbine generators are technically sophisticated, and it is doubtful that large cost reductions can be expected in the smaller units through technical improvements. However, increased production would have some limited cost benefits.

The costs per kW projected for the larger units are less than half those of the smaller units (Figure 4-8), in part because of economies of scale associated with the major components such as generators, blades, and control towers. These lower costs represent goals at this time and are not as firm as those indicated for smaller units. Even the cost projections for large units indicate that wind turbine power systems have a relatively modest cost reduction potential (as compared, for example, with the order-of-magnitude cost reductions projected for photovoltaic power systems). Therefore, their widespread implementation is predicated primarily on increasing costs of conventional power sources over and above the inflation rate.

Figure 4-9 shows typical costs of electric power from commercially available wind turbine systems as a function of average wind speed. As indicated, the cost of power increases rapidly with decreasing wind speeds. This further suggests the importance of operating wind turbine generators only in areas that have favorable wind regimes — probably in areas where wind speeds average 14 mph or higher. In such areas power costs below \$0.10/kWh may be achieved even with smaller wind generators. The cost of power in favorable wind areas is almost competitive with conventional power costs in areas with high-cost electricity (parts of the East Coast). As a result, there could be significant implementation of selected wind turbine generator applications in the near term as conventional power costs increase or the government provides incentives to install energy systems using renewable resources.

FIGURE 4-8 COST OF WIND GENERATORS

TABLE 4-10

TYPICAL COST BREAKDOWN FOR WIND TURBINE SYSTEM

Windplant* (25-ft blade diam.)	\$19,900
Tower (45 ft)	1,960
Batteries (40 kWh)	2,520
Inverter (5 kW)	<u>4,860</u>
Total Component Cost	\$29,240
Installation Cost**	<u>1,600</u>
Installed Cost	\$30,840
Cost Per Operational kW***	\$12,340
Cost Per Rated kW	2,050

*Rated capacity — 15 kW (Grumman Rating at 26 MPH)

**Four-man crew for two days (with light-duty crane). This assumes a fairly straightforward installation procedure with no high winds, rain, etc. resulting in delays.

***Average Wind Speed of Approximately 14 MPH

FIGURE 4-9 POWER COST AS A FUNCTION OF WIND SPEED FOR FOUR SMALL WIND GENERATORS

The widespread implementation of on-site wind turbine generators clearly depends primarily on providing systems that are cost-competitive with other power sources. In addition wind power systems could be affected by institutional barriers associated with such issues as the ability to provide sufficient numbers of skilled technicians for system installations, integration with central utility grids, and component production limitations. However, the most serious barriers to the widespread implementation of wind turbines for on-site use will probably be those associated with:

- Negative visual impacts resulting from the high towers required for the deployment of wind turbines. The size of the system (blade diameter, tower height, etc.) for any given application will depend on the prevailing wind velocities. Three wind regimes are considered:

Strong Winds (16 mph): as in parts of the Great Plains and coastal areas of New England.

Average Winds (12 mph): as in the middle Atlantic States and parts of the Rocky Mountain area.

Low Winds (9 mph): as in parts of the West Coast and the Southwest.

A single family house in an area of "average" wind conditions would require a turbine blade diameter of 19 ft to satisfy a major portion of the electric power requirements. A wind turbine this size requires a support tower 30-50 ft high, depending on local topographical conditions.

Small apartment houses would require a tower about 80 ft high with wind turbine blades 100 ft in diameter if a single wind turbine generator were used, and a typical commercial building would require a tower more than 100 ft high to support a turbine with a blade diameter of 150 ft.

Clearly, there are serious questions whether it would be acceptable to use a multiplicity of wind turbines of the size indicated above in residential/commercial areas. This naturally suggests either the design of systems that are smaller (and thus less offensive) or restriction of wind systems to more remote locations (rural areas, etc.).

- Low-frequency noise resulting from the blade motion. Typical rotational speeds are from 40 rpm to 120 rpm and, therefore, any noise tends to be rather low frequency, which has the capability to travel long distances. There are relatively few quantitative data at this time about the noise levels resulting from wind turbine operation. There is little doubt, however, that sufficient noise is generated to cause potential problems when wind turbines are located close to a residential area, where even low noise levels would be noticed, particularly when people are sleeping.
- Interference with T.V. reception. The motion of wind turbine blades can seriously interfere with television reception, particularly for larger machines that might service groups of houses, apartments, or commercial properties. For these large machines, the range of the interference can exceed one mile and, therefore, could severely limit the placement of wind turbine systems.

4.3 COST AND RATINGS OF TECHNOLOGIES

This section considers the operating characteristics of the technology groupings in two parts: (1) the capital cost and annual operating savings of each technology grouping in each building/market and each region and (2) a rating of the non-economic characteristics of each of the technology groupings as a function of the building/market. Ratings were derived for those non-economic factors judged to be the most important to the principal decision-makers in the various markets of the R/C sector.

The focus in the analysis has been on determining the market penetration of the various energy technologies into the major markets in the R/C sector. The approach has required the reduction of a very large and diverse market, a wide range of building types, and numerous geographic regions with differing climatic characteristics to a relatively restricted number of markets, buildings, and regions. While this approach may be necessary if all technologies are to be considered on a comparable basis, and though it may be an acceptable way to consider technologies with relatively widespread applicability, under these highly *averaged* circumstances it will have a tendency to overlook those technologies with applicability only in particular favorable circumstances. For example, wind systems are likely to be used in very specific areas where wind speeds exceed the average, and penetration estimates (based on our methodology) will understate the penetration of wind systems.

For all technologies, the basis for the capital cost and the annual operating cost savings is derived from Arthur D. Little assumptions about a "reasonable" design and size for each of the prototypical buildings. Some of the assumptions are based on reasonable rule-of-thumb design principles and not on an optimization of a detailed life cycle costing analysis. For example, the solar thermal systems were designed to carry 50% of the hot water load, 40% of the combined heating and hot water load, and 50% of the combined cooling, heating, and hot water load. Such systems may be considerably smaller or larger than the "optimum" based on a life cycle cost approach or other design principles.

The somewhat simplified approach was chosen primarily for two reasons. Because the focus in this analysis has been from a market viewpoint, a guiding principle has been to use the procedure that best represents the normal approach of most of the decision-makers in the market, and not that approach which may be the best or most sophisticated. The second reason is to simplify the analytical process wherever possible, particularly when the simplifications would appear to have no important effect on the results of the analysis.

Conservation Technologies

Table 4-11 includes estimates of the cost and effects of conservation technology improvements as applied to single family residences. (Table 4-2 showed similar data for other types of buildings.) A complete listing of the capital cost and operating savings assumptions for all building types, regions, and periods is included in Appendix B.

Heat Pumps

Heat pump capacity is calculated to carry either the air-conditioning load or the heating load for the largest number of hours per year, whichever requires the larger heat pump. Thus, to size heat pumps, we must calculate the capacity required for the cooling load and the capacity required for the space heating load, and compute the system costs for the larger of these.

TABLE 4-11

**CAPITAL COST AND OPERATING SAVINGS
NEW SINGLE FAMILY RESIDENCES**

	<u>Northeast</u>	<u>North Central</u>	<u>South</u>	<u>West</u>
Conservation Level I				
Cost	690	690	330	330
Savings/Unit*	26	40	20	41
Conservation Level II				
Cost	1,150	1,150	830	830
Savings/Unit*	35	50	30	50
Conservation Level III				
Cost	1,900	1,900	1,330	1,330
Savings/Unit*	42	56	37	56

*(10⁶ Btu/yr)

The energy saved by the heat pump in comparison with resistance heating is estimated from the Seasonal Performance Factor (SPF_H) for the heating season — the ratio of the space heating load (Q_h) measured by the input energy which would be required with resistance heating to that measured by the input energy required with a heat pump supplemented by resistance heating. The energy saved (ES_H) is thus:

$$ES_H = Q_h \frac{(SPF_H - 1)}{SPE_C}$$

General Electric has published data showing the Seasonal Performance Factors (SPF) in various locations. The table below indicates the locations used as the basis for our calculations. If the heat pump has a different — typically, a lower — SPF_C in the cooling season than an air conditioner would have (typically 3.0), the energy savings must be modified accordingly.

<u>Region</u>	<u>City</u>	<u>SPF_H</u>	<u>Heating Degree Days</u>	<u>Cooling Degree Days</u>	<u>SPF_C</u>	<u>Design Temperature Heating (T_{mh})</u>
NE	New York City	1.7	4871	1350	2.5	37°F
NC	Omaha	1.8	6218	1270	2.5	32°F
S	Atlanta	2.2	2980	1530	2.5	45°F
W	Albuquerque	2.0	4350	1150	2.5	42°F

The energy lost (EL_C) during the cooling season is thus the cooling load (Q_c), times the difference between the reciprocals of the seasonal performance factor of the heat pump in its cooling mode, SPF_C , and that of the air conditioner, SPF_{AC} . Thus,

$$EL_C = Q_c \left(\frac{1}{SPF_C} - \frac{1}{SPF_{AC}} \right)$$

Cooling loads are expressed as the total Btu's that must be removed annually from each building type in each region, including sensible heat, latent heat, and internal dissipation. To calculate required heat-pump capacity for a given building, per unit or per 1000 ft², first compute the size required to carry the air-conditioning load. Next, divide the cooling load in Btu/yr by the degree-days of cooling (DDC tabulated above) characteristics of the region, and by 24 hours per day, to establish the Btu/hr-degree characteristic of the building and the outside temperature against which the cooling load must be pumped. Finally, multiply this number by the 15° temperature difference for which air-conditioning equipment is normally rated, and divide by 12,000 Btu/hour to obtain the cooling capacity required of the heat pump in tons/unit or tons/1000 ft². This approach ignores influences of regional variations in humidity, but nevertheless yields reasonable estimates for buildings in which the cooling load results primarily from heat in-leakage and infiltration.

For buildings, such as retail establishments, with high internal dissipation in relation to heat in-leakage and infiltration, the cooling load is spread over more hours than the DDC would indicate. Thus the above procedure tends to overestimate cooling capacity requirements. Therefore the cooling capacity required in retail buildings is reduced by one-third.

Heating loads are already corrected for internal heat gain from lighting, people, auxiliaries, etc. To calculate the heat-pump capacity required to carry the heating load, per unit or per 1000 ft², divide the heating load in Btu/yr by the degree-days of heating characteristic of the region (tabulated above), and by 24 hours per day. The result is the capacity required in Btu per hour per degree of temperature difference across which the heat is to be pumped. The rating in tons corresponds to pumping 12,000 Btu/hr across roughly a 20° temperature differential (i.e., 85-65 for cooling and 45-65 for heating).

It is becoming conventional to size heat pumps to run continuously and just meet the load when the outside temperature is that temperature, T_{mh} , below 70° that occurs for the maximum number of hours per year. These temperatures for the regions of interest are tabulated above. (Atlanta, for which 45° is used as the outside temperature at which a heat pump sized to carry the cooling load could just carry the heating load, is an exception. In this case, capacity is calculated as though it must be delivered from a 45° outside source, and even that capacity is less than the capacity dictated by the cooling load.)

The temperature difference across which the rated heat load is to be pumped ($70^\circ - T_{mh}$) must be corrected for a loss in capacity with outside temperature below 45°. A multiplying correction factor which fits the derating curve reasonably well is:

$$\left(\frac{60}{15 + T_{mh}} \right)$$

The formulas for computing the heat pump capacity are:

$$C_c \text{ (Tons)} = \frac{Q_c}{24DDC} \cdot \frac{15}{12,000} = \frac{Q_c \text{ (Btu/yr)}}{19,200 \text{ DDC}}$$

$$C_h \text{ (Tons)} = \frac{Q_h}{24DDH} \cdot \frac{(70 - T_{mh})60}{(15 + T_{mn})} \cdot \frac{1}{12,000} = \frac{Q_h \text{ (Btu/yr)} (70 - T_{mh})}{4,800 \text{ DDH} (15 + T_{mh})}$$

C_{hp} is equal to the greater of C_c or C_h .

Applying these formulas to the computation of heat pump capacity for single-family residential new construction in the 1976-1980 period, gives the results tabulated below. Fuel savings are presented also for the case of the heat pump versus electric resistance heating and electric air conditioning.

The total estimated cost of a total heating system with an electric heat pump in new single family residences are as follows:

NE	\$4830
NC	5130
S	4440
W	5130

The method presented for calculating cooling capacity for electric heat pumps is equally applicable to gas heat pumps. However, a gas heat pump of given capacity calculated in this manner has significantly more heating capacity than the electric heat pump of similar cooling capacity because almost all of the heat unconverted to work in the gas engine is available for space heating. In addition, because the availability of this heat is invariant with temperature difference across the vapor-compression cycle, reduced COP in the vapor compression cycle results in a much smaller reduction in the overall COP of the engine and heat pump in combination. Thus, the capacity as well as the efficiency of the gas heat pump in its heating mode falls off much less with outside temperature than is the case with the electric heat pump.

Therefore, to calculate gas heat pump capacity requirements, calculate cooling capacity and a heating capacity and use the larger of the two in calculating capital cost. Capacity in all instances is expressed in tons of equivalent cooling capacity. The appropriate formulas are:

$$C_c \text{ (Tons)} = \frac{Q_c}{24DDC} \cdot \frac{15}{12,000} = \frac{Q_c \text{ (Btu/yr)}}{19,200 \text{ DDC}}$$

$$C_h \text{ (Tons)} = \frac{Q_h}{24DDH} \cdot \frac{1.5 (70 - T_{mh})}{12,000} = \frac{(70 - T_{mh}) Q_h \text{ (Btu/yr)}}{192,000 \text{ DDH}}$$

C_{hpg} is equal to the greater of C_c or C_h .

Fuel costs must be computed from the seasonal performance factor, which is relatively invariant with climate for gas heat pumps in both cooling and heating modes. In the cooling mode a seasonal performance factor (SPF_c) of 0.85 is used, and in the heating mode (SPF_h) a factor of 1.45.

The seasonal performance factors are consistent with steady-state coefficients of performance of 1.15 in the cooling mode, and 1.75 in the heating mode. These figures, in turn, correspond to a COP in the vapor-compression cooler of 3.5, an engine efficiency of 33%, and just over 80% utilization of all input heat in the heating mode.

Thus, the energy cost with the gas heat pump is:

$$\text{Energy Cost} = \left(\frac{Q_h}{SPF_h} \right) + \left(\frac{Q_c}{SPE_c} \right) \quad (\text{unit cost of gas})$$

Capital costs of gas heat pumps for single family residences are estimated to be \$1700 plus \$450 per ton of capacity in the period beyond 1985. For multi-family residences, they are estimated to be \$1000 plus \$450 per ton of capacity, and for other buildings \$1000 per 1000 sq. ft. plus \$450 per ton of capacity.

Solar Systems

The capital cost of solar thermal systems is expected to decline and the operating efficiency to improve over time as the industry matures. Because the technology is expected to remain relatively simple, and because the primary cost component of the solar collectors (the major cost element of the solar system) is materials, dramatic cost improvements through technical breakthroughs or mass production techniques are unlikely. Nevertheless, engineering improvements and an increasingly mature manufacturing, distribution, and installation infrastructure are expected to reduce the cost of systems in 2000 by as much as 40% from current levels.

