Regional Conceptual Design and Analysis Studies for Residential Photovoltaic Systems

Volume I - Executive Summary

Prepared by the Westinghouse Electric Corporation, Research and Development Center, for Dr. Gary Johes of the Sandia Laboratories for the U.S. Department of Energy under Contract 07-6924 by P.F. Pittman - Program Manager E.F. Federmann - Principal Investigator M. Brodzik, W.J. McAllister, R.W. Stoeltzing; S. Nearhoof, P.R. Rittelmann (BHKR Associates)

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REGIONAL CONCEPTUAL DESIGN AND ANALYSIS STUDIES
FOR RESIDENTIAL PHOTOVOLTAIC SYSTEMS

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1. ABSTRACT

Solar residential photovoltaic energy systems, suitable for incorporation into single-family residences and typical of future construction practices, were studied. The country was subdivided into ten regions, and the three best systems for each region were determined from the many possible system configurations. Cost projections based on high volume production indicated that solar total energy systems would be viable. If a sufficiently comprehensive government program is forthcoming, they can be economically advantageous in some areas within 10 years and in many areas of the country by 2000. Achievement of the goals described in this study will result in 6 to 12 percent of the residential energy demand (and about 2 to 4 percent of the total demand) being supplied by the sun by the year 2000. The three best system configurations found independent of the specific sites are those with combined electrical/thermal modules; electrical-only modules with a heat pump; and possibly, separate side-by-side electrical and thermal arrays. Order of preference is determined by the site/structure characteristics. In general, systems were assumed to include battery storage. Non-storage systems employing energy sellback to the utility were assumed only in the very early, low penetration stages. This volume contains a summary of the results of the study, and includes a brief discussion of some of the factors that led to these results.
2. CONCLUSIONS

I. If high volume production of the solar cell modules and auxiliary subsystems is attained, solar photovoltaic total energy systems (which supply residential requirements for both electrical and thermal energy) will be viable for new residences in most regions of the United States before 2000, and, in favorable locations, considerably earlier.

II. High volume production will not be achieved without some form of precommercialization program.

III. A precommercialization program geared to the 1986 DOE solar cell module cost goal of $500/kWp (in 1975 dollars) will be an adequate starting point. When high-volume production has been achieved for all subsystems, photovoltaic total energy systems will be viable immediately in favorable locations.

IV. When designing systems, the goal should be to supply the bulk of the total energy requirements of the residence from solar energy.

V. Electrical storage is essential if large scale implementation is to be achieved. Sell-back of power to the utility is not considered viable on a large scale.

VI. For optimum performance and economic viability, the building should be designed as part of the system.

VII. Residences designed now should be capable of future application of photovoltaic systems. This will allow for back-fit when the system becomes viable, and for much earlier high production levels.

VIII. The use of passive solar design techniques improves overall system performance.

IX. Based on estimated subsystem costs, three basic systems dominate:
(1) all electric, (2) electrical/thermal combined collectors,
(3) electrical/thermal separate side-by-side collectors (usually the last choice. All systems use fixed, flat-plate collectors.

X. Stand-alone systems (which do not require a utility connection) are viable virtually everywhere that utility backup systems are viable. Stand-alone systems favor the combined collector in the cooler regions.
3. RECOMMENDATIONS

I. Modularized test bed facilities should be designed now to assist in the test and design of system and subsystem configurations. This will be necessary for specific hardware development.

II. As soon as the test bed experiments have determined practical systems for the various regions of the United States, their feasibility should be verified by testing the systems in habitable residences. Stand-alone systems should be included in hot, cold, and mild regions.

III. The details of a government precommercialization program that will ensure high volume production of all system components should be studied now. It is recommended that the program be aimed at long-term assured sales of those components at gradually reducing prices, and minimum mark-up.

IV. While electrical storage is technically feasible now, development is still needed to: (1) increase cycle life, and (2) eliminate maintenance. This — plus very high volume production — is needed to reduce storage costs to the required levels.

V. Immediate design and development programs aimed at optimizing the performance of a combined photovoltaic-thermal collector are needed. They are particularly advantageous in the cooler regions and for stand-alone systems.

VI. Design of residences that can easily be back-fitted to solar total energy systems should start as soon as practical incentives can be devised. This will provide a large reservoir of suitable homes when the National Program reaches its cost goals, and will greatly accelerate large-scale production.
4. SITE SELECTION

In order to analyze the performance of systems located throughout the continental United States, the country was divided into ten regions, each to be represented by a site city. Region dependent parameters affecting system performance include:

- Solar radiation (direct and diffuse)
- Space heating requirements (daily, seasonal profiles, and peaks)
- Space cooling requirements (daily, seasonal profiles, and peaks)
- Electric energy requirements (total and daily profile)
- Prices of electricity (present and projected)
- Prices of fossil fuels (present and projected, curtailments)
- Housing growth projections
- Regional preferences (housing style, fuel, space cooling)

Selection of the sites representing the regions (as shown in Figure 1) was based on analyses of the above parameters and the availability of SOLMET data.*

The variety of photovoltaic total energy systems were then analyzed for typical residential loads (determined by this study) and SOLMET insolation and weather data (using tapes obtained from the National Climatic Center of the National Oceanic and Atmospheric Administration) for each site. Twenty years of SOLMET data were applied to residential electric and thermal loads for each site. A typical year was then selected to be considered representative of the twenty-year data for each site. Statistical variations from simulation results obtained using this representative year gave a very close approximation to performance of most of the twenty years analyzed.