The cost estimates used in the analysis were based on other Arthur D. Little work which relates the specific cost of the solar system to its size, its particular application (hot water, heating, and/or cooling), and the experience of the industry (essentially a learning curve function) expressed in square feet of collector sales. Because retrofit applications of solar systems will be more expensive, the installed cost is increased by 15% for hot water systems and 25% for combined systems. Additional cost functions can be found in Appendix B.

The capital cost of solar hot water and space heating systems for new electrically-heated, single-family residences in four regions and throughout the period are shown in Table 4-12. Complete cost estimates for solar systems in all buildings are in Appendix B.

Design calculations for photovoltaic systems (and wind power systems) assume a system sized to carry about 60% of the non-space conditioning and hot water loads in both residential and commercial buildings. This sizing criterion has been chosen to limit the comparatively large capital investment that will be required to equip buildings with photovoltaic systems, given the cost assumptions used in this analysis. The cost components for the photovoltaic system used in the analysis were as shown in Table 4-13.

TABLE 4-12

**CAPITAL COST* OF SOLAR HOT WATER AND HEATING SYSTEMS IN
NEW ELECTRICALLY-HEATED, SINGLE-FAMILY RESIDENCES**

<u>Region</u>	<u>1975-1980</u>	<u>1980-1985</u>	<u>1985-2000</u>	<u>2000-2025</u>
NE	5,750	4,540	3,630	2,920
NC	6,060	4,910	3,850	3,280
S	3,470	2,730	2,230	1,830
W	4,330	3,240	2,480	2,180

*1975 dollars.

TABLE 4-13

PHOTOVOLTAIC SYSTEM COST COMPONENTS

	<u>Photovoltaic Panels</u> <u>(\$/Wp)</u>	<u>Installation</u> <u>(\$/Wp)</u>	<u>Power Conditioning</u> <u>(\$/Wp)</u>	<u>Batteries</u> <u>(\$/kWh)</u>
1975-80	15.00	5.00	.56	50
1981-85	2.00	2.00	.25	40
1986-00	.50	1.00	.10	30
2001-25	.20	.75	.04	20

The peak discharge rate (for which the power conditioning equipment is sized) to meet the load requirements is estimated to be five times the peak charge rate. The storage capacity required is about five hours times the peak charge rate. The system is sized to produce about 1 peak watt for every 5 watt hours of energy expected from the photovoltaic panels which produce about 10 watts per square foot. Thus, system costs are calculated according to the following formula:

$$\begin{aligned}
 & \text{(\$ / Wp)} \qquad \qquad \qquad (\$ / \text{Wp}) \qquad \qquad \qquad (\$ / \text{kWh}) \\
 & \left[\text{Panel Cost} + 5 \times \text{Power Conditioning} + \frac{5}{1000} \times \text{Battery} \right] \\
 & \left[\frac{.6 \times \text{Daily Load}}{(\text{kWh})} \times \frac{1000 \text{ Wp}}{(5 \text{ kWh})} \right]
 \end{aligned}$$

The energy saved per day with such a system is region-dependent because of the variations in average insulation. The system size according to this formula is estimated to save 0.6/kWh of daily load on the average in the South, 0.5/kWh in the Northeast, 0.55/kWh in the North Central, and 0.66/kWh in the West. Thus, for the lighting and appliance loads in the average single family house, the photovoltaic system costs are:

1976-80	1981-85	1986-2000	2000-2025
\$2,730	\$654	\$258	\$150

Appendix B provides the capital cost of photovoltaic systems for each building in each region in each time period. The estimated capital cost of photovoltaic systems for new single family houses is shown in Table 4-14.

TABLE 4-14

**CAPITAL COST* - PHOTOVOLTAIC SYSTEMS
NEW SINGLE FAMILY RESIDENCES**

<u>Region</u>	<u>1975-1980</u>	<u>1980-1985</u>	<u>1985-2000</u>	<u>2000-2025</u>
NE	55,170	13,220	5,210	3,030
NC	54,940	13,160	5,190	3,080
S	45,980	11,100	4,350	2,530
W	45,780	10,970	4,330	2,520

*1975 dollars.

The approach of designing prototypical buildings to represent an entire market, designing energy systems for these buildings, and using an average fuel cost for the region has the probable effect of overlooking certain specific applications where particular technologies may be most appropriate and economical. This is particularly true for wind systems where the use of average wind velocities, relatively small system sizes, low average fuel cost, and applications that always require storage can be expected to result in relatively few wind systems penetrating these major markets. The average wind velocities assumed for the different regions were:

Northeast — 10 mph
North Central — 12 mph
South — 9 mph
West — 9 mph

As with the photovoltaic system, the wind powered systems have been sized to carry 60% of the non-heating, cooling and hot water load of the structures. These energy requirements are relatively stable without the seasonal variations of heating and cooling.

Table 4-15 estimates the cost of the different components of the wind powered systems and the savings for each of the four regions through 2025. Although no cost improvements are projected for the turbine generators, power conditioning and storage costs decrease markedly over the period with the total effect being a one-third capital cost reduction in the North Central region by 2000, the region in which the higher wind speed creates the most favorable economic situation for wind power systems.

TABLE 4-15

CAPITAL COST* AND OPERATING SAVINGS – WIND POWER SYSTEMS

		<u>Turbine Generator¹</u> (\$/kWh)	<u>Power Conditioning of Daily Load for 10:1 Peak to Average Load²</u> (\$/kWh)	<u>Storage of Daily Load for 0.6 kWh Storage/ kWh of Load³</u> (\$/kWh)	<u>Total Cost of Daily Load¹</u> (\$/kWh)	<u>Energy Saved in Daily Load</u> (kWh/kWh)
1976-80	NE	300	120	30	450	0.6
	NC	180	120	30	330	0.6
	S	420	120	30	570	0.6
	W	420	120	30	570	0.6
1981-85	NE	300	60	24	384	0.6
	NC	180	60	24	264	0.6
	S	420	60	24	504	0.6
	W	420	60	24	504	0.6
1986-00	NE	300	24	18	342	0.6
	NC	180	24	18	222	0.6
	S	420	24	18	462	0.6
	W	420	24	18	462	0.6
2001-25	NE	300	10	12	322	0.6
	NC	180	10	12	202	0.6
	S	420	10	12	442	0.6
	W	420	10	12	442	0.6

*1975 dollars.

1. \$/kWh of daily load.

2. \$/kWh of daily load for 10:1 peak to average load.

3. \$/kWh of daily load for 0.6 kWh storage/kWh of load.

Table 4-16 shows the estimated capital cost for wind power systems in single family residences. Appendix B provides capital costs for all buildings considered in the analysis.

TABLE 4-16

**CAPITAL COST – WIND POWER SYSTEMS
SINGLE FAMILY RESIDENCES**

	<u>1976-1980</u>	<u>1981-1985</u>	<u>1986-2000</u>	<u>2000-2025</u>
NE	7,580	6,470	5,750	5,420
NC	6,100	4,880	4,090	3,730
S	9,600	8,480	7,790	7,430
W	10,500	9,290	8,530	8,140

Market penetration appears to be influenced by a wide range of financial and non-financial factors. We have analyzed the market impact of technologies through a several-step process. First, each of the markets was analyzed to identify the principal decision-makers and their relative importance in making energy-related decisions. Second, we developed a list of characteristics of energy technologies which were felt to be important to these decision-makers. Third, each of the technologies was rated against each of the non-financial characteristics on a scale from + 5 to -5 through a modified Delphi technique, by a group of Arthur D. Little personnel familiar with the technologies and the R/C markets. Fourth, the technology ratings were combined with the decision-maker rankings, and the importance of the characteristics to the decision-makers, to arrive at the summary ratings, which essentially describe the comparative attractiveness of that particular technology in that particular market sector. This rating was then used to modify a market response function based on the economic attractiveness of the technology. The effect of the non-financial characteristics ratings is to bias the market response either up or down.

Table 4-17 summarizes the assessments of the non-financial characteristics for each of the technology groupings and for each of the time periods. Where a single assessment is made, it is assumed that it will not change over time. Generally, the ratings improve over time as the market becomes more experienced with and accommodated to the characteristics of the particular technologies. Some characteristics, however, may not be affected by time. For example, the space requirements of wind generators will always be an issue affecting their acceptability. These assessments do not suggest that they are intrinsic characteristics of the technologies themselves, but rather that they are the market perceptions of the technologies. Although a particular technology may be reliable today (as proved by extensive testing and field experience), it may be some time before the market recognizes this fact.

The product of these ratings, the decision-maker rankings, and the importance of the characteristics to the decision-makers results in a summary matrix (Table 4-18). This matrix describes the weighted value of the non-financial characteristics for each technology grouping in each market sector in each period. A rating of 0 would mean that the market penetration, determined solely on the economic performance of a technology, would not be affected by these non-financial characteristics. However, a positive rating would mean that the market penetration would be increased by the non-financial attribute to the technology, whereas a negative rating would result in a decrease of the market penetration.

TABLE 4-17

ASSESSMENT OF THE MARKET'S PERCEPTION OF THE VARIOUS CHARACTERISTICS OF SELECTED TECHNOLOGIES

	Electric Heat Pump				Gas Heat Pump				Conservation Option I				Conservation Option II				Conservation Option III				Solar Water Heating				Solar Space and Water Heating				Space Cooling Space Heating and Water Heating				Wind Generators				Solar Photovoltaic			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV				
Societal																																								
Non-Depleting	+1				+1				+2				+3				+4				+3				+4				+5				+4							
Certain Fuel Supply	+1				-3				0				0				+5				+5				+5				+5				+5							
Ecologically Sound	+1				+1				+2				+2				+2				+5				+5				+5				+5							
Aesthetically Pleasing	0				0				0				-1 -1 0 0				-1 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-3 -2 -1 0				-5 -4 -3 -2				-2 -2 -1 0			
Safe	0				-2 -2 -1 0				+1				+1				0 0 +1 +1				-1 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-4 -4 -3 -2				-1 -1 0 0			
Technical																																								
Performance	0				0				+1				-1				-1				-1				-1				-1				-1							
Reliability	-2 -1 0 0				-4 -3 -1 0				+4				+4				+2 +3 +4 +4				-2 -1 0 +1				-2 -1 0 0				-4 -3 -2 0				-3 -2 -1 0				-3 -2 -1 +1			
Technical Complexity	-2 -1 -1 0				-3 -2 -1 0				0				-1 0 0 0				-2 -1 0 0				-3 -2 0 0				-4 -3 -1 0				-5 -4 -2 -1				-3 -2 -1 0				-3 -2 -1 0			
Space Requirements	0				0				0				0				-1 -1 0 0				-2 -2 -1 0				-3 -3 -2 -1				-4 -4 -3 -1				-5 -5 -4 -2				-2 -2 -1 0			
Maintenance Complexity	-1 -1 0 0				-3 -2 -1 0				+5				+3 +4 +4 +4				-1 -1 0 +1				-2 -2 -1 0				-3 -3 -2 -1				-4 -3 -2 -2				-3 -3 -2 -2				-1 -1 0 0			
Industry																																								
Predictability of Installed Costs	-1 -1 0 +1				-3 -2 -1 0				+5				+3 +3 +4 +4				-1 -1 0 +1				-2 -2 -1 0				-3 -3 -2 -1				-4 -3 -2 -1				-3 -3 -2 -1				-1 -1 0 0			
Designer Familiarity	0				-2 -1 0 0				0				-1 -1 0 0				-2 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-4 -3 -2 -1				-4 -3 -2 -1				-4 -3 -2 -1			
Code or zoning barriers	-1 0 0 0				-3 -2 -1 0				0				0				-1 -1 0 0				-3 -2 0 0				-4 -3 -1 0				-5 -4 -2 -1				-5 -4 -3 -2				-5 -4 -2 -1			

Time Period Key

I - 76-80

II - 81-85

III - 86-00

IV - 01-25

-5 unfavorable 0 favorable +5

No effect

	Electric Heat Pump				Gas Heat Pump				Conservation Option I				Conservation Option II				Conservation Option III				Solar Water Heating				Solar Space and Water Heating				Space Cooling Space Heating and Water Heating				Wind Generators				Solar Photovoltaic			
	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV	I	II	III	IV				
Societal																																								
Non-Depleting	+1				+1				+2				+3				+4				+3				+4				+5				+4				+4			
Certain Fuel Supply	+1				-3				0				0				+5				+5				+5				+5				+5				+5			
Ecologically Sound	+1				+1				+2				+2				+2				+5				+5				+5				+5				+5			
Aesthetically Pleasing	0				0				0				-1 -1 0 0				-1 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-3 -2 -1 0				-5 -4 -3 -2				-2 -2 -1 0			
Safe	0				-2 -2 -1 0				+1				+1				0 0 +1 +1				-1 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-4 -4 -3 -2				-1 -1 0 0			
Technical																																								
Performance	0				0				+1				-1				+1				-1				-1				-1				-1				-1			
Reliability	-2 -1 0 0				-4 -3 -1 0				+4				+4				+2 +3 +4 +4				-2 -1 0 +1				-2 -1 0 0				-4 -3 -2 0				-3 -2 -1 0				-3 -2 -1 +1			
Technical Complexity	-2 -1 -1 0				-3 -2 -1 0				0				-1 0 0 0				-2 -1 0 0				-3 -2 0 0				-4 -3 -1 0				-5 -4 -2 -1				-3 -2 -1 0				-3 -2 -1 0			
Space Requirements	0				0				0				0				-1 -1 0 0				-2 -2 -1 0				-3 -3 -2 -1				-4 -4 -3 -1				-5 -5 -4 -2				-2 -2 -1 0			
Maintenance Complexity	-1 -1 0 0				-3 -2 -1 0				+5				+3 +4 +4 +4				-1 -1 0 +1				-2 -2 -1 0				-3 -3 -2 -1				-4 -3 -2 -2				-3 -3 -2 -2				-1 -1 0 0			
Industry																																								
Predictability of Installed Costs	-1 -1 0 +1				-3 -2 -1 0				+5				+3 +3 +4 +4				-1 -1 0 +1				-2 -2 -1 0				-3 -3 -2 -1				-4 -3 -2 -1				-3 -3 -2 -1				-1 -1 0 0			
Designer Familiarity	0				-2 -1 0 0				0				-1 -1 0 0				-2 -1 0 0				-2 -1 0 0				-3 -2 -1 0				-4 -3 -2 -1				-4 -3 -2 -1				-4 -3 -2 -1			
Code or zoning barriers	-1 0 0 0				-3 -2 -1 0				0				0				-1 -1 0 0				-3 -2 0 0				-4 -3 -1 0				-5 -4 -2 -1				-5 -4 -3 -2				-5 -4 -2 -1			

Time Period Key

I - 76-80

II - 81-85

III - 86-00

IV - 01-25

-5 unfavorable 0 favorable +5

No effect

TABLE 4-18

SUMMARY RATINGS OF TECHNOLOGIES

	CT	Markets																Time Periods
		SFC	SFS	SFR	MFR	MFC	MFRF	MFCR	MHN	MHR	COON	COLN	COOR	COLR	IPBN	IPRN	IPBR	IPRR
TECHNOLOGIES	EHP	-0.09	-0.10	-0.10	-0.10	-0.09	-0.09	-0.09	-0.13	-0.09	-0.08	-0.10	-0.09	-0.09	-0.07	-0.08	-0.07	-0.08
	GHP	-0.38	-0.36	-0.38	-0.36	-0.36	-0.36	-0.37	-0.41	-0.38	-0.35	-0.36	-0.36	-0.36	-0.33	-0.34	-0.33	-0.34
	CO1	0.31	0.31	0.34	0.32	0.31	0.33	0.32	0.34	0.34	0.30	0.32	0.32	0.33	0.29	0.30	0.30	0.30
	CO2	0.20	0.21	0.22	0.21	0.21	0.23	0.21	0.20	0.23	0.20	0.21	0.21	0.23	0.20	0.20	0.21	0.21
	CO3	-0.05	-0.05	-0.06	-0.04	-0.04	-0.02	-0.04	-0.10	-0.04	-0.04	-0.04	-0.04	-0.03	-0.01	-0.03	-0.01	-0.03
	SWH	-0.27	-0.24	-0.22	-0.24	-0.22	-0.19	-0.20	-0.30	0.18	0.20	0.25	-0.20	-0.21	-0.16	-0.19	-0.16	-0.18
	SSWH	-0.35	-0.37	-0.35	-0.36	-0.35	-0.31	-0.33	-0.44	-0.31	-0.32	-0.37	-0.32	-0.33	-0.27	-0.30	-0.27	-0.30
	SCSH	-0.49	-0.52	-0.49	-0.51	-0.50	-0.45	-0.47	-0.60	-0.45	-0.45	-0.52	-0.46	-0.47	-0.40	-0.44	-0.40	-0.43
	WG	-0.50	-0.54	-0.49	-0.53	-0.52	-0.47	-0.48	-0.57	-0.45	-0.48	-0.54	-0.47	-0.50	-0.43	-0.47	-0.43	-0.46
	SPV	-0.27	-0.29	-0.25	-0.29	-0.28	-0.23	-0.24	-0.34	-0.21	-0.24	-0.30	-0.23	-0.25	-0.20	-0.23	-0.20	-0.22
	EHP	-0.04	-0.04	-0.05	-0.04	-0.04	-0.04	-0.04	-0.06	-0.04	-0.03	-0.04	-0.04	-0.04	-0.02	-0.03	-0.02	-0.03
	GHP	-0.26	-0.27	-0.28	-0.26	-0.26	-0.27	-0.27	-0.29	-0.28	-0.26	-0.26	-0.27	-0.27	-0.25	-0.25	-0.25	-0.25
	CO1	0.31	0.32	0.34	0.32	0.31	0.33	0.32	0.34	0.34	0.30	0.32	0.32	0.33	0.29	0.30	0.30	0.30
	CO2	0.23	0.22	0.25	0.23	0.22	0.25	0.24	0.23	0.26	0.22	0.23	0.24	0.25	0.22	0.22	0.23	0.23
	CO3	0.00	0.00	-0.01	0.00	0.00	0.02	0.00	-0.04	0.00	0.01	0.00	0.00	0.02	0.03	0.02	0.03	0.02
	SWH	-0.13	-0.14	-0.13	-0.14	-0.13	-0.11	-0.12	-0.20	-0.11	-0.11	-0.15	-0.11	-0.12	-0.07	-0.10	-0.07	-0.09
	SSWH	-0.24	-0.26	-0.24	-0.25	-0.24	-0.20	-0.22	-0.33	-0.21	-0.21	-0.26	-0.21	-0.22	-0.16	-0.19	-0.17	-0.19
	SCSH	-0.35	-0.37	-0.35	-0.36	-0.35	-0.31	-0.33	-0.45	-0.32	-0.32	-0.38	-0.32	-0.34	-0.27	-0.30	-0.27	-0.30
	WG	-0.41	-0.44	-0.40	-0.44	-0.43	-0.38	-0.39	-0.47	-0.37	-0.39	-0.45	-0.39	-0.41	-0.35	-0.38	-0.34	-0.37
	SPV	-0.20	-0.23	-0.19	-0.22	-0.22	-0.17	-0.18	-0.26	-0.16	-0.18	-0.23	-0.18	-0.19	-0.14	-0.17	-0.14	-0.16
EHP	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.00	0.02	0.02	0.01	0.02	0.02	0.03	0.02	0.03	0.02	
GHP	-0.13	-0.13	-0.14	-0.13	-0.13	-0.14	-0.14	-0.14	-0.15	-0.13	-0.13	-0.14	-0.13	-0.12	-0.12	-0.13	-0.13	
CO1	0.31	0.32	0.34	0.32	0.31	0.33	0.32	0.34	0.34	0.30	0.32	0.32	0.33	0.29	0.30	0.30	0.30	
CO2	0.29	0.29	0.30	0.29	0.29	0.30	0.29	0.30	0.31	0.28	0.29	0.29	0.30	0.28	0.28	0.28	0.28	
CO3	0.16	0.16	0.16	0.17	0.17	0.18	0.16	0.13	0.16	0.17	0.17	0.17	0.19	0.18	0.18	0.18	0.18	
SWH	0.05	0.06	0.06	0.04	0.05	0.06	0.06	0.01	0.06	0.07	0.03	0.06	0.04	0.10	0.08	0.10	0.08	
SSWH	-0.06	-0.07	-0.06	-0.07	-0.06	-0.03	-0.05	-0.12	-0.04	-0.04	-0.08	-0.04	-0.05	-0.00	-0.02	0.00	-0.02	
SCSH	-0.17	-0.18	-0.17	-0.18	-0.17	-0.14	-0.15	-0.24	-0.14	-0.14	-0.19	-0.15	-0.17	-0.10	-0.13	-0.10	-0.13	
WG	-0.26	-0.28	-0.25	-0.28	-0.27	-0.23	-0.24	-0.31	-0.23	-0.24	-0.29	-0.24	-0.26	-0.20	-0.23	-0.20	-0.22	
SPV	-0.03	-0.05	-0.02	-0.05	-0.04	-0.01	-0.01	-0.07	0.00	-0.02	-0.06	-0.01	-0.03	0.02	-0.01	0.02	0.00	
EHP	0.04	0.05	0.05	0.04	0.05	0.04	0.05	0.05	0.05	0.04	0.04	0.04	0.04	0.05	0.04	0.05	0.05	
GHP	-0.03	-0.03	-0.04	-0.03	-0.03	-0.04	-0.04	-0.01	-0.05	-0.03	-0.03	-0.04	-0.04	-0.03	-0.03	-0.03	-0.03	
CO1	0.31	0.32	0.34	0.32	0.31	0.33	0.32	0.34	0.34	0.30	0.32	0.32	0.33	0.29	0.30	0.30	0.30	
CO2	0.29	0.29	0.30	0.29	0.29	0.30	0.29	0.30	0.31	0.28	0.29	0.29	0.30	0.28	0.28	0.28	0.28	
CO3	0.20	0.19	0.19	0.20	0.20	0.22	0.20	0.17	0.20	0.20	0.20	0.20	0.22	0.21	0.21	0.21	0.21	
SWH	0.12	0.12	0.12	0.11	0.12	0.13	0.13	0.08	0.14	0.13	0.10	0.13	0.12	0.16	0.14	0.16	0.14	
SSWH	0.05	0.05	0.05	0.05	0.06	0.07	0.06	0.01	0.07	0.07	0.04	0.07	0.05	0.11	0.08	0.11	0.09	
SCSH	0.00	0.00	0.00	0.00	0.01	0.03	0.02	-0.05	0.02	0.03	0.00	0.02	0.01	0.07	0.04	0.07	0.04	
WG	-0.11	-0.12	-0.10	-0.12	-0.11	-0.09	-0.09	-0.13	-0.08	-0.09	-0.13	-0.09	-0.11	-0.06	-0.08	-0.06	-0.08	
SPV	0.09	0.09	0.10	0.09	0.09	0.12	0.11	0.05	0.12	0.11	0.08	0.11	0.10	0.14	0.12	0.14	0.12	

Key:

SFC - Single Family Custom
 SFS - Single Family Speculative
 SFR - Single Family Retrofit
 MFR - Multi Family Rental
 MFC - Multi Family Condominium
 MFRF - Multi Family Rental Retrofit
 MFCR - Multi Family Condominium Retrofit
 MHR - Mobile Home New
 MHR - Mobile Home Retrofit

Markets

COON - Commercial Owner Occupied New
 COLN - Commercial Owner Lessor New
 COOR - Commercial Owner Occupied Retrofit
 COLR - Commercial Owner Lessor Retrofit
 IPBN - Institutional Public New
 IPRN - Institutional Private New
 IPBR - Institutional Public Retrofit
 IPRR - Institutional Private Retrofit

Technologies

EHP - Electric Heat Pump
 GHP - Gas Heat Pump
 CO1 - Conservation Option I
 CO2 - Conservation Option II
 CO3 - Conservation Option III
 SWH - Solar Water Heating
 SHHW - Solar Space Heating and Water Heating
 SCHHW - Solar Space Cooling, Space Heating and Water Heating
 WG - Wind Generators
 SPV - Solar Photovoltaic

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5. RESULTS AND CONCLUSIONS

5.1 INTRODUCTION

The previous chapters described the quantitative methodology that formed the basis for the analysis (Section 2.0), the residential/commercial market (Section 3.0), and the energy technologies applicable to the R/C market (Section 4.0). This section discusses the results of the Arthur D. Little analysis performed in the spring of 1977. The objective was to gain insights into the possible roles of new energy technologies in the R/C sector through the year 2000.

The results described in this section incorporate the contributions of a number of other members of the working group. Oak Ridge National Laboratory (fuel elasticity analysis); Brookhaven National Laboratory (sensitivity analyses of end use demand); Argonne National Laboratory (integrated energy systems); the Office of Solar, Geothermal and Advanced Energy Systems (geothermal), etc. The focus, however, is principally in those areas where the Arthur D. Little effort was directed. Therefore, while integrated energy systems, geothermal, and coal are included, their roles are not discussed in depth.

The Arthur D. Little model did not have the capability to provide a complete analysis in a single run, although it can analyze the market penetration of all of the energy technologies in one market sector, in one time period, in one region. Therefore, a complete analysis of the R/C market for a single period required 72 separate computer runs (9 market sectors, 4 regions, new and retrofit). Most of the numerous computer runs concentrated on the year 2000, although selected runs were made for 1985.

A summary sheet from the output is shown in Table 5-1. This example is for new single-family houses in the Northeast region built between 1976 and 2000. It reflects the effects of the penetration of new energy technologies against a Reference Case. In the Reference Case all new construction is assumed to use energy efficiency standards prevalent in 1975, and buildings are assumed not to be retrofitted beyond levels existing in 1975. Although this case is artificial in some respects, it shows what might be expected if there were no government policy effort directed to reducing R/C energy consumption and no improvements in technology. The Base Case, then, is created by allowing the new energy technologies to penetrate the R/C market sectors.

Numerous runs were made under a variety of assumptions to develop the data described in this chapter. The analysis offers considerable insight into the possible roles of new energy technologies in the R/C sector under a defined set of circumstances. Because of significant uncertainties about fuel availability, energy prices, costs and characteristics of the technologies, and the market response to these technologies there is considerable uncertainty implicit in the results. Nevertheless, the approach is intended to provide a basis for a comparison of the different technologies. Although some effort was directed toward defining the high and low range for the contribution of the individual technologies, additional analysis is required to define this range with greater confidence. This is particularly true of technologies in the earliest stages of market development.

It should also be noted that government energy policy can have a particularly significant effect on the market development of new technologies. We have not assumed a major federal commitment to new technologies in this analysis.

TABLE 5-1

SUMMARY SHEET

Market = SF Custom New High
Time Period = 1975-2000

Units = 2866
Run At = 1977 6 9 14 45 53 871

	Gas	Oil	Electricity	Total	
Reference Case Demand	204.71	76.43	149.50	430.64	
Savings from Technologies (Trillion Btu's)					
	Gas	Oil	Electricity	Total	Penetration (%)
Electric Heat Pump	0.00	0.00	10.48	10.48	16.88
Gas Heat Pump	3.19	0.00	0.23	3.42	2.13
Conservation I	17.73	5.82	1.70	25.25	28.25
Conservation II	53.67	22.39	31.89	107.96	71.04
Conservation III	0.00	0.00	0.86	0.86	0.71
Solar Hot Water	0.50	0.21	2.97	3.68	12.65
Solar Heat and Hot Water	0.27	0.14	2.97	3.38	3.46
Solar Cool Heat and Hot Water	0.00	0.00	0.00	0.00	0.00
Solar Photovoltaic	0.00	0.00	0.00	0.00	0.00
Windmill	0.00	0.00	0.00	0.00	0.00
Total Savings	75.36	28.56	51.11	155.04	
% Savings	36.81	37.38	34.19	36.00	
Net Demand	129.35	47.86	98.39	275.60	

It would also be desirable to be more precise about the markets to which the technologies are most appropriately applied to obtain a better estimate of the impact of specific technologies. In the commercial market, in particular, the market groupings include a broad range of building sizes and configurations, some of which are less amenable to particular technologies than others. For example, electric heat pumps and solar heating and hot water systems are not as likely to be applicable on large high-rise buildings as on small buildings in the same commercial category. While the market potential may be overestimated in some of these buildings, it is likely to be underestimated in others.

5.2 FUEL USE PROJECTIONS

Energy demand in the Reference Case is compared to the Base Case in Figure 5-1 and in Table 5-2. The difference between the two cases represents the energy savings from the application of the energy technologies. Thus, the increase in energy consumption in the Reference Case comes primarily from the increase in the building inventory and assumes increases in the penetration of air-conditioning. Some improvement in overall unit consumption is attributable to the replacement of low-efficiency structures by somewhat more efficient new units. The Base Case represents the energy demand that would result through the application of new energy technologies in the residential/commercial market.

Base Case demand in this scenario increases 0.7% per year from 1975 to 1985 and 0.4% per year between 1985 and 2000 as the new energy technologies begin to have more effect. The demand for gas increases slightly through the early 1980's, but then declines steadily through 2000. The combination of increased conservation and a decline in gas' share of the new construction market results in the same amount of gas being consumed in 2000 as in 1975. The use of liquid fuel remains relatively constant early in the period, then declines steadily through 2000. Although liquid's share of the new construction market is relatively small, almost 4 quads of demand remain by 2000, primarily in older structures in the Northeast and the Midwest.

The primary growth in energy demand is in electricity, with consumption in 2000 more than 60% higher than in 1975. Although new energy technologies have a significant impact on electricity consumption, increase in electricity demand is attributable to increased penetration of air conditioning, and the continued growth in the use of electricity for heating.

The fuel share projections were based on price elasticity analyses by Oak Ridge National Laboratory. Although this analytical approach is the most reasonable way to project fuel shares, it has inherent limitations. Such analyses are founded on historical experience over the last 15 years when the use of electricity for heating increased dramatically despite its obvious price disadvantage compared with gas and oil. This experience has led to projections of continued high penetration of electricity for heating purposes. Historical cross-price elasticities may not represent elasticities at future higher prices, however, and increasing consumer sensitivity to these prices may result in a lesser role for electricity in the heating market. These analyses may not reflect the extent to which factors other than price may have influenced fuel share. The strong promotional effort of electric utilities (all-electric homes) and emerging supply restrictions on natural gas certainly influenced consumer response. The electric utilities have been particularly effective in influencing builders, who are most sensitive to capital costs, to install all-electric systems.