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*SOLMET data/weather data available from the National Oceanic and Atmospheric Administration. Data are given in hourly intervals over about a 20-year period for insolation and meteorological measurements.
Figure 1 — Site-region representation.
5. SYSTEM DESCRIPTION AND SELECTION PROCESS

An almost limitless variety of photovoltaic total energy systems might be used in on-site residential applications. In this Section, likely systems will be described and classified, and the techniques used for evaluation (to select the superior systems for each region) will be discussed. The value of the photovoltaic system relative to the value of energy purchased from alternate sources will be appraised.

5.1 System Description

Figure 2 is a block diagram depicting the many possible variations in photovoltaic system configuration. It is evident that an unmanageable number of systems could be generated from this diagram; however, arranging the systems into generic classifications results in groups with the following attributes:

- Air cooled photovoltaic collectors
- Separate photovoltaic and thermal collectors
- Combined photovoltaic/thermal collectors
- Concentrating collectors
- Tracking and concentrating collectors
- Thermal air conditioning
- Passive space heating (for example, a Trombé wall)
- Other special techniques such as phase change thermal storage, radiative cooling, and the like

A generic system classification is defined as one using a specific collection technique to supply specific loads.

By analyzing generic systems, whole classes of systems could be eliminated with no need to consider the vast number of individual systems which comprise the class. This technique is described in Section 5.2.

*Trombé wall: A wall with large thermal mass located a short distance behind a south-facing glass wall.
Figure 2 — Residential system variations.
Figure 3 shows the major elements involved in a typical residential total energy system. The array is a combined photovoltaic-thermal collection system, using a glazed flat-plate collector placed on the roof of the residence, facing approximately south and tilted at latitude. Reject heat from the array is used for space heating and for hot water, with water storage and water heat transfer from the array. Electrical output is either used directly (being converted to a-c voltage through the power conditioning equipment), or is stored in the battery.

Electrical backup energy can be provided by connection to the utility or by a small (1-1/2 kW) engine-generator that, in effect, does not allow the storage to be depleted beyond a certain point. Thermal backup energy can be supplied via a heat pump and the electric utility, or by oil or gas for a fossil backup system using a small heat exchanger to the water storage tank. While oil seems a likely backup fuel for the stand-alone systems, other fuels such as liquified gas could just as easily be used. Hourly computer simulations indicate that, for an average site, only 10% of the electrical and 20% of the thermal residential requirements would require the use of backup fuel and that the 1-1/2 kW electrical backup would always suffice.

An all-electric system would use an air-cooled photovoltaic array, and a heat pump for space heating. Energy for hot water is partially supplied by excess electrical energy in the spring and fall, and by reject heat from the air-conditioning system in the summer. The all-electric system does not require thermal storage.

Residential loads include nominal electrical loads, air conditioning, space heating, and hot water. The air-conditioning load is always electrical; the space-heating load uses thermal energy either directly or through a heat pump. The nominal electrical loads are based on practical energy-conserving equipment used in the average household. The hot water load is based on average use for a typical family.

Space-heating and air-conditioning loads are structure- and site-dependent. Conceptual designs of specific residences for each site were made to determine the structural characteristics needed for dynamic evaluation of the heating and cooling loads.

System effectiveness is determined by calculating the insolation received each hour by the array, and matching this energy to the electrical and thermal loads (also computed for each hour of the year). Efficiencies of transfer within the system are also included in the calculation. Details of the computer simulation comprise the next topic.
Figure 3 — Representative total energy system block diagram.
5.2 Simulation

Grouping the vast number of conceivable photovoltaic total energy residential systems into a small number of generic classifications enables a generic class to represent a large number of specific systems.

It is also logical to limit the degree of analysis needed to determine the performance of a system. Figure 4 illustrates, in levels of increasing complexity, the various computer simulation models which were developed. All proposed systems were analyzed at the lowest level (CSCL 1). Those systems not rejected at a given level were analyzed at the next higher level. At increasingly higher levels, both the complexity of the simulation model and the detail of the system specification increased. Thus, at lower levels, whole generic classes of systems were analyzed simultaneously. As the level increased, the size and number of these generic classes decreased so that, at the highest level, the system specifications were very detailed and only a few systems were analyzed.

Figure 5 shows the elements entering into a representative CSCL 3 analysis. The hourly totals of collected photovoltaic energy and of solar thermal energy are each computed from hourly analyses of collector performance, together with the collector array specification. Similarly, the hourly total electrical and thermal loads are computed from hourly load analyses, and the load composition is specified.