FIGURE 5-1 DELIVERED FUEL REQUIREMENTS

TABLE 5-2

DELIVERED FUEL REQUIREMENTS – BASE CASE

Energy Source	1975	1985	2000
Liquids	5.00	5.00	3.78
Gas	7.80	8.20	7.78
Electricity	4.00	4.80	6.49
Coal	0.25	0.25	0.46
Solar		0.06	0.26
Geothermal		0.02	0.24
Other*	0.02	0.04	0.16
Total Delivered Fuels R/C Sector	17.12	18.37	19.17
Fuel Savings**			1

* Includes Industrial Waste, Biomass.

** Reference Case less Base Case.

Electricity consumption, measured at the source rather than delivered, increases from 12.0 quads in 1975 to 19.5 quads in 2000, and total Base Case demand from 25.12 quads to 32.2 quads, a growth rate of 1.0%, compared with a 0.55% growth rate when measured as delivered. Energy demand declines most dramatically in the Northeast where lower growth in new construction, relatively higher prices, and the large potential for energy savings through conservation measures have the greatest impact. Although the use of oil for heating in new structures declines over the period, significant oil consumption continues in existing structures. Electricity consumption increases in all regions, but its growth is particularly dramatic in the high growth areas of the South and West where its use for heating is highest. Although gas maintains a strong market share throughout the country, its use for heating follows the pattern of recent years more than that of the 1950-1970 period when gas dominated the new heating market.

The fuel consumption breakdown is shown by market categories in Table 5-3. Consumption of energy in residential structures existing in 1975 continues to dominate even by 2000. Although the potential for savings in these older structures through the application of new technologies is significant, their energy efficiency cannot achieve the levels possible in new structures. In particular, the older buildings are not usually susceptible to significant amounts of fuel switching and their fuel consumption pattern is unlikely to be significantly affected by even dramatic changes in the price relationships between fuels. Although electricity consumption is 46% of the residential new market, it is only 21% of the residential retrofit market. A similar relationship holds in the commercial sector with retrofit having 44% electricity and new construction having 66%.

Although 60% of the residential units in 2000 will be pre-1975 structures, these units account for 70% of the residential energy demand. Pre-1975 commercial structures represent 46% of the

TABLE 5-3

DELIVERED FUEL DEMAND — BY MARKET SECTORS IN 2000
(Quads)

	Energy Source	Residential		Commercial		Integrated Systems	Total
		New	Retrofit	New	Retrofit		
Reference Case	Gas	2.852	6.153	1.078	1.083		11.166
	Liquids	0.223	3.964	0.545	1.102		5.834
	Electricity	2.598	2.165	2.382	1.771		8.916
	Coal		0.042				0.042
	Other**		0.010	0.052	0.020		0.082
	Total Demand	5.673	12.334	4.057	3.976		26.040
Base Case	Gas	1.791	4.424	0.538	0.758	0.265	7.776
	Liquids	0.124	2.426	0.250	0.758	0.217	3.775
	Electricity	1.734	1.906	1.589	1.209	0.048	6.486
	Solar*	0.091	0.106	0.027	0.019	0.020	0.263
	Coal	—	—	—	—	0.464	0.464
	Geothermal	—	Integrated System		—	0.240	0.240
	Other**	—	0.010	—	—	0.147	0.157
	Total Demand	3.740	8.872	2.404	2.744	1.401	19.161
	Purchased Energy	3.649	8.766	2.377	2.725	1.381	18.898

* Described also as "Savings" of Fossil Fuels — Not a purchased source of energy.

**Wastes, wood, etc.

floor space in existence in 2000 but account for 53% of the energy demand. Thus, even though the "savings" between the Reference Case and the Base Case are significant in the retrofit sector (3.5 quads in the residential and 1.2 quads in the commercial) these units continue to be considerably less efficient than the new buildings to be built in the 1975-2000 period.

5.3 TECHNOLOGY IMPACTS

The energy savings by fuel type in 1985 and 2000 are shown in Table 5-4. As expected, the most significant savings are realized from the conservation technologies, which in most cases are familiar to the market, are widely applicable, and provide an attractive economic return. Conservation savings (6.3 quads) represent 85% of the energy savings realized from new technologies in 2000. The 0.25 quad savings from the solar technologies (solar thermal, photovoltaic, and windmill) is much smaller than the conservation savings, and is subject to considerable uncertainty because of the difficulty in predicting market response for technologies that are now relatively unknown and economics that are not well established. The estimates for integrated energy systems and geothermal systems were made separately from the analysis but are included for completeness. Although a significant number of electric heat pumps will have been installed by 2000, the energy savings are not so great as might be expected because an efficiency improvement is noted only in the heating season and only when the heat pump is operating at temperatures above 32°F.

TABLE 5-4

ENERGY SAVINGS, BY FUEL TYPE, 1985 & 2000
(Delivered Fuel in Quads)

	Technology	Gas	Liquids	Electric	Coal	Solar & Geothermal	Biomass & Waste	Total Savings
1985	Electric Heat Pump	—	—	0.030				0.030
	Gas Heat Pump	0	—	0				0
	Conservation I	0.399	0.180	0.026				0.605
	Conservation II	0.771	0.563	0.404				1.738
	Conservation III	0.326	0.261	0.453				1.040
	Solar Hot Water	0.006	0.003	0.031		(0.040)		0.040*
	Solar Heating & Hot Water	0.002	0.001	0.017		(0.020)		0.020*
	Solar Cooling, Heating & HW	0.0005	< 0.0001	0.001		(0.0015)		0.0015*
	Photovoltaic	—	—	< 0.0001		(< 0.0001)		0
	Windmill	—	—	< 0.0005		(< 0.0005)		0
	Integrated Energy Systems	0.073	0.067	0.076	(0.125)		(0.019)	0.072 Net
2000	Geothermal	0.014	0.001	0.005		(0.020)		0.020
	Totals	1.591	1.076	1.043	(0.125)	(0.081)	(0.019)	3.5665 3.485
	Electric Heat Pump	—	—	0.160				0.160
	Gas Heat Pump	(0.010)	—	0.034				0.024
	Conservation I	0.749	0.128	0.163				1.040
	Conservation II	1.499	1.095	0.785				3.379
	Conservation III	0.589	0.471	0.817				1.877
	Solar Hot Water	0.035	0.026	0.085		(0.146)		0.146*
	Solar Heating & Hot Water	0.012	0.030	0.048		(0.090)		0.090*
	Solar Cooling, Heating & HW	0.002	0.001	0.003		(0.006)		0.006*
	Photovoltaic	—	—	0.003		(0.003)		0.003*
	Windmill	—	—	0.001		(0.001)		0.001*
	Integrated Energy Systems	0.344	0.303	0.270	(0.422)	(0.020)	(0.005)	0.420 Net
	Geothermal	0.170	0.010	0.060		(0.240)		0.240*
	Totals	3.390	2.064	2.429	(0.422)	(0.266) ^s (0.240) ^g	(0.055)	7.386 6.900

() = Increase in Use

* = Fuel or Energy Substitution

Total savings by 1985 are almost 3.5 quads, rising to almost 7.5 quads by 2000. The significant impact by 1985 is attributed largely to the incentives contained in the National Energy Plan (NEP). These incentives provide the impetus for owners of many existing structures to install conservation technologies. In essence the responsive part of the market will be captured by 1985. In the 1985-2000 period, additional savings are created by higher fuel prices, a market that continues to be more sensitive to conservation, and the increasing maturity of the newer technologies.

The new technologies will be applied first in special situations, not specifically considered in this broad analysis. Areas where the fuel supply situation is particularly critical and/or where fuel costs are unusually high will represent opportunities for certain of the solar technologies that were not considered here.

Table 5-5 shows the savings by market subsector in 2000. In the residential sector, 70% of the savings are provided by older houses, which comprise 57% of inventory. Although application of energy-conserving technologies is usually more complicated and expensive in existing structures, the thermal inefficiency of these buildings provides a significant opportunity. More savings are provided in new buildings in the commercial sector than in the pre-1975 structures with 54% of the 2000 inventory being new buildings accounting for 59% of the energy savings.

Energy savings are greatest for gas because of the large number of older, inefficient gas-heated structures, which present particularly favorable opportunities for conservation technologies. Electrically heated structures, on the other hand, tend to be more thermally efficient but the lesser opportunity for conservation is offset partially by the high price of electricity. In particular this results in a higher penetration of the more expensive energy technologies (Conservation III and Solar) where they have an opportunity to replace electricity.

Table 5-6 translates the impact of the energy technologies into the number of residential units and square feet of commercial floor space employing these technologies. The number of structures feeling the effect of energy technologies is large, although the quad impact in some cases may appear to be small. Virtually all of the residential and commercial structures install some level of the conservation technologies and almost 20% of residential units and 10% of commercial floor space utilize some form of solar energy.

Electric heat pumps are installed in almost a quarter of all new residential units and the vast majority of electrically heated residential units. The impact of gas heat pumps is not as significant since they are not projected to be commercially available until after 1985 and will not begin to achieve full market acceptance until well into the 1990's. However, almost 4 million gas heat pumps are projected to have been installed in residential units by 2000. Heat pumps have less applicability in the commercial sector, particularly in larger commercial buildings; electric and gas heat pumps combined are expected to be installed in 8% of commercial floor space by 2000.

Although the quad impact of solar systems in this scenario is small compared with the impact of conservation technologies — 0.25 quad or 0.6 quad in primary equivalent — the number of residential units with solar systems is large. Over 13 million homes will have solar hot water systems, 2.3 million homes will have solar heating systems, and almost 45,000 homes will be equipped with solar cooling systems. This translates into over 1 billion square feet of collector area and results in sales of almost \$25 billion of solar equipment by 2000.

TABLE 5-5

ENERGY SAVINGS, BY MARKET SECTOR IN 2000
(Delivered Fuel in Quads)

Technology	Residential		Commercial		Integrated	Total
	New	Retrofit	New	Retrofit		
Electric Heat Pump	0.135	0.016	0.007	0.002		0.160
Gas Heat Pump	0.009	—	0.004	0.011		0.024
Conservation I	0.435	0.540	0.004	0.061		1.040
Conservation II	0.817	1.649	0.475	0.438		3.379
Conservation III	0.202	0.318	0.903	0.454		1.877
Solar Hot Water	0.062	0.067	0.009	0.006		0.144
Solar Heating & Hot Water	0.029	0.037	0.012	0.012		0.090
Solar Cooling, Heating & HW	0.0002	0.002	0.003	0.0003		0.006
Photovoltaic	—	0.0001	0.002	0.0002		0.002
Windmill	—	0.0001	0.0007	0.0002		0.001
Integrated Energy Systems	—	Integrated Systems		—	0.420	0.420
Geothermal	—	Integrated Systems		—	0.240	0.240
Total	1.690	2.629	1.420	0.984	0.660	7.383

TABLE 5-6

BUILDINGS WITH NEW TECHNOLOGIES (2000)

Bldg. Stock Projected	Residential				Commercial			
	New		Retro		New		Retro	
	Units (10 ³)	%	Units (10 ³)	%	Sq. Ft. (10 ⁶)	%	Sq. Ft. (10 ⁵)	%
Bldg. Stock	46,013	—	61,780	—	23,908	—	20,194	—
Electric Heat Pump	10,671	23	1,721	3	1,182	5	294	1
Gas Heat Pump	2,316	5	1,512	2	1,698	7	427	2
Conservation I	18,232	40	30,565	49	72	.30	2,221	11
Conservation II	20,662	45	25,350	41	8,920	37	9,849	49
Conservation III	7,128	15	4,965	8	14,915	62	8,130	40
Solar — Hot Water	8,001	17	5,365	9	2,577	11	1,502	7
Solar — Heating	1,301	3	1,011	2	662	3	403	2
Solar — Cooling	6.4	.01	38.2	.06	58.3	.2	5.0	.02
Photovoltaic	—	—	5.0	—	52.0	.2	4.0	.02
Windmills	—	—	.5	—	16.0	.06	7.0	.03

The market position of solar systems by 2000 also suggests the possibly greater impact of solar technologies. Sales of solar equipment in this scenario have reached the rapid growth phase in the market development cycle; installations could reach significantly higher levels if the commercialization of solar technologies is accelerated by only five to ten years. Furthermore, market success for solar technologies is likely to lead to the installation of systems that will meet a greater percentage of the energy requirement of the structures because of the installation of larger and more efficient systems.

Photovoltaic systems and windmills are installed on a comparatively limited basis in this scenario, with 5000 homes and 56 million square feet of commercial space provided with some type of photovoltaic system. Only 500 windmills are projected to be installed in residential units and 23 million square feet of commercial floor space are projected to have energy requirements supplemented by wind power systems. As mentioned previously, the broad nature of this analysis is not adequate to pick up the specific applications where these particular technologies may achieve higher penetration.

The conservation technologies are described in more detail in Table 5-7 and Figure 5-2. Each of the conservation levels is additive: i.e., Conservation II includes Conservation I plus additional measures, Conservation III includes Conservation I and II plus additional measures. The II refers to the savings in Conservation II that are not attributable to Conservation I; similarly III refers to savings in Conservation III that are not attributable to either Conservation I or II. The precise Btu impact for each of the levels in each of the markets is determined primarily by their cost relationships. The specific measures included in Conservation II in the residential retrofit market provide the greatest savings in that sector; Conservation I measures provide the primary savings in the new residential market.

In the new commercial market, the investment in Conservation III was attractive enough to induce almost two-thirds of the market to move to this level of conservation. In the residential retrofit market half of the market was content to stay at Conservation I, but 41% were attracted further to Conservation II and another 8% moved all the way to Conservation III.

The significant response to the conservation investments suggests the usefulness of a further categorization of these conservation technologies. Although most of the savings are attributable to investment in Conservation I measures (2.6 quads) and Conservation II (3.3 quads), there is a significant 0.4 quad contribution by Conservation III. The inclusion of additional conservation technologies in a Conservation IV package could be expected to provide additional savings.

Perhaps more notable is the extent to which additional savings could be achieved if a larger percentage of the market could be induced to respond to the full potential of the conservation technologies. Although virtually all of the residential and commercial markets did choose to invest in some level of conservation, a major commitment to conservation (represented by 100% penetration of Conservation III) could provide even more significant savings. If all of the markets were to move to Conservation III, an estimated 4.3 quads more could be saved.