The large blocks represent major subsystem functions: parallelograms—the collectors, hexagons—the loads, large circles—the storage, rectangles—the auxiliary energy sources, and triangles—the energy wasted. The efficiencies of various system components are taken into account at the appropriate places, as indicated by the smaller circles. In CSCL 3, only the heat pump efficiency (COP) has been computed hourly. (The other efficiencies are examined in more detail in CSCL 4.) Numbers shown outside of blocks or along lines indicate the order in which energy is dispersed from a given source; numbers shown inside blocks indicate the order in which energy is received by a given process.

The system simulation models are needed to (1) optimize the photovoltaic energy system in terms of array area and storage capacity, and (2) determine the amount of the energy being displaced by solar. This information is needed to estimate system cost and value.

*COP — coefficient of performance.
COMPUTER SIMULATION COMPLEXITY LEVEL (CSCL)

CSCL 1  Determination of system figure-of-merit based on estimates derived from typical year data and estimated system costs

CSCL 2  Analysis of system performance based upon a condensed year using a daily energy balance simulation

CSCL 3  Refinement of system performance based on an hourly energy balance simulation over the typical year

CSCL 4  An hourly analysis of system performance which includes hourly array and battery voltage and current, module temperature and structure thermal lag

Figure 4 — System rejection technique.

Figure 5 — CSCL-3 combined electric/thermal energy flow simulation.

Efficiencies

- $e_i = 0.93$ (inverter)
- $e_c = 0.95$ (charger)
- $e_s = 0.85$ (storage)

COP - Computed (heat pump)
The importance of considering the residential building as part of the system (as depicted in Figure 6) has been stressed in our approach to solar total energy system simulation and selection. The basic approach is to design conventional residences of moderate cost that, in addition to minimizing the thermal loads, reduce the magnitude of the peak requirements. This allows solar energy systems of reasonable area and storage capacity to supply a high percentage of the energy requirements of the residence. It also makes stand-alone residences practical.

While the residential nominal electrical load and the domestic hot water load are not particularly site dependent, the space-heating and air-conditioning loads are both site and structure dependent. In fact, the proper structure-site combination removes the need for air-conditioning (for most individuals) in five of the ten sites analyzed.

Space heating is influenced by the structure, the site, alternate fuel sources, and the type of backup used. Buildings designed for solar application in colder regions include reduced average load, as well as reduced magnitude, duration, and number of peaks. Solar energy can be applied to the space heating load electrically—via a heat pump, or thermally—using either a combined thermal/electric collector or a separate thermal collector. Backup can be provided by electricity or fossil fuel, or both.

Because the energy consumption for space heating in properly designed solar residences is reduced, the domestic hot water load assumes greater importance. In fact, the capability of satisfactorily supplying the hot water load is a decisive factor for some all-electric systems and for air heat-transfer thermal systems.

Space-heating and air-conditioning loads are computed by the hour; typical-year SOLMET data are used for each site. The data are applied to the types of structures that are desired in the region and are designed to optimize solar displacement with reasonable sizing.
Figure 6 — Building-system interplay.
5.3 Evaluation

Figure 7 shows the elements needed to evaluate solar energy systems, and to compare them with alternate possibilities, both solar and conventional. The Figures-of-Merit used are defined as follows:

\[ F_M = \frac{\text{Total Present Value of Solar Energy System Costs} \ast \ (S)}{\text{Annual Energy Displaced}} \]

\[ F_{MS} = \frac{(S) + \text{Present Value of All Auxiliary Energy Needed}}{\text{Annual Energy Requirement of the Residence}} \]

\[ F_M' = \frac{\text{Present Value of All Energy Needed for Non Solar Residence}}{\text{Annual Energy Requirement of the Residence}} \]

It should be noted that \( F_M \) does not require projection of alternate energy costs; it is therefore very useful for comparing the substantial and near equivalent solar displacement of various systems.

In contrast, \( F_M' \) requires both a projection of energy rates and a multiplier \( M \) to account for escalation of energy costs and the value of money. Thus \( F_M' = rM \):

where \( r = \text{Energy rate at the time of system installation} \)

and \( M = \frac{1 - \exp \left[-(i - f)N\right]}{i-f} \)

where \( N = \text{System life} \)

\( f = \text{Energy rate escalation} \)

\( i = \text{Mortgage interest} \)

A solar energy system becomes viable when the total present-value of the system to the owner is equivalent to the present-value of an alternate means, or when \( F_{MS} = F_M' \). Thus, \( F_{MS}/F_M' \) is a viability ratio; when it is equal to one, the solar system is just viable. When the viability ratio is less than one, the solar energy system is advantageous to the degree that the viability ratio is less than one.

*Total system cost, including initial capital, repair, maintenance, and replacement, on the basis of present values.
Figure 7 — Computation of Figures-of-Merit.
Determination of the system $F_M$ relies upon estimates of subsystem and installation costs. Figure 8—a simplification of a detailed cost analysis—approximates the costs of systems that were eventually selected as superior. The bases for the estimates are high-volume production and learning curves, plus lower cost limits derived from experience with similar apparatus.

Major subsystem costs in 1975 dollars used for the selected systems are tabulated below:

<table>
<thead>
<tr>
<th>Installed Array</th>
<th>Cumulative Volume (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>$105/m^2</td>
</tr>
<tr>
<td>Combined</td>
<td>$160/m^2</td>
</tr>
<tr>
<td>Power Conditioning, Control/Protection</td>
<td>$2600</td>
</tr>
<tr>
<td>Sellback addition</td>
<td>400</td>
</tr>
<tr>
<td>Battery Subsystem</td>
<td>$120/kWh+$1000</td>
</tr>
<tr>
<td>Repair &amp; Maintenance (PV)</td>
<td>$1000</td>
</tr>
<tr>
<td>Thermal System for Combined</td>
<td>$4800</td>
</tr>
</tbody>
</table>

The above values can be used for a quick calculation of approximate costs, such as is offered by the curves on Figure 8. In the actual determination of $F_M$, computer calculations containing many minor subsystem variations are employed. All costs are for direct delivery as a single electrical subsystem package.
Figure 8 — Simplified high-volume cost for selected systems.
In addition to the costs associated with the solar energy system, determination of system viability and the calculation of $F_{MS}$ and $F_M'$ requires an estimation of conventional energy costs. The calculation of life-cycle cost and life-cycle benefit for systems installed between 1985 and 2000 can involve projections for half a century. While extrapolation of past data is often satisfactory for near-term projection, energy costs extending into the next century should be based on a scenario of the likely situation at that time.

The scenario for residential electric rate escalation (shown in Figure 9) assumes the following:

1. Near-term electric rate escalation will be based on this decade's experience.
2. The escalation of the electric rate will gradually be reduced.
3. Eventually — say, in 50 years — most generation will be from coal or nuclear, at equivalent cost, and that cost will increase 1% per year over inflation.
4. At that time, load peaking will be reduced, due to both altered use patterns and to storage.
5. To a large extent, regional price differences will have gradually disappeared.

Based on present generation plant costs and using 1975 dollars, the following electric rate escalation formula was derived for the scenario outlined above:

$$R = \left[ R_0 + (R_0 - R_0)e^{-0.07N}\right]e^{1.05(1-e^{-0.04N})}$$

where

- $R$ = regional electric rate at time $N$
- $R_0$ = average present electric rate in 1975 dollars = $0.034/kWh$
- $R_0$ = regional present electric rate in 1975 dollars
- $N$ = year projected — 1975

The residential electric rate projected in Figure 9 results in a reduced escalation over inflation in the future. By the year 2000, electric rate escalation for the lifetime of the solar energy system will be under one percent; higher escalations are projected only for the near term.

Alternate heating fuel (gas, oil) cost is projected to eventually be about equivalent to the fuel cost of heating electrically by means of a heat pump. So the delivered cost of energy equals the cost of oil or gas divided by the efficiency of the heat exchange system, or the electric rate divided by the heat pump's overall COP (coefficient of performance). In this case, the electric or fossil costs to the user are about the same.
Figure 9 — Projected electric rate (residential).
The balance shown in Figure 10 may be explained by a recollection of the following equation:

\[
\text{Economic Viability} = \frac{\text{Solar Energy System Cost} + \text{Present Value of Backup Cost}}{\text{Present Value of Alternate Costs}}
\]

System costs are dependent on system sizing and on subsystems makeup and cost, which in turn depends upon production volume. Most systems, if properly designed and optimized, achieve high solar displacement, reducing backup costs thereby. On the left-hand side of the scale are the effects of the costs projected for conventional energy over the system lifetime, the interest rate assumed to obtain present value, and the equivalent reduction of system costs attained by possible tax benefits.

Beyond the achievement of component cost goals and high volume production, viability is very much dependent on assumptions relating to energy cost escalation, money rates, and tax benefits. Therefore the choice of the proper future scenario relating to these topics can be vital. After careful analysis, and based on related experience in other areas, the following scenario appears to us the most likely one for the year 2000:

- **Mortgage Rate**: 4% over inflation of 5%.
- **System Life**: 20 years
- **Battery Life**: 5000 cycles
- **Energy Escalation**: As shown in Figure 9
- **Tax Scenario I**: 30% Tax bracket for benefit from mortgage interest deduction. No property tax.
- **Tax Scenario II**: Tax bracket mortgage interest deduction balanced by increased property tax and insurance.

System sizing, as optimized by computer simulation, has the following range:

### Array Area

- Photovoltaic only - from 80 m² in Phoenix to 100 m² in Lake Charles.
- Combined Photovoltaic - Thermal - 60 m² combined in Santa Maria to 80 m² combined plus 40 m² thermal only in Great Falls.