TABLE 5-7
ENERGY SAVINGS OF CONSERVATION TECHNOLOGIES

	Total Savings (10 ¹² Btu)	Savings by Technology (10 ¹² Btu)		
		Conservation I	Conservation II	Conservation III
Residential — New				
Conservation I	435	435		
Conservation II	817	546	269	
Conservation III	198	120	44	34
Total	1,450	1,103	313	34
Residential — Retro				
Conservation I	540	540		
Conservation II	1,649	529	1,070	
Conservation III	315	78	166	71
Total	2,504	1,197	1,236	71
Commercial — New				
Conservation I	2	2		
Conservation II	475	70	405	
Conservation III	903	35	689	179
Total	1,380	107	1,094	179
Commercial — Retro				
Conservation I	61	61		
Conservation II	438	16.0	422	
Conservation III	454	82	232	141
Total	3,053	159	654	141
Grand Total	6,287	2,566	3,297	425

FIGURE 5-2 ENERGY SAVINGS OF CONSERVATION TECHNOLOGIES - 2000
SAVINGS (10^{12} Btu)

5.4 SENSITIVITY ANALYSES

The market development of each of the technologies is unlikely to follow precisely the pattern predicted in this analysis. Not only are the technologies likely to have different performance characteristics, but the barriers they encounter in the marketplace are certain to influence their acceptability. Table 5-8 provides a qualitative assessment of the principal barriers likely to influence acceptance of each of the technologies. The analysis does not suggest that these barriers may not be overcome, only that their influence could be the primary factor affecting the contribution of the technologies. The categories are obviously related. The high cost of photovoltaic systems may be resolved by technical breakthroughs. A reliable system with attractive economics is likely to overcome institutional barriers more quickly. These barriers are also assessed in the time frame of the analysis. Beyond 2000, high fuel costs, further technical development, and market familiarity may reduce the impediments in the market acceptability of some of the technologies. In a certain respect, these ratings are descriptions of assumptions made in the analysis and are reflected in the results. Photovoltaic systems at \$0.20 per peak watt do not have a major impact in the residential/commercial market; at \$0.05 per peak watt this economic barrier will have been reduced and the market impact of photovoltaic systems would be more significant.

TABLE 5-8
TECHNOLOGY BARRIERS

Technology	Barrier Category			
	Technical	Institutional	Economic	Overall
Electric Heat Pump	○	●	○	○
Gas Heat Pump	●	●	●	●
Conservation I	○	○	○	○
Conservation II	○	●	●	●
Conservation III	●	●	●	●
Solar Hot Water	●	●	●	●
Solar Heat/HW	●	●	●	●
Solar Cooling	●	●	●	●
Photovoltaic	●	●	●	●
Wind Power	●	●	●	●

Low

High

○ ● 1 2 3 Relative Importance of Barrier

Perhaps the most significant uncertainty in any market penetration analysis is the assessment of future market response. Analysis of the market's response to technologies that cannot be precisely described and in a future environment that is even less quantifiable is worthwhile only if the high degree of uncertainty in the results is recognized. With this caveat in mind, Table 5-9 describes the high and low levels of contribution for each of the technologies around our "most likely" case and notes the primary reason for this wide range. The low estimate corresponds roughly to a 10% point on a probability distribution curve and the high estimate the 90% point. Although quantitative analysis was used to develop the estimates, full sets of computer runs were made only to develop the most likely case.

TABLE 5-9
TECHNOLOGY SAVINGS UNCERTAINTIES – 2000
(Quads in Base Case)
R/C Technology Savings Uncertainties in 2000 (Base Case Quads)
Energy Savings

Technology	Low	Most Likely	High	Main Uncertainties
1. Electric Heat Pump	0.040	0.160	0.320	Reliability, Market Response
2. Gas Heat Pump	0.004	0.024	0.096	Technology Performance
3. Conservation I	4.335	6.296	8.806 (99% level)	Market Response
4. Conservation II				Market Response
5. Conservation III				Market Acceptance (Commercial) Economics, Incentives (Residential)
6. Solar Hot Water	0.072	0.144	0.576	Economics, Incentives
7. Solar Heating and Hot Water	0.050	0.090	1.000	Technology Advances, Economics, Incentives
8. Solar Cooling, Heating and Hot Water	0	0.006	0.150	Technology Development
9. Photovoltaic	0.0004	0.0023	0.058	Technology Development, Costs
10. Windmill	0.0002	0.001	0.012	Costs Technology
11. Integrated Energy Systems	0.070	0.420	2.100	Regulations, Incentives
12. Geothermal	0.040	0.240	0.480	Resources Near Population Centers
	4.617	7.383	13.600	

Although the range for any particular technology may be broader than that suggested, the range for all the technologies combined, from 4.6 to 13.6 quads, overestimates the range because the probability of all of the technologies meeting the high or low estimate is unlikely.

Demand Sensitivity

The Reference Case is intended to provide a reasonable estimate of energy demand if there were no incentives provided nor significant improvements in the technologies. Table 5-10 summarizes the sensitivity of energy demand to a number of variables.

TABLE 5-10
ENERGY SERVICE DEMAND SENSITIVITY – 2000

Variable	Effect on Demand (%)	
	Increase	Decrease
Existing Building Stock		
Residential – +10%	10 (Residential)	
Residential – - 6%		6 (Residential)
Commercial – +20%	20 (Commercial)	
Commercial – -10%		10 (Commercial)
Population Migration		
to South/West		5
to Northeast/North Central	5	
Housing Mix/Size		
Larger, SF, Suburban	8	
Smaller, MF, Urban		6
Disposable Income		
Increase (+20%)	10	
Decrease (-20%)		8
Technology		
New Developments		5
Technical Failure	5	
Market Acceptance	15	10
Conservation Ethic	15	15
Energy Prices/Supply	15	15
Energy Policy	25	20
Summary	+30%	-25%

*Compared to Reference Case.

Building Stock

Although most estimates for new residential construction do not differ significantly from ours, some are as much as 15% higher. The effect of high or low new construction forecasts is diluted by the large number of existing buildings that will still be in existence in 2000. Thus, the outer limits in the residential sector will lead to energy demand 10% higher than that forecast, or 6% lower. There is a greater variation in projections of commercial space in 2000, both because of the greater complexity in making projections and a lack of agreement on how much non-residential space is currently in existence. Although some commercial stock projections are as much as 30% higher than our forecast, most estimates are within 20%. The highest forecasts generally are based on higher assumptions about current building stock and thus implicitly assume somewhat lower unit energy demand for commercial space, both current and forecasted. The reasonable range of estimates is felt to be 20% increase or 10% decrease in energy demand in the commercial sector.

New Housing

Regional construction forecasts rely on census projections of population movement. The migration to the warmer areas of the South and West is projected to continue in the Reference Case; acceleration of this trend could decrease energy demand by as much as 5%, a decline in the trend could increase demand by as much as 5% by 2000.

The Reference Case assumptions predict a stabilization in the size of the average housing unit and a slight continuation in the trend toward higher-density housing. There are some expectations about future emphasis on smaller, urban, and multi-family units because of energy, employment, and other economic pressures. However, a reversal of the American preference for the single-family house in the suburbs is not yet evident nor is there a clear indication of a commitment to support such a movement (mass transit, zoning revisions, suburban life style, etc.). Other economic factors including family size, family income, employment, migration patterns, etc. will determine housing characteristics. For example, the average single-family house constructed in 1976 contained over 1,600 square feet. Demand could increase 8% as the result of a continued trend to even larger single-family suburban houses or could decrease 6% with a reversal of this trend.

The level of disposable income has traditionally been strongly correlated with energy demand. Higher income levels have led to larger houses, more appliances, better comfort conditions, etc. because consumers have been able to afford the increased cost. A similar correlation in the commercial sector is related to the movement toward a service economy. Significant increases in income above the projected levels would provide a strong force for increased energy consumption. Lower income levels create pressures for consumers to make energy-conserving decisions. A 20% change in income up or down could increase energy demand by as much as 10% or reduce it by 8%.

Technical/Institutional Environment

The availability of energy conserving or modifying technologies in themselves is not adequate to reduce energy service demand. Technologies are affected by experience, standards and regulations, an energy-conserving ethic, government commitment, and a variety of other institutional and technical forces. It is conceivable that technologies other than those considered in this analysis could be forthcoming but it is unlikely that major new developments

could be perfected, introduced, and achieve market acceptance to reduce energy consumption by more than 5% by 2000. Technical failures or the inability of technologies to achieve performance as projected could increase consumption from projected levels by 5%. The most critical issue for technologies is the degree to which they are able to achieve market acceptance. Maximum acceptance of relevant technologies (use of Conservation Level III on all buildings and wide acceptance of heat pumps and solar systems) could reduce demand from our projected levels by as much as 35-40%. However, it is unlikely that market acceptance of technologies would have a demand-influencing factor in itself (not considering a broader conservation ethic or strong government action) that could reduce demand more than 10%. At the other extreme, the market could fail to respond to technologies as projected and demand could be as much as 15% higher.

If energy conservation becomes a full fledged element of the American ethical code, energy consumption could be reduced from the Reference Case by 15%. While the Reference Case assumes only a slight improvement from the current ethic, public perception that the energy crisis is not serious could lead to an increase in demand of 15%. A conservation ethic might be revealed into two contexts: hard and soft. Hard application of the ethic would be where the consumer physically modifies the energy-consuming aspects of the building, through investment in energy conservation devices or solar energy systems. Energy consumption could be reduced significantly also by soft applications of the conservation ethic, such as turning down thermostats in the winter, reduced use of lighting and appliances, and other similar life style modifications.

Decreasing supply and increasing costs of energy have been the driving forces to increase awareness of the need for energy conservation. The elasticity of the market to changes in the price of all forms of energy is the motivation for energy consumers to consider investments in energy-conserving technologies. Higher energy prices would reduce demand by inducing consumers to invest in energy-conserving equipment and to modify energy-consuming patterns. Supply shortages of natural gas or oil force a switch to higher-priced electricity and would further motivate consumers to reduce energy consumption perhaps as much as 15%.

The government's energy policy and its perception by the energy consuming public will be one of the strongest determinants of future energy demand. Government policy can address most of the other variables explored in this section. Energy policy could neutralize the conservation ethic if energy is seen simply as another problem to be resolved by American technology and free enterprise that does not require significant public commitment. This analysis assumes the implementation of the National Energy Plan; intensification of this program could reduce energy demands still further, projected here to be 20%. Energy policy can not only influence public opinion, but can significantly reduce energy consumption through the implementation of regulations and standards as well as through financial inducements to conserve.

We estimate that reasonable parameters for variation from the Reference Case would be a 30% increase or a 25% decrease in demand.

Standards and Incentives

A number of other policy options and scenarios were examined to determine their effect on energy consumption. The results of these analyses are summarized below.

There are two basic approaches for improving energy efficiency in the R/C sector: offering incentives to persuade energy consumers to invest in energy saving devices, and/or mandatory energy conservation standards. The National Energy Plan follows the voluntary approach by offering tax credits to consumers who invest in energy conserving technologies. The effect of these incentives, coupled with higher energy prices, creates the significant levels of savings shown in this analysis. Although the savings achieved through conservation in the Base Case are significant (18% of Base Case demand), imposition of a mandatory Conservation III standard would increase energy savings by 4.3 quads, 70% over that saved in the Base Case. Additional tax credits could be offered to try to induce the same level of savings; however, analysis suggests that many energy consumers who do not respond to the already favorable economics of Conservation I and II (with paybacks on an investment from less than a year to four or five years) are not likely to be attracted by further improvements in these economics.

The establishment of energy-conserving codes and standards in recent years has established a precedent for further expansion of these policy options in the R/C sector. However, effective enforcement is a relatively recent phenomenon in new construction, and there is no precedent for implementation in existing buildings. Traditionally, codes and standards have been under the purview of local authorities; in recent years, state agencies have been created to establish state-wide uniform codes and standards. It is likely that full implementation in new buildings will require several years in order to establish appropriate regulations, create the mechanism for enforcement, and become fully integrated into new construction.

While the opportunities for conservation in existing structures are more limited than for new buildings, the potential savings are significant. Implementation will be more difficult. One proposal would require an energy inspection when any building is sold in which funding would be provided by financial institutions. Thus, before a purchaser of a building could borrow the necessary funds, the building would be required to pass an inspection indicating that reasonable energy conservation standards were being met.

The energy impact of solar technologies is heavily dependent on financial incentives. If the tax credit on solar equipment is increased to 40%, the contribution of solar technologies increases fourfold to almost 1.0 quad by 2000. The effect of the tax credit in this case was measured simply by the extent to which an improvement in the economic performance of the solar system is reflected in a greater market response. The effect of such an incentive would be not only to increase the number of solar systems bought by the public during the time the incentive is in effect, but also to develop and strengthen the solar industry. This could provide lower cost and better equipment, increase the public's exposure to solar systems, and thus improve the market response. In essence, success breeds success. And once solar energy systems went beyond a threshold level of performance and market acceptance, the contribution could be more significant than projected here.

5.5 IMPLICATIONS

The projected growth in energy consumption (delivered) in the Reference Case for the 1975-2000 period (1.7% annually) is well below the historical 1950-1975 average of 2.9%. And the growth in the Base Case (0.45%) represents a dramatic reversal in the seemingly inexorable growth in energy demand. Although the Reference Case was a somewhat artificial construction, it is not an unreasonable projection of demand if energy efficiency does not improve from current

levels and if the major factors directly influencing demand (house size, appliance usage, etc.) begin to stabilize. (Growth in the penetration of air conditioning is projected to continue.)

Although the projections of growth in R/C energy use appear modest in the Base Case, the potential for additional savings, and indeed, a decline in energy use is evident. Energy technologies with proven technical performance and good economic returns are and will be available to the R/C market over the next 25 years; and if their application became the rule rather than the exception, energy use in the R/C sector could approach the levels prevalent in other industrialized countries. The analysis does project a favorable market response, in particular to the conservation technologies, but the market penetration declines sharply when the undiscounted payback of any technology exceeds three to five years. With a return on investment of 20-35% annually, energy saving investments are very attractive.

However, certain inherent characteristics of the R/C sector inhibit its response to the potential of these energy technologies. The market is extremely fragmented, with millions of users, decision-makers, and suppliers; very diverse, with many types of structures, major climatic differences, and a wide variety of market sectors; and slow to change, with new construction annually averaging only 2-3% of the inventory. These factors result in a market that has high inertia and requires many individual decisions before a significant impact can be noted.

Policy actions obviously must be designed with these characteristics in mind. The fact that buildings constructed today will be energy consumers for years to come, and that many energy efficiency measures can be incorporated only during the initial construction period emphasizes the importance of influencing new construction standards quickly and on a widespread basis if the full potential for long-term reduction in energy consumption is to be realized. Capitalizing on the large potential for energy savings in new construction is complicated in particular by the fact that many of the critical decision-makers in the R/C sector have little incentive to implement energy-conserving measures. They can and will respond to the demands of their market, the building users, but these participants often are not directly involved in the decision process and usually do not have technical knowledge of appropriate energy-conserving techniques.

Financial incentives clearly have an effect, both through their direct improvement in the economics of energy saving technologies and through the awareness they create in the market. A mandatory approach through implementation of codes and standards on all new structures has the effect of insuring the application of at least minimum standards of energy efficiency and at a cost to the energy user, not the taxpayer. The belated recognition of the criticality of the energy situation supports vigorous extension of energy standards into the building industry. Such standards also need to be dynamic; as new products and techniques are tested and accepted, the standards should evolve to incorporate them.