### Inverter

- 15 kilowatts (High volume cost = $800)

### Electrical Storage

- 15 kWh in Santa Maria to 30 kWh in Phoenix.

Data presented in the next four pages will be based on the above sizing, costs, and Tax Scenario I.
Solar Energy System is favored when the Viability Ratio is less than 1.

Figure 10 — Factors affecting the economic viability ratio.
5.4 Selected Systems

All the information needed to select superior systems, based on energy displacement and economic viability, has now been defined. Tables 1 and 2 describe the selected photovoltaic systems, the energy displaced, and the Figures-of-Merit for each site. Utility-connected systems (Table 1) as well as stand-alone systems (Table 2) are considered. The stand-alone systems employ 1-1/2 kW on-site electrical generation; for combined systems, there is also a small heat exchanger to the water storage system.

In Nashville, Washington, and Omaha, the Figures-of-Merit for stand-alone systems differ from those for utility-connected systems because of our requirement that on-site electrical generation should not exceed 1000 hours per year. The all-electric system has the lower $F_M$, but cannot supply sufficient energy; therefore, a combined system is needed. The stand-alone system is viable everywhere but Seattle; however, the performance of the utility backup system is also marginal there ($F_M = 1.06$).

As noted in Section 5.2, residential demand includes heating and cooling loads based on building designs which were geared towards solar total energy system application. This allows photovoltaic systems of reasonable size (average 80-m$^2$ arrays and 20-kWh electrical storage) to displace a high percentage of the load, due both to load reduction and to the closer match of year-round insolation to load.

The Figure-of-Merit ($F_M$) relates the total cost (at present value) of the solar total energy system to the energy it displaces. Back-up energy and the value of the displaced energy are not involved here. Energy displacement is obtained from the hourly simulation previously described; system cost is based on very high volume production. A low $F_M$ indicates that a relatively inexpensive system displaces considerable energy. An $F_M$ much greater than 1 is not considered viable for the alternate energy cost projected for this study.

An electrical equivalent (see Residential Total Demand column on the tables) allows for easy comparison of systems involving either all-electric or part-thermal systems, since the electrical equivalent represents approximately the same base fuel use and cost. The use of an electrical equivalent for the thermal space heating requirement does not necessarily mean that a heat pump is employed.
### TABLE 1 — ENERGY DISPLACEMENT OF SELECTED SYSTEM: UTILITY BACKUP

<table>
<thead>
<tr>
<th>SITE</th>
<th>SOLAR DISPLACED ENERGY (kWh)</th>
<th>RESIDENTIAL TOTAL ENERGY DEMAND** (kWh)</th>
<th>% ENERGY DISPLACED</th>
<th>FIGURE-OF-MERIT ($F_M$)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E) Nashville</td>
<td>12,000</td>
<td>17,400</td>
<td>69</td>
<td>0.67</td>
</tr>
<tr>
<td>(E) Washington, D.C.</td>
<td>11,100</td>
<td>15,600</td>
<td>71</td>
<td>0.78</td>
</tr>
<tr>
<td>(E) Omaha</td>
<td>12,500</td>
<td>17,600</td>
<td>71</td>
<td>0.72</td>
</tr>
<tr>
<td>(C) Boston**</td>
<td>11,900</td>
<td>16,100</td>
<td>74</td>
<td>0.92</td>
</tr>
<tr>
<td>(C) Madison**</td>
<td>12,900</td>
<td>17,200</td>
<td>75</td>
<td>0.94</td>
</tr>
<tr>
<td>(C) Great Falls**</td>
<td>15,000</td>
<td>19,500</td>
<td>77</td>
<td>0.77</td>
</tr>
<tr>
<td>(E) Phoenix</td>
<td>16,050</td>
<td>17,800</td>
<td>90</td>
<td>0.48</td>
</tr>
<tr>
<td>(E) Lake Charles</td>
<td>14,750</td>
<td>17,150</td>
<td>86</td>
<td>0.59</td>
</tr>
<tr>
<td>(C) Santa Maria**</td>
<td>13,600</td>
<td>14,800</td>
<td>92</td>
<td>0.63</td>
</tr>
<tr>
<td>(C) Seattle**</td>
<td>8,100</td>
<td>14,700</td>
<td>55</td>
<td>1.06</td>
</tr>
</tbody>
</table>

### TABLE 2 — ENERGY DISPLACEMENT OF SELECTED SYSTEM: STAND-ALONE

<table>
<thead>
<tr>
<th>SITE</th>
<th>SOLAR DISPLACED ENERGY (kWh)</th>
<th>RESIDENTIAL TOTAL ENERGY DEMAND*** (kWh)</th>
<th>% ENERGY DISPLACED</th>
<th>FIGURE-OF-MERIT ($F_M$)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>(C) Nashville</td>
<td>14,700</td>
<td>17,400</td>
<td>90</td>
<td>0.86</td>
</tr>
<tr>
<td>(C) Washington, D. C.</td>
<td>13,000</td>
<td>15,600</td>
<td>88</td>
<td>0.90</td>
</tr>
<tr>
<td>(C) Omaha</td>
<td>14,500</td>
<td>17,600</td>
<td>88</td>
<td>0.82</td>
</tr>
<tr>
<td>(C) Boston**</td>
<td>11,900</td>
<td>16,100</td>
<td>85</td>
<td>0.92</td>
</tr>
<tr>
<td>(C) Madison**</td>
<td>12,900</td>
<td>17,200</td>
<td>83</td>
<td>0.94</td>
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<tr>
<td>(C) Great Falls**</td>
<td>15,000</td>
<td>19,500</td>
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<td>86</td>
<td>0.59</td>
</tr>
<tr>
<td>(C) Santa Maria**</td>
<td>13,600</td>
<td>14,800</td>
<td>92</td>
<td>0.63</td>
</tr>
</tbody>
</table>

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* A low $F_M$ indicates greater viability.

** No central air-conditioning required.

*** Thermal energy converted to equivalent electrical requirement to satisfy load via a heat pump (that is, includes C.O.P.)

$E = $ Photovoltaic system only; $C = $ Combined photovoltaic/thermal collector.
Tables 3 and 4 consider the system costs and economic viability of residential photovoltaic total energy systems. Viability is achieved when $F_{MS} / F_M$ (the system Figure-of-Merit) divided by $F_M'$ (the present-value cost of alternative energy divided by the energy requirement in kWh/year) is equal to one: that is, when $F_{MS}$ equals $F_M'$. A lower $F_{MS} / F_M'$ ratio results in a net fractional benefit to the user equal to one minus the viability ratio.

The effect of income tax deduction of mortgage interest on the viability ratio can be calculated either (1) by comparing the present value cost of the photovoltaic system to a fund set aside to defray the cost of alternate energy over the system lifetime, or (2) by comparing the annual net cost of the mortgage payment on the photovoltaic system and the annual alternate energy costs. While the ratio of photovoltaic systems to alternate energy, $F_{MS} / F_M'$, will be the same for either method, the actual values in the numerator and denominator will be different, depending on which method of comparison is chosen. This results in a difference in perspective. The first method changes $F_M'$ to allow for the increased funding set aside for alternate energy payments due to income tax on interest earned by the fund. This, in effect, increases the allowable cost of the photovoltaic system because of an apparent increase in alternate energy costs. The second allows for a higher photovoltaic system cost by reduction of the mortgage payment due to the income tax deduction of mortgage interest. This reduces the $F_M'$ value because the net mortgage payment is reduced.

While the second method is more in accord with the actual condition of monthly payments, either on the photovoltaic system mortgage or for alternate energy, the first method was used in calculating the viability ratios shown in Tables 3 and 4 because of convenience of calculation and conformity with other evaluation techniques.

The viability ratio is derived from our earlier Figure-of-Merit formulation (Figure 7) and the projected electric rate ($r$) in 1975 dollars at the time of system installation. (Figure 9). Using the expression on page 14, with an inflation-discounted mortgage rate of 4%, a projected fuel escalation rate (in 2000 AD) of 1%, and a 20-year system life, $M = 15$ for Scenario II and $M = 20$ for tax Scenario I. Scenario I (30% tax benefit) was used to determine the viability ratios in Tables 3 and 4. The results indicate that when high volume production of the solar energy system is achieved, it will be viable everywhere and quite beneficial to a person in the 30% tax bracket. Were the tax benefit not considered, the viability ratio is still favorable for all sites except Seattle. The increase in the viability ratio for removing the tax benefit is $\Delta F_{MS} / F_M = 0.25 F_M \times \beta$ where $\beta =$ energy displaced/energy required.

The lifetime utility backup cost (Table 3) is based on a linear charge for energy consumed. This is a not unreasonable assumption, since the system allows for approximately 1-1/2 kWh maximum delivery (because of on-site storage) and permits short-term interruption. In any event, the stand-alone system costs (in Table 4) are about equal to the utility backup costs (in Table 3) at the linear rate. Since stand-alone systems are viable nearly everywhere, the stand-alone system cost in effect puts a limit on an acceptable utility backup charge.
### TABLE 3 - PROJECTED COSTS BY THE YEAR 2000: UTILITY BACKUP

(All Costs in 1975 Dollars)