Another approach provides incentives to reduce energy consumption to participants who have the technical knowledge of, and experience with, energy technologies and the capital resources to implement them. In Europe, energy management firms have evolved, with strong government support. These companies manage the energy consumption of buildings (primarily commercial buildings and multi-family residences) with their financial return dependent on their ability to reduce energy consumption in the structures they manage. There are a range of contractual arrangements, from one-year contracts, where the energy manager provides only the operating personnel, to fifteen-year contracts, where the energy manager guarantees an annual

maximum level of energy consumption (despite weather variations, which are assumed to average out over the life of the contract) and makes capital investments in equipment to provide a favorable return. Although this concept is beginning to be pursued in the United States, active support and encouragement of this or similar approaches would begin to address the structural inertia of the R/C market.

The U.S. energy situation has focused particular attention on the need to reduce consumption of liquid fuels. While the initial fuel-share price elasticity analysis did not incorporate any restrictions on oil availability, the comparatively high price of oil and its declining market share in recent years resulted in an oil share of the new construction market of less than 10% annually, concentrated in the Northeast. These additions are more than offset by the removal of older oil-heated structures and the application of energy-saving technologies so oil use declines from 5.0 quads in 1975 to 3.8 quads in 2000, a reduction of 24%.

Table 5-11 shows the breakdown of oil use remaining in 2000 by regions and by market sector. As shown, almost 90% of oil consumption is in pre-1975 buildings, over half is in the Northeast, and 68% is in residential structures. Major reduction in oil consumption from the projected level would require either extensive application of energy saving technologies to these oil heated structures or conversion of these buildings to an alternative fuel. However, most of the oil heated structures are assumed to have installed some level of the conservation technologies and without a more extensive financial incentive to increase further their thermal efficiency (an incentive directed either to conservation investments in all buildings or in oil-heated structures only), or the incentive of higher oil prices (natural price increases or an oil tax), oil consumption would not be reduced significantly. Since much of this consumption is in residences, strict measures to force switching or an oil tax are likely to create political resistance.

Conversion to other fuels may be a reasonable alternative in many oil-heated commercial buildings, but such conversion is difficult in many residential structures. Many oil-heated homes switched to natural gas over the last 15 years as gas service was extended to many areas and many of these homes already were using gas for cooking, water heating, and clothes drying. Additional conversions are limited by the lack of natural gas service and the economic unattractiveness of heating many of these thermally inefficient structures with electricity. In addition, the type of heating system may limit economical conversion to electricity. Many oil heated homes use hydronic heating (hot water or steam) rather than forced air systems. Because hydronic systems are not adaptable to the use of electricity, conversion to electricity would require the expensive installation of a complete new heating system.

This analysis presents the comparative potential contribution of a variety of technologies in the R/C sector. This approach is useful in determining the appropriate future course of government action for these technologies, but further effort is required before specific strategies can be developed. In particular, the very great uncertainty that exists in the many variables that affect the market potential of these technologies must be addressed through sensitivity analyses.

One of the purposes of this analysis, of course, was to treat all of the technologies in a consistent fashion, and not to try to analyze and compare technologies that have been assessed on a different basis. There may be disagreement about the methodology or the many assumptions in the analysis, but the market model allows penetration by all technologies on a similar basis.

TABLE 5-11

R/C OIL USE REMAINING IN 2000 (QUADS)

<u>Sector</u>	<u>Region</u>				<u>Total</u>	<u>Percent*</u>
	<u>Northeast</u>	<u>North Central</u>	<u>South</u>	<u>West</u>		
Single Family						
New	0.048	0.018	0.015	0	0.081	
Retro.	0.788	0.360	0.385	0.118	1.651	46.1
Low Density						
New	0.013	0.002	0.002	0	0.017	
Retro.	0.320	0.066	0.027	0.014	0.426	11.9
Multi Family						
New	0.012	0.002	0.001	0	0.015	
Retro.	0.268	0.027	0.023	0.010	0.328	9.2
Mobile Homes						
New	0.007	0.003	0.001	0	0.011	
Retro.	0.013	0.005	0.010	0.003	0.031	0.9
Office and Bank						
New	0.040	0.017	0.012	0.005	0.074	
Retro.	0.119	0.046	0.051	0.014	0.230	6.4
Retail and Other						
New	0.052	0.029	0.012	0.005	0.098	
Retro.	0.138	0.057	0.045	0.015	0.255	7.1
Schools						
New	0.017	0.012	0.004	0.002	0.035	
Retro.	0.086	0.053	0.032	0.009	0.179	5.0
Hospitals						
New	0.029	0.016	0.007	0.003	0.056	
Retro.	0.050	0.025	0.014	0.004	0.093	2.6
Total	2.000	0.738	0.641	0.202	3.580	89.2
Percent	55.9%	20.6%	17.9%	5.6%		

*Percent remaining in older facilities.

APPENDIX A

DESCRIPTION OF MULTIPLE DEVICE PENETRATION ALLOCATION LOGIC

The allocation logic used in the A.D. Little model revolves around a series of steps which progressively allocates more penetration into the higher first cost devices. The process terminates when the last device is investigated. The logic is explained in general terms for the three-stage (three device) case with an example depicted in Figure 5.

ϕ th Stage

The allocation procedure first assigns $P_\phi = 1.0$ (no device or "null" device case); the other penetration variables are set to 0.0.

$$P_i = 0.0, i = 1, M (M=3)$$

1st Stage

- $P_{TOT} (PB_1; FC_1; U)$ is calculated
- $P_1 = P_{TOT} (PB_1; FC_1; U)$
- $P_\phi = 1.0 - P_1$

2nd Stage

- $P_2^{max} = P_{TOT} (PB_2; FC_2; U)$ is calculated
(maximum penetration for device 2)
- P_{12} and FC_{12} are calculated
 $P_{12} = P_{TOT} (PB_{12}; FC_{12}; U)$ is calculated
- P_2, P_1 and P_ϕ are defined by sequential replacement using the following sequence of formulas:

$$P_2 = \min \{ P_{12}, P_2^{max} \}$$

$$P_\phi = P_\phi - \max \{ P_2 - P_1, 0.0 \}$$

$$P_1 = \max \{ P_2 - P_1, 0.0 \}$$

3rd Stage

- $P_3^{max} = P_{TOT} (PB_3; FC_3; U)$ is calculated
(maximum penetration for device 3)

- $P_{B_{23}}$ and FC_{23} are calculated
 $P_{B_{13}}$ and FC_{13} are calculated
 $P_{23} = P_{TOT} (P_{B_{23}}; FC_{23}; U)$
 $P_{13} = P_{TOT} (P_{B_{13}}; FC_{13}; U)$
- P_3, P_2, P_1 and P_ϕ are defined by sequential replacement
define $P'_3 = \min \{ P_{23}, P_3^{max} \}$
There are two cases I: $P'_3 > P_2$
 II: $P'_3 \leq P_2$

CASE I

$$\begin{aligned}
P_3 &= P'_3 \\
P_2 &= 0.0 \\
\Delta P_{13} &= \min \{ P_{13} - P_3, 0.0 \} \\
P_3 &= P_3 + \Delta P_{13} \\
P_1 &= P_1 - \Delta P_{13} \\
\Delta P_{\phi 3} &= \min \{ P_3^{max} - P_3, 0.0 \} \\
P_3 &= P_3 + \Delta P_{\phi 3} \\
P_\phi &= P_\phi - \Delta P_{\phi 3}
\end{aligned}$$

CASE II

$$\begin{aligned}
P_3 &= P'_3 \\
P_2 &= P_2 - P'_3 \\
P_1 &= P_1 \\
P_\phi &= P_\phi
\end{aligned}$$

The complex chain of roles depicted in the three above stages is numerically illustrated by the penetration vector results as shown in Table A-1.

TABLE A-1

MULTI-DEVICE PENETRATION ALLOCATION LOGIC ILLUSTRATIVE EXAMPLE

	<u>FC</u>	<u>OCS</u>	<u>PB</u>	<u>PB_{1-Step}</u>	<u>PB_{2-Step}</u>
Device 1	1000	300	3.33	—	—
Device 2	2000	500	4.00	PB ₁₂ = 5.0	—
Device 3	4000	800	5.00	PB ₂₃ = 6.66	PB ₁₃ = 6.0

P _{TOT} (PB; FC; U)	= 40%	PB = 3.33 (independent of FC and U)
	30%	PB = 4.00
	20%	PB = 5.00
	15%	PB = 6.00
	10%	PB = 6.66

P _φ = 1.0	P _φ = 0.60	P _φ = 0.60	P _φ = 0.60
P ₁ = 0.0	P ₁ = 0.40	P ₁ = 0.25	P ₁ = 0.25
P ₂ = 0.0	P ₂ = 0.0	P ₂ = 0.15	P ₂ = 0.05
P ₃ = 0.0	P ₃ = 0.0	P ₃ = 0.0	P ₃ = 0.10
<u>φth Pass</u>	<u>1st Pass</u>	<u>2nd Pass</u>	<u>3rd Pass</u>

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APPENDIX B

DETAILS OF NEW TECHNOLOGIES

B.1 HEAT PUMP

The thermodynamic performance of a heat pump may be established from a theory by Carnot, which relates the efficiency of any heat engine to the temperatures of the source and sink between which it transfers heat. The measure of performance for a heat pump is its coefficient of performance (COP), defined as the ratio of the thermal energy rejected at the higher temperature sink to the mechanical energy input required for this to occur. Stated more simply, for a rate of heat rejection to the sink of Q_H and a work input rate of W , the COP is defined as:

$$\text{COP} = \frac{Q_H}{W}$$

and is dimensionless. The theory by Carnot establishes an upper bound on this ratio. For a device that operates without thermodynamic irreversibilities, the maximum COP which can be achieved is given by:

$$\text{COP}_{\text{maximum}} = \frac{T_H}{T_H - T_L}$$

where T_H and T_L are the absolute temperatures of the sink and source between which the device operates. From an inspection of this simple relationship it can be seen that the value of the theoretical COP has a lower bound of 1 and no upper bound.

The classic approach to building a real device that will function as a heat pump is found in a Rankine cycle heat engine. This "vapor compression" engine consists of a circuit through which flows a working fluid for the device. It incorporates various components along this circuit that include as a minimum: a compressor, an expansion device, and two heat exchangers. Their arrangement is shown schematically in Figure B-1.

The working fluid is a substance capable of changing phase between liquid and gas at temperatures near both the source and sink temperatures and at pressures corresponding to the suction and discharge pressure levels associated with the compressor. Absorption of heat at the lower temperature source causes the fluid to evaporate at a relatively low pressure. It is then compressed to a higher pressure in the compressor and allowed to condense at this higher pressure (and higher temperature) thereby transferring heat to the higher temperature sink. The liquid is then reduced to the original (lower) pressure level in the expansion device and another cycle begins. Interactions of this device with its environment consist of the two heat exchange processes at the source and sink and a work input to the compressor. Choice of working fluid, compressor, heat exchangers, and expansion device is governed almost entirely by the temperature and character of the thermal source and sink.

FIGURE B-1 SCHEMATIC DIAGRAM OF A HEAT PUMP

When the heat pump is to be used for space heating, as in a residential application, the working fluid is typically a fluorocarbon compound. The compressor is usually a small positive displacement device of either reciprocating or rotary design. Its required shaft power input would be 2 to 5 HP (1.5 to 3.0 kW). The heat exchangers would be designed to transfer heat between the working fluid and the heat source and sink, which would most likely be either air or water. Typical source and sink temperatures for space heating might be 45°F and 95°F, respectively. Expansion devices are either capillary tubes or thermostatically controlled expansion valves.

Electric Heat Pump

For residential and commercial space heating, virtually all heat pumps now on the market are powered by an electric motor. Through many years of development of the electric heat pump, manufacturers have opted for use of a hermetic motor-compressor much like the devices employed in the household refrigerator. Heat pumps that include these hermetic units are more reliable than other designs because they eliminate problems associated with shaft seals. They also reduce the operating noise level of both the motor and the compressor.

The electric heat pump is commonly available in two basic types, depending upon the character of the thermal source available. By far the most popular is the air-to-air* heat pump, which utilizes ambient air as its thermal source. The other type is the water-to-air, or "water-source" heat pump, which extracts heat from a flow or reservoir of water.

Among other components found in an electric heat pump are two circulating fans (in the case of the air-to-air type) to move air through the heat exchangers and thereby transfer heat to the working fluid, which is also circulating through the heat exchanger. Some controls are also included that activate the heat pump in response to the indoor thermostat and also provide other functions such as overload protection for the compressor.

Gas Heat Pump

A gas heat pump commonly refers to a combustion-fired heat engine or absorption cycle that will deliver heat to a load in a proportion greater than would be achieved by direct heat transfer from the combustion process. Implicit in this designation is the ability of the device to extract heat from the same load and in effect function as an air conditioner. Virtually any fuel would suffice for such a device, but much of the research effort on heat-actuated heat pumps has assumed the use of natural gas as the fuel. The research effort has centered around two basic types of combustion-fired heat pump: the absorption cycle heat pump and the engine-driven variant.

The absorption heat pump is identical in concept and operation to the common absorption-cycle air conditioner. Whereas the air conditioning version concerns itself solely with the heat absorption capability at the low temperature end of the machine, its consideration as a heat pump would make the heat rejected from the condenser also of interest.

The operation of an absorption cycle unit in the heating mode is as follows. Heat from a combustion process Q_G , is added to the generator, which contains a solution of refrigerant and absorbent. The heat addition vaporizes the refrigerant (at high pressure), which flows to the

* The common hyphenated description of the electric heat pump always refers to the "source-to-sink" nature of its operation when heat rejection to the sink is used for space heating.

condenser and rejects its latent heat, Q_C , to a heating load, whereupon it condenses. The liquid flows through an expansion device, which reduces the pressure of the liquid and is in turn evaporated by a heat addition, Q_E , in the evaporator. Low-pressure vapor flows back to the absorber where it redissolves in the absorbent and is in turn pumped back to its high pressure level in the generator to begin a new cycle.

The reabsorption process itself is exothermic and requires rejection of the heat of absorption, Q_A , in order for reabsorption of the refrigerant to continue. An additional heat exchanger in the system, called the recuperator, is used for regenerative heat exchange between: (1) the high-temperature, absorbent-rich mixture returning from the generator to the absorber, and (2) the high-pressure absorbent-refrigerant solution being pumped into the generator. This regenerative process reduces the generator's heat input requirement.

The cycle just described is known as the "single effect" absorption cycle because of the single stage of heat addition to the refrigerant-absorbent solution. A "double effect" cycle provides for a second (regenerative) heat addition to the absorbent-rich solution remaining after the initial evaporation of refrigerant to drive more of the refrigerant out of solution. For the same original heat input to the generator, then, a larger flow of refrigerant is available for the heating and cooling load served by the cycle. Both capacity and cycle efficiency improve as a result.

Common working fluids for absorption cooling cycles are either lithium bromide and water or ammonia and water. Other fluids have been considered for various applications, but commercial cooling equipment seems to favor one of these two.

An engine-driven heat pump is identical, in part, to the electric heat pump. It contains all of the components described in conjunction with a vapor compression machine, viz., the compressor, heat exchangers, and expansion device. It is in fact quite like the electric heat pump except in one major way; the shaft power for the compressor is provided by a combustion-driven engine rather than by an electric motor. The circulating fans and controls are activated electrically, but the prime mover for the compressor is not. Because of its intended use for space heating and cooling, the working fluid in the vapor-compression machine will be a "Freon." Perhaps it will not be the identical substance used in an electric heat pump, but it will be quite similar.

Virtually any engine with a torque-speed characteristic that is suitable for the compressor in an electric heat pump could be used as the prime mover in the gas heat pump. Practical considerations, however, have imposed limitations both on the type of prime mover that can be efficiently driven by a gas flame and on the nature of the vapor compression device with which it must operate. The prime candidates for the thermodynamic engine cycle of a gas heat pump are those based on the Stirling, Brayton, and Rankine cycles.

Most of the current development efforts of the gas heat pump are funded by the American Gas Association (AGA). Its development program goals are defined as follows:

- To have gas-fired heat pumps available for the residential market by 1981.
- To have gas-fired heat pumps available for the commercial market by 1983.

- To demonstrate gas-fired heat pumps with a reliability equivalent to that of a conventional gas-fired air furnace.
- To achieve a first cost on initial gas-fired heat pumps within 15% of a combination forced air furnace-electric air conditioned system with a payback period of less than 4 years.

The first two goals relate to an annual market of 10,000 residential units and 2000 commercial units.

The AGA-funded programs now under way include a Stirling and a Brayton cycle engine development, and a vapor-compression machine for each that is dynamically compatible with its engine driver. Also under way is AGA's development of an absorption cycle heat pump. Finally, there are programs under way for the development of a Rankine engine-driven heat pump.

Among manufacturing companies there is perhaps only one activity in combustion-fired heat pumps. A subsidiary of one of the Philips group, United Stirling, has several Stirling cycle engines under test as prime movers for standby power generators in the field. Plans are to attempt combining that engine with a vapor-compression machine for application as a heat pump.

As in the electric heat pump, the figure of merit for a gas heat pump is also defined as a coefficient of performance (COP). Note, however, that the two values are in no way comparable. Whereas the COP of an electric heat pump compares its heating or cooling capacity with its electrical work input, the comparison for the gas heat pump is based on the same capacity as it relates to the heat input from the combustion process. So the COP for a gas heat pump is defined as

$$\text{COP} = \frac{\text{Heating Capacity}}{\text{Heat Input from Combustion Process}}$$

A cooling COP would be calculated simply by substituting the machine's cooling capacity for the heating capacity in this expression.

For current commercially available absorption air conditioners, the cooling COP for a single-effect machine is 0.6 to 0.8. Double-effect machines can achieve cooling COPs of 1.0 to 1.1 depending upon the generator temperature. Applying the simple relationship that

$$\text{COP}_{\text{Heating}} = \text{COP}_{\text{Cooling}} + 1$$

the corresponding nominal heating values for the single- and double-effect absorption machines will be about 1.7 and 2.0, respectively. These performance estimates relate to lithium bromide/water or ammonia/water absorption units and not necessarily to the improved absorption units which are being developed for AGA. Performance targets for those units are a 75% improvement over the cooling performance of commercial ammonia/water units.

For the engine-driven heat pumps, the performance targets for the Stirling engine variant are usually given as 1.5 for the heating mode and 1.1 to 1.5 for the cooling. The Brayton cycle

engine with a turbocompressor-driven refrigerant cycle is anticipated to have cooling COPs between 1.0 and 1.5 and heating COPs between 1.8 and 2.2.

B.2 SOLAR THERMAL SYSTEMS

In contrast with other solar energy technologies (photovoltaic conversion, solar thermal conversion, ocean thermal energy conversion, etc.), the technology for solar heating and cooling systems is simple in concept and well established.

A solar heating and cooling system includes the following components:

- *Solar Collector*: a surface or composite surface which, by virtue of its geometry or surface properties, absorbs solar energy and converts the energy to heat that can be imparted to a suitable heat-transfer fluid circulating through the collector;
- *Heat Storage System*: a material which, by virtue of its high specific heat or because it experiences a change of phase, is capable of storing the collected solar heat when it is available, and allows it to be withdrawn as needed with minimum losses;
- *Source of Auxiliary Energy*: conventional fuels or electricity, which provide heat during extended cloudy periods or at night to avoid the need for uneconomically large solar collectors and thermal storage facilities;
- *Heat Actuated Cooling Unit*: a unit that can be driven by the collected solar heat; and
- *Auxiliary Equipment*: required piping control, heat exchangers, heat transfer fluids, valves, pumps, controls, etc., to connect the individual elements into an operating system.

The solar system must be integrated with either a new or an existing building. To the fullest extent possible, energy conservation measures — such as double-pane windows, thermal insulation, roof overhangs, exterior color and building orientation — should be taken to minimize the requirements on the solar system and reduce system costs.

The solar collector is the unique feature of a solar system; the other components represent either available or modest extensions of known technology. The most widely used solar collectors are based on the flat-plate design (Figure B-2) in which one or two glass or plastic panes allow solar radiation to reach the absorber plate, typically a metal surface coated with black paint or with selective-radiation coatings on the absorbing surface that are more effective absorbers of solar energy. The absorbed heat is then conveyed to a heat-transfer fluid which is pumped through passages in the absorber plate. The heat-transfer fluid may be water (plus antifreeze solution if freezing temperatures are likely to be encountered) or air. The solar collector is provided with thermal insulation to reduce heat losses on the sides not exposed to the solar radiation. The solar collector can be integrated directly with the roof or be mounted on the roof, on the wall or near the building. The typical flat-plate collector can reach temperatures of about 185°F when the system is operating at an efficiency of about 40-50%. The efficiency of the collector drops rapidly at higher operating temperatures because of increased heat losses.

Source: Arthur D. Little, Inc.

FIGURE B-2 **FLAT-PLATE SOLAR COLLECTOR**

To achieve higher operating temperatures, one can combine solar collectors with solar reflectors to concentrate solar radiation onto the absorber. To reach and maintain higher concentration factors (e.g., 8-10), the solar collector must be constructed to follow the sun during the day, thus complicating the system. An alternative approach is to use a solar collector of more complex geometry (e.g., the compound parabolic concentrator).

Another class of solar collectors capable of achieving temperatures of 200-250°F is represented by high-performance evacuated collectors, which reduce convection-heat loss from the absorbing surface and thus require less solar collector area for a given application. Typically, such collectors are in the form of glass tubes* and can operate at temperatures as high as 250°F at efficiencies of 50-70%. The solar radiation absorbers can be made of aluminum, copper, or steel. The specific material will depend upon the heat-transfer fluid to be used, corrosion protection requirements, and cost considerations.

Thermal storage materials represent another unique requirement for a solar system. The thermal storage material may be required to supply heat for several days or to provide seasonal storage (store summer heat for use in winter). The choice of thermal storage material will be influenced by the desired operating temperature. For example, temperatures of 180-210°F may be required when a heat-actuated air conditioning unit is to be used, while for space heating, temperatures of 90-160°F would be adequate. In addition, the cooling system may require storage temperatures of 40-50°F. Thermal storage can be accomplished with either high-specific heat materials or phase-change materials. Water and rocks are typical of the former while salt compounds and their hydrates and some organic compounds are typical phase-change materials. Because large volumes of storage materials may be required, among the desirable properties of thermal storage materials are good heat transfer in and out of the thermal storage, non-corrosive and safe operation, and low cost (including the cost of the containment vessel). Although inorganic salt hydrates have considerable promise, water and rock (particularly when air is used) have an overwhelming cost advantage over other materials.

Heat-actuated air conditioners — based on the absorption, Rankine or desiccant cycles — are available. However, all of the heat-actuated air conditioning devices operate at a substantial performance disadvantage in comparison with that of vapor-compression engines driven by electricity. Thus, considerable work will be required before heat-actuated air conditioners become competitive with electrically driven refrigeration machinery.

B.3 PHOTOVOLTAIC CONVERSION SYSTEMS

The National Photovoltaic Conversion Program

In recognition of the potential contribution of photovoltaic conversion, DOE has established the National Photovoltaic Program with a focus on silicon solar cells because of their already advanced state of development. The objectives of this program are to develop low-cost solar cells for use in reliable photovoltaic systems and to stimulate the creation of a viable industrial and commercial capability to achieve the production volumes for the projected applications at predictable and reasonable costs. The cost reduction goals (1977 dollars) are as follows:

- By 1982, reduce silicon solar array costs in combination with solar concentrators to \$25/Wp.

* Glass tubes are already being mass-produced for use in fluorescent lighting.

- By 1986, reduce silicon solar array costs to \$0.5/Wp.
- By 2000, achieve a technological capability to meet 3% of the U.S. electrical power demand with arrays at a market price of \$0.1 to \$0.3/Wp.

Silicon Technology

Silicon solar-cell arrays are being produced with efficiencies (based on total area) of about 12% for circular cells and up to 15% when rectangular cells are used. The present silicon solar cells are produced using techniques developed by the electronic industry where cylindrical single-crystal silicon ingots up to 5 inches in diameter are grown by the Czochralski method from a hot melt of silicon. These ingots are sliced into wafers, typically 100 μm thick, and these are cut to desired circular, rectangular or hexagonal shapes. Kerf losses in the slicing process and material lost during cutting to shape ranges from 30-50%. Subsequent steps to produce solar cells from the silicon wafers are batch operations and rely on hand-assembly techniques. As a result, up to 30% of the arrays being produced require some form of rework and failure rates of completed arrays, particularly of solar cell interconnections, degrade power output after prolonged use.

Because of repeated temperature cycling of the material going through the various process steps, energy consumption during the present solar cell manufacturing process is high. With current technology, for example, energy payback time of silicon solar cells (for the energy produced during operation of the system) is 12 years.

In addition to power conditioning devices, most photovoltaic systems require storage batteries to smooth out the power delivered to the load. Lead-acid batteries are available that can be cycled about 2000 times before failure, equivalent to a six-year life. Costs for reliable batteries are in the range of \$100/kWh of capacity. Development of improved and lower-cost storage batteries could reduce costs to about \$50/kWh.

The substantial growth in the markets for photovoltaic systems is predicated on reducing costs significantly. To achieve commercialization, the industry is investigating improved production processes for the following:

- Solar-cell-grade silicon materials;
- Growth of large-area silicon sheets;
- Solar-cell packaging methods; and
- Automated assembly of solar cell arrays.

Concurrently, test and demonstration programs are being undertaken to establish performance criteria and the environmental requirements of photovoltaic systems.

The refining of ores and the processing of metallurgical-grade silicon as a starting material for solar cell production will require a substantial expansion of output to meet projected cost goals. Achieving the production levels projected for the year 2000 will require a near doubling of present metallurgical silicon production. Attempts are under way to develop significantly less expensive silicon refining processes to reduce costs from the present \$65/kg of semiconductor grade silicon to about \$5/kg. The impurities in the silicon starting material will have to be controlled in the large-scale processes, and the technical and commercial feasibility of reducing the present cost of silicon by an order of magnitude will have to be demonstrated.

Single Crystal Silicon — if large production rates are to be achieved, new techniques for growing single-crystal silicon suitable for solar cell production will have to be developed. Processes to grow continuous ribbons of single-crystal silicon are based on edge-defined film-fed growth (EFG), and web-dendritic growth. The challenge to the EFG process is to overcome the contamination by the wet die during the process, since contaminants would make this material unsuitable for producing solar cells with an efficiency greater than 11%. If this challenge can be overcome, the EFG process could reduce the cost of single-crystal silicon ribbons to \$0.20-0.30/Wp.

Solar cells produced from single-crystal silicon ribbons grown by the web-dendritic growth process have an efficiency of about 16%. However, the process is limited by the slow growth rate and narrow ribbon width. Laser-zone ribbon growth and inverted Stepanov growth of single-crystal ribbons are also being investigated.

Polycrystalline Silicon — Several processes to produce polycrystalline silicon sheets are being investigated — among them dip coating of ceramic substrates in molten silicon, chemical vapor deposition of volatile silicon compounds on low-cost substrates, hot forming of silicon, and cast silicon. Among these processes, cast silicon with oriented polycrystalline structures have considerable promise for producing thin sheets, from which AEG, Telefunken, and Solarex have already produced rectangular, low-cost solar cells that have an efficiency of 10-12%.

The processes being investigated will have to compete with the present single-crystal silicon technology based on the Czochralski process. Competing processes will have to improve substantially before they supplant the Czochralski process. The disadvantage of the Czochralski process is that a significant portion of the ingot is wasted in the wafer slicing and finishing operations. Therefore, improvements in slicing of ingots by multiple wire and breadknife sawing are being investigated to reduce slice thickness, material loss, and wafer-surface degradation.

An advantage of the ribbon and cast-sheet processes is that they can be produced in rectangular shapes for installation in solar cell arrays, with minimum wasted space between adjoining solar cells. Wafers cut from Czochralski grown ingots result in considerable material wastage and sharply increased costs if rectangular solar cells are required.

Assembly and encapsulation of solar cells into arrays present a major challenge because these steps constitute about one-third of the cost of producing solar cell arrays. Solar cells have to be encapsulated in a suitable compound such as silicon and/or covered by plastic or glass sheets to keep out moisture and protect the solar cells from other environmental influences. New solar-array assembly processes, including reliable interconnection of solar cells to eliminate this labor-intensive step, will be essential if costs are to be reduced.

The costs for the individual steps required in the production of silicon solar cell arrays to meet the 1986 cost objective of \$0.50/Wp are projected by JPL as follows:

polysilicon	\$0.03/Wp
forming single sheet	\$0.14/Wp
fabricating solar cells	\$0.13/Wp
encapsulation	\$0.08/Wp
assembly	\$0.12/Wp
Total	<u>\$0.50/Wp</u>

The objective of the DOE/JPL low-cost silicon solar array project is to test how closely these cost projections can be met. Although several of the companies involved in this project — e.g., Texas Instruments, Motorola, and RCA — are reasonably confident that the projections can be met, based on detailed cost calculations for the individual process elements, significant production volumes will be required to demonstrate this fact. In recognition of the uncertainties associated with meeting the cost goal of \$0.50/Wp by 1986, DOE efforts are focused on reducing the cost to \$2/Wp by 1982.

Non-Silicon Technology

Several approaches are being pursued to develop alternative materials for solar cells. Efforts to develop non-silicon materials have concentrated on thin-film semiconductors, which require a minimum amount of material.

Cadmium Sulfide/Copper Sulfide — Cadmium sulfide/copper sulfide solar cells have been investigated for over a decade as an alternative solar cell material, because they could have highly attractive manufacturing costs. Cadmium sulfide can be deposited by a variety of inexpensive processes, such as spray pyrolysis onto metallized polymer or conductive glass substrates. The copper sulfide layer is formed by ion-exchange dipping and low-temperature heat treatment.

Although the theoretical efficiency of the cadmium sulfide/copper sulfide heterojunction solar cell is 16%, conversion efficiencies of only about 8% have been demonstrated. Degradation of the solar cell with time because of diffusion of copper across the junctions has limited the lifetime of the cell. To overcome the instability of copper sulfide, researchers have used indium phosphide with cadmium sulfide and thereby attained efficiencies reaching to 15%. However, the relative unavailability of cadmium and indium may impose a limit on widespread use of these materials for solar cells.