<table>
<thead>
<tr>
<th>SITE</th>
<th>SYSTEM COST</th>
<th>SYSTEM BREAK-EVEN COST*</th>
<th>LIFETIME UTILITY BACKUP COST*</th>
<th>% ENERGY DISPLACED</th>
<th>VIABILITY RATIO ((F_{MS}/F_{M}')^*)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E) Nashville</td>
<td>8,050</td>
<td>16,000</td>
<td>7,200</td>
<td>69</td>
<td>0.66</td>
</tr>
<tr>
<td>(E) Washington, D.C.</td>
<td>8,650</td>
<td>14,800</td>
<td>6,000</td>
<td>71</td>
<td>0.71</td>
</tr>
<tr>
<td>(E) Omaha</td>
<td>9,000</td>
<td>16,600</td>
<td>6,800</td>
<td>71</td>
<td>0.68</td>
</tr>
<tr>
<td>(C) Boston***</td>
<td>10,950</td>
<td>15,800</td>
<td>5,600</td>
<td>74</td>
<td>0.78</td>
</tr>
<tr>
<td>(C) Madison***</td>
<td>12,100</td>
<td>17,100</td>
<td>5,700</td>
<td>75</td>
<td>0.78</td>
</tr>
<tr>
<td>(C) Great Falls***</td>
<td>11,600</td>
<td>19,900</td>
<td>6,000</td>
<td>77</td>
<td>0.68</td>
</tr>
<tr>
<td>(E) Phoenix</td>
<td>7,700</td>
<td>21,300</td>
<td>2,400</td>
<td>90</td>
<td>0.43</td>
</tr>
<tr>
<td>(E) Lake Charles</td>
<td>8,700</td>
<td>19,600</td>
<td>3,200</td>
<td>86</td>
<td>0.53</td>
</tr>
<tr>
<td>(C) Santa Maria***</td>
<td>8,600</td>
<td>18,100</td>
<td>1,600</td>
<td>92</td>
<td>0.52</td>
</tr>
<tr>
<td>(C) Seattle***</td>
<td>8,600</td>
<td>10,800</td>
<td>8,800</td>
<td>55</td>
<td>0.89</td>
</tr>
</tbody>
</table>

* Tax Scenario I — owner in 30% tax bracket
** Net benefit = 1-viability ratio
*** No central air conditioning

E = Photovoltaic system only; C = Combined photovoltaic/thermal collector
All systems have electrical storage; the combined system also has the thermal storage.

In Nashville, Washington, and Omaha, different systems are used for stand-alone residences than for utility-backed: hence the difference in system cost. This is necessitated by our 1000 hours/year limit on on-site generation. It results in a more expensive solar system, but this is approximately offset by reduced backup costs.
6. TEST BED FACILITY

Superior systems were selected by matching insolation to residential loads (based on conceptual system designs and computer simulation). The conceptual designs involved a variety of subsystems, including photovoltaic modules, power conditioning systems, storage systems, and thermal collectors, as well as specific residence designs for each site. Before hardware is applied to a habitable dwelling, an intermediate step seems advisable. A flexible approach to hardware for specific systems, along with a comparison of various nearly equivalent systems, will enable better optimization by avoiding the inflexibility inherent in an already-installed system. This will also supply considerable initial experience on the problems inevitably encountered in hardware development and its assembly into a system.

The test bed facility can be considered as the final step in system optimization by viewing the constructed habitable residence as the ultimate model, linked by telephone to the solar energy system on the test bed. The sized system can then be placed on the residence for actual use by the occupants.

Most solar systems, whether electrical or thermal, are combinations and permutations of three systems: collection, storage, and distribution. The test bed facility will accommodate a pre-established set of system combinations to identify the best total system option for each of the pre-selected representative sites. In addition to system combinations, the test bed facility will house all of the system monitoring equipment.

Figure 11 illustrates the test bed mechanism at various stages of the testing. Generally, the array structure will have the abilities to:

- Dismantle and reconstruct any array configuration identified for investigation in each region
- Construct surface-mounted or watertight array configurations, and accommodate ductwork or plumbing
- Accommodate side-by-side, combined photovoltaic or separate solar collector configurations, and modify array tilt

Provision is made for various types of electrical and thermal storage, and for dummy and real loads.

The test bed facility will contain no distribution system per se. All electrical and thermal loads will be artificially supplied, with distribution losses estimated and based on schematic distribution system layouts for habitable residences. All modes of operation for both the thermal and the electrical system will be simulated, so that all types of mechanical systems and energy distribution schemes can be analyzed.
Figure 11—Test Bed Mechanical System.
6.1 Test Bed I

Test Bed I, as depicted in Figure 12, is a site-built facility based on a pre-engineered building system. Building components would arrive on site ready for assembly. On-site labor would be reduced to a process that is simpler than traditional building methods. Grade changes to the site would be minimized because the building is elevated on steel columns. Foundations are isolated footings at each column. The array is a separate and adjacent structure, with an integral deck that provides floor level access to the building and a work platform below the array.

The roof structure is a 4-ft by 4-ft grid, uni-strut space frame. Shop-assembled space frame sections would arrive at the site ready to be bolted together and lifted into place. The roof membrane is a neoprene sheet, installed dry over gypsum board on a steel deck.

Exterior wall panels are 4-in. thick foam core panels. They would arrive on site with all glazing in place. Joints between panels are a simple neoprene gasket. Both interior and exterior faces would be finished to eliminate on-site painting.