Gallium Arsenide — Gallium arsenide is one of the most promising thin-film materials because of its high theoretical efficiency (28%) and its demonstrated efficiency of about 23% when used with solar concentrators. Gallium arsenide is a well-researched semiconductor material for which an extensive device technology exists for applications such as light emitting diodes, semiconductor lasers and microwave field-effect transistors. Successful results have been obtained with individual solar cells that consist of gallium aluminum arsenide/gallium arsenide with a film thickness of about 5 μm . These cells have efficiencies of about 17% when grown by a chemical vapor deposition process that uses trimethyl gallium and trimethyl aluminum and arsenic hydride at a growth rate of about 0.25 μm per minute, deposited on a gallium arsenide substrate. Solar cells produced from the thin-film gallium arsenide devices can use Schottky barrier contacts or heterojunctions. Although a major advantage of the gallium arsenide solar cells is their ability to operate at high solar concentrations, successful results with the chemical vapor deposition process indicate the potential use of such solar cells at low concentration ratios as well as in large-area flat solar arrays.

Amorphous Silicon — Significant advances have been achieved in the preparation of amorphous silicon solar cells. The amorphous silicon is formed by introducing silane into DC discharge plasma. The amorphous silicon can be deposited on metal or conductively coated glass and plastic substrates. Because amorphous silicon acts more like direct band gap material, only a few micrometers need be used to produce solar cells. The theoretical efficiency is about 15% for Schottky barrier type cells while measured efficiencies of about 6% have been demonstrated. The efficiencies of heterojunction amorphous silicon solar cells have been very poor.

The properties of amorphous silicon depend critically on fabrication parameters such as substrate material, temperature, deposition rate, and doping. The complexity of the material is due to its multicomponent nature; even an undoped, discharge-produced, amorphous silicon contains bonding defects, voids, bonded hydrogen, and interstitial atomic and molecular hydrogen. The impetus for further study of amorphous silicon solar cells is the promise of improved efficiency based on a better understanding of the semiconductor properties and the possibility of fabricating amorphous silicon solar cells using large-scale continuous processes.

Solar Concentrators

The use of solar concentrators as part of a photovoltaic conversion system can reduce the system costs, because the solar cell area can be small. Therefore, high-performance cells can be used despite their higher cost. Solar concentrators in combination with solar cells will be cost-effective if the concentrating mirrors, sun tracking mechanism, and supports can be produced at costs which are significantly less per unit area than the cost of the solar cells.

Optical constraints limit concentration ratios to about 2000. Thermal and electrical properties of a solar cell, mounting, interconnections, and cooling requirements also place limitations on concentration ratios. For silicon solar cells, therefore, the highest practical concentration ratio is about 300 and an active cooling system must be used because efficiency decreases rapidly at elevated temperatures. Sandia Laboratories has demonstrated a silicon-solar-cell, Fresnel-lens, solar-concentrator array with 1 kW of electrical power output and 4 to 5 kW of low-grade thermal power (80°C water) which may be suitable for hot water or space heating at a projected manufacturing cost of \$3.50/Wp. This cost compares very favorably with the present cost of flat-silicon solar-cell arrays of \$15/Wp.

Actively cooled gallium arsenide solar cells can be used at concentration ratios of nearly 2000 with measured efficiencies of about 20%. These solar cells can also be operated at temperatures up to 140°C, without a significant loss in efficiency, so the cooling water could be used to drive, for example, absorption air conditioning equipment. Meaningful cost estimates for the gallium arsenide concentrator systems are not available, since neither the solar cells nor the solar concentrators are being manufactured commercially.

Only a modest degree of solar concentration is required to make the total solar-cell-array cost, which includes solar cells and solar concentrators, relatively insensitive to the cost of a solar cell. As solar cell costs are reduced below \$10/Wp, most of the potential cost reduction of a combined solar cell-solar concentrator system could be achieved with concentration ratios of 3 to 10. These modest concentration ratios can be attained without a high degree of precision in the reflector optics. Furthermore, at these low concentration ratios, silicon solar cells can be cooled by natural convection without suffering loss of efficiency.

At present, photovoltaic conversion systems do not utilize solar concentrators to reduce costs, in part because of the high reliability required for remote, unattended system applications. This situation is expected to change as the performance of solar concentrating systems is demonstrated. For cost-sensitive applications, it is likely that systems with low concentration ratios will permit costs to be reduced in the near term.

A promising approach to low concentration ratios is represented by the compound parabolic concentrator, which has a concentration ratio of 3 to 5. The compound parabolic concentrator reflector can accept solar radiation over a wide angle, depending on the concentration ratio. Therefore, the collector need not track the sun on a daily basis, and can accept a high percentage

of diffuse solar radiation. At concentration ratios of about 5, a tilt adjustment would be required about once a month. This concentrator can be provided with a transparent cover plate of glass or plastic to protect the reflective surface from dirt and moisture and thereby stabilize performance and permit the use of inexpensive reflector materials. The cost of a compound parabolic concentrator ranges from \$6 to \$8 per square foot of aperture area. The installed cost of a photovoltaic conversion system which utilizes a compound parabolic concentrator in combination with silicon solar cells to provide an output of about 10 kW, would have a system cost of about \$2500/kWp, assuming that the solar cell array cost \$1500/kWp.

B.4 WIND TURBINE SYSTEMS

Turbine Types

Two basic types of wind generators are being used for electric power generating applications: horizontal-axis turbines and vertical-axis turbines.

Most high-performance horizontal-axis wind turbine generators for electric power generation have either two or three blades. Figure B-3 shows one such machine. The design of these blades is similar to that of airplane propellers (and, in fact, wind turbine blades are often made by companies that make propellers for small airplanes). The resultant sophisticated aerodynamic shapes result in wind turbines that have a high efficiency, approaching 65% of that theoretically available. It is doubtful, therefore, that the aerodynamic efficiency of these machines can be improved significantly and thereby permit reductions in size for a given output. Commercial wind turbine/generators are being made with blade diameters up to 25 feet.

The most common vertical-axis wind generators utilize Darrieus rotor and Savonius S-shape rotor configurations. Darrieus rotor machines have higher efficiencies and better wind-speed output characteristics than Savonius rotor machines and, therefore, are probably better suited for larger-scale applications. One firm* now offers vertical-axis wind generators of the Darrieus rotor type with outputs up to 6 kW. A photograph of a scaled-up unit is shown in Figure B-4.

The principal advantages of vertical-axis wind generators is that: (1) they can accept wind from any direction, which can simplify rotor design, whereas horizontal-axis machines must pivot in order to face into the wind; (2) the position of the electric generator is fixed relative to the blades, which simplifies mechanical design and improves access to the generator equipment; and (3) the aerodynamics of the rotor minimize the likelihood of destructive overspeed in extremely high winds.

The above advantages must be balanced against somewhat lower efficiency levels than those obtained with horizontal-axis equipment and a long, precisely shaped blade which complicates their manufacture.

The emphasis of the following discussion is on the horizontal-axis wind turbines since these are the only type now in widespread use for electric power production and since the potential advantages of the vertical-axis machines are not expected to be sufficient to affect the basic economics of wind-power generation.

*Dominion Aluminum Fabricating, Canada

FIGURE B-3 THREE-BLADE HORIZONTAL-AXIS WIND TURBINE

FIGURE B-4 VERTICAL AXIS WIND POWER UNIT

Operational Characteristics

The most salient feature about wind turbines is that their power output is proportional to the cube of the wind speed. Figure B-5 shows the resultant power output for an efficient, commercially available, wind turbine system. As indicated, relatively small increases in average wind velocity can significantly affect the performance of a wind turbine. For example, a 16% increase in wind speed from 12 mph to 14 mph increases output 50% (and vice versa). As a result of this strong sensitivity to average wind speed, the viability of wind turbine systems can vary strongly with location. Consequently, locations only a few miles apart can have significantly different potentials for wind power utilization, depending on factors such as tree cover, bodies of water, and local topography.

As indicated in Figure B-5, wind turbines usually require a minimum wind speed (cut-in speed) of 6-8 mph before operation is initiated. Output then increases rapidly until a limiting wind velocity (determined by electric generator capacity) is reached. The output is constant for all greater wind speeds and is limited by using a blade "feathering" arrangement which changes the angular position of the blades. Wind turbine generators are usually rated at their maximum output capability, which occurs typically at wind speeds of 20-30 mph for commercially available equipment. Even in areas of favorable wind regimes, average wind speeds are rarely over 16 mph near ground level. In these areas the average output of a wind turbine is only $1/5$ - $1/3$ of the rated output, which indicates that the rated output is usually a poor indicator of average power capabilities.

Equipment Availability

Table B-1 lists the more important manufacturers of small wind turbine generators, and the characteristics of commercially available wind power units. These units have rated outputs of 0.1 kW to 15 kW. The corresponding blade diameters are 6 ft to 36 ft. Many of the companies indicated in Table B-1 offer complete wind power systems including the required towers, controls, etc.

System Description

A schematic of a typical small wind turbine generator system is shown in Figure B-6. The system shown consists of several major components:

- A wind turbine subassembly which includes the blades, hub mechanism with overspeed controls, generator, and turntable to allow the blade to rotate continuously into the wind.
- A tower to support the wind turbine subassembly at the proper height given the size of the blades and the variation in wind velocity with height above the ground.
- A battery pack (with appropriate charging circuits) to store excess output for use as determined by load profiles.
- An inverter system to convert the DC output of the wind turbine generator and from the battery pack into AC power consistent with conventional distribution systems, and appliance loads.

FIGURE B-5

VARIATION IN POWER OUTPUT WITH WIND SPEED FOR A
COMMERCIALY AVAILABLE WIND GENERATOR

TABLE B-1

SMALL COMMERCIAL WIND TURBINE GENERATORS (WTGs)*

Name	Size (kW)	Blade Diameter (ft)	No. Blades	Rated Speed (mph)	Cut In Speed (mph)	Cut Out Speed (mph)	Governor	Generator Type
Aero Power (USA)	1.000	6.00	2	32.0	10.0	—	Full Feathering 12-Volt	DC Generator
Aerowatt-24FP7 (France)	0.028	3.30	2	15.7	6.7	—	Centrifugal Pitch Control	30 Alternator
150 FRP7	0.130	6.70	2	15.7	6.7	—	"	"
300FP7	0.350	10.70	2	15.7	6.7	—	"	"
1100FP7	1.125	16.70	2	15.7	6.7	—	"	"
4100FP7	4.100	30.7	2	16.0	3.3	55	"	"
American Wind Turbine SST (USA)	0.450 0.900 1.800	8.00 12.00 16.00	24 36 48	20.0 20.0 20.0	10.0 10.0 10.0	30 adjustable —	Vane Deflect " "	— — Alternator
	or water pumper							
Ameranalt (USA)	1.500 2.500	8.00 8.00	24 24	30.0 40.0	9.0 10.0	adjustable adjustable	Vane Deflect "	Alternator "
Domenico Sperandio & Ager (Italy)	0.250 0.500 1.000							
Dominion Aluminum DAF (Canada)	2.000 4.000 6.000 8.000	15.00 15.00 20.00 30.00	2-Darrieus " " "	23.0 23.0 23.0 23.0	7.0 7.0 7.0 7.0	65 65 65 65	Spoilers or Induction Generation "	Alternator " " "
Dunlite (Quirks) (Australia)								
L	1.000	12.00	3	25.0	10.0	—	80° Feather	Alternator
M	2.000	12.00	3	25.0	10.0	None	"	"

Source: Reference 15

TABLE B-1 (Continued)

Name	Size (kW)	Blade Diameter (ft)	No. Blades	Rated Speed (mph)	Cut In Speed (mph)	Cut Out Speed (mph)	Governor	Generator Type
Elektro (Switzerland)								
W50	0.050	1.42	Savonius	39.0	7.0	None	—	Alternator
W250	0.250	2.20	"	40.0	7.0	"	—	"
WV05	0.600	8.33	2	20.0	7.0	50	Full Feathering	"
WV15G	1.200	9.83	2	23.0	7.0	50	"	"
WV25G	1.800	11.50	2	22.0	7.0	50	"	"
WV25/3G	2.500	12.50	3	23.0	7.0	50	"	"
WV35G	4.000	14.42	3	24.0	7.0	50	"	"
WVG50G	6.000	16.42	3	26.0	7.0	50	"	30 Alternator
Enag (France)	0.400	N/A	2	N/A	N/A	N/A	N/A	N/A
	1.200	N/A	3	N/A	N/A	N/A	N/A	N/A
	2.500	N/A	3	N/A	N/A	N/A	N/A	N/A
Jacobs J47 (USA)	3.000	14.00	3	20.0	8.0	—	Centrifugal Feathering	DC Generator 120-Volt
J45	2.500	14.00	3	20.0	8.0	—	Flyball	DC Generator 120-Volt
J46	2.800	14.00	3	20.0	8.0	—	"	32-Volt
J49	2.500	14.00	3	20.0	8.0	—	"	"
J50	2.000	14.00	3	20.0	8.0	—	"	"
J51	1.800	14.00	3	20.0	8.0	—	"	"
Kedco — 1200 (USA)	1.200	12.00	3	21.0	7.0	—	Centrifugal Feathering	Alternator
Lubing (French)	Water Pumpter	7.22	3	11.2				
MO22-3	0.400	7.22	6	18.0	6.7	35	3 Flared 3 Feathered	Alternator
NOAH (Switzerland)	55.000	36.00	10 Double Rotor	20.0	6.7	—	Electronic	28 Perm. Mag- net AC Generator

TABLE B-1 (Continued)

Name	Size (kW)	Blade Diameter (ft)	No. Blades	Rated Speed (mph)	Cut In Speed (mph)	Cut Out Speed (mph)	Governor	Generator Type
Sencenbaugh (USA)	0.750	12.00	3	20.0	8.0	30	Vane Deflect	DC Generator 14-Volt
Winco Wind- charger 1222H (USA)	0.200	6.00	2	23.0	7.0	—	Air Brake	Double Carbon Brush
Windstream-25 Grumman (USA)	15.000	25.00	3	26.0	9.0	60	N/A	Alternator
Zephyr	15.000	20.00	3		8.0	45	Spoilers and Servo Control	Alternator

FIGURE B-6 WIND POWER MODULE

This schematic is for commercially available wind power units that generate DC power and thereby eliminate the need to operate at a well controlled constant speed for AC power generation. The larger (100 kW+) wind turbine systems operate at constant speed (by proper control of blade angle) so that a synchronous AC generator can be driving directly. With these larger wind power systems, an inverter would still be necessary to convert the DC output of the battery storage systems to AC power.

In considering system options, it is important to account for the losses associated with battery storage and with the inverter subsystems. The efficiency of transmitting electric energy from the wind turbine generator to the electrical loads is given by:

$$n_T = n_B \times n_I$$

where:

n_T — transmission efficiency

n_B — efficiency of the battery charge/discharge cycle

n_I — efficiency of the inverter.

With properly sized lead acid batteries, the throughput efficiency is about 80%. High-efficiency, solid-state inverters have an efficiency of about 90%. The resultant transmission efficiency for electric energy through the battery pack is, therefore,

$$n_T = 0.8 \times 0.9 = 72\%$$

As a result of these sizeable transmission losses, the capacity of the wind turbine units may often have to be increased by almost 30%, with corresponding increases in the cost of systems that use a wind turbine to generate power.

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