The array structure is also a uni-strut space frame. The uni-strut system includes many factory-supplied hangers and brackets that can be bolted to the frame support wiring and plumbing. The frame can accommodate any size of collector by means of a secondary uni-strut grid which is bolted to the frame to provide connection points where required. Tilt adjustment is accomplished with a screw-type jacking device. The deck and railings below the array are fiberglass to provide an electric-shockproof work platform.

The cost is projected to be less than two-hundred thousand dollars (in 1975 dollars).
Figure 12 — Test Bed I.
6.2 Test Bed II

Figure 13 illustrates Test Bed II: a building concept that utilizes the existing technologies of the shipping container as the basic building module of the facility. Insulated containers provide a weathertight enclosure for each of the program's spaces. The recessed end wall, a standard feature of the insulated container, will be used to incorporate heat pumps or other HVAC equipment into each unit. Therefore, space conditioning can be provided as needed for the specific requirements of the activities in each container. Auxiliary spaces between containers (conference room, circulation corridor), would receive conditioned air from equipment mounted in HVAC recesses of adjacent containers.

In addition to the enclosed insulated container, the concept makes use of an open platform container as a base structure for the construction of an adjustable tilt array. All units are designed with structural corners so that they may be stacked and then securely fastened together. The subframe of both platform and insulated containers are built to receive a forklift.

The primary conceptual difference between Test Beds I and II is that all the mechanical and monitoring equipment on Test Bed II would be installed at a central location, by a single team of qualified technicians, prior to shipment to the test sites. Quality control would be optimized thereby, and all equipment could be tested at the assembly location to ensure site-to-site uniformity.

Site set-up would be a process of placing containers that were shipped as complete mechanical packages on pre-constructed concrete foundations. Platform containers with complete arrays would then be forklifted into place on top of containers and foundation walls. The conference room would be constructed of light metal framing, spanning between containers. Insulated aluminum-clad roof panels would be installed in one step to form the roof. The corridor framing would also span the space between the containers, independent of foundations. The final step would be to make utility hookups and all container-to-container connections.

Test Bed II is designed to be set up as a complete testing facility through Phase 2 of the program. When the best array and mechanical systems have been identified and implemented in a habitable residence, the modular test bed could be dismantled and moved to another region to begin a new Phase 1. The monitoring module could be moved to the habitable residence test site.

The projected cost of Test Bed II is also just under $200,000 (in 1975 dollars).
Figure 13 — Test Bed II.
7. HABITABLE RESIDENCE DESIGN

Several residential schemes were developed — using actual floor plans with windows, entrances, and site associations — so that realistic heating and cooling load evaluation could be made. Actual sketches and floor plans of residences help everyone involved in the project, and allow building array integration concepts to be related to actual physical forms. Because each climatic region presents a different set of physical design constraints, residential designs must be developed to reflect these constraints and to interact in an optimized manner with the photovoltaic energy systems. The designs should also consider the stylistic differences preferred for each region.

The sites selected for this study cover six major climate categories: (1) BALANCED (Santa Maria, Seattle), (2) HOT-DRY (Phoenix), (3) HOT-HUMID (Lake Charles), (4) SEASONAL (Omaha, Boston), (5) TEMPERATE (Nashville, Washington), and (6) COOL (Great Falls, Madison). The basic emphasis is on designing residences that are compatible with the operational requirements of photovoltaic total energy arrays in the various climate areas, and are also in keeping with the mores of the region.

Evaluation of the SOLMET Weather Tapes indicated that different designs for five candidate sites — Boston, Nashville, Great Falls, Phoenix, and Santa Maria — would be sufficient to represent all ten regions. The living area ranges from 1600 to 1800 square feet. Figure 14 shows a residential schematic for Santa Maria having the following characteristics:

- 50 m\(^2\) combined array
- Water drain-back solar thermal system with a purge coil for summer array cooling
- Oil-fired combination domestic hot water tank and a space heating boiler for backup with a coil from the main solar storage tank for the primary heating source
- 1-1/2 kilowatt engine generator for backup electricity

When habitable residences are constructed for ultimate evaluation, the test bed can be used to tie the solar configuration to the residence for comparison and optimization of several design variations. In essence, the habitable residence is used as a model. Dummy loads can be placed in the residence and controlled by the equipment in the test bed facility via a phone link. The array configurations of the test bed can then be linked to a real building load situation to verify the computer load simulation. When the final system has been selected and placed in the residence, an actual family would be asked to live in the home.
Figure 14 — Santa Maria Residence - Elevation and Perspective.
7.1 Townhouses

In addition to the more standard residential prototypes, some variations were explored. Architectural options — such as townhouses and underground single-family residences that would, by their design, further reduce the building loads — were identified. Figure 15 illustrates some concepts for a townhouse development in Washington, D.C. It was discovered that it was still possible, architecturally, to integrate enough active array area to satisfy an appropriate portion of the reduced load requirements. While townhouse systems have not gone through extensive simulation analysis, it is felt that the reduced collection area will be offset by the reduced loads. Some advantage may also be gained by operating a load center for the townhouse application. Although further study is needed, townhouses will probably be a viable and substantial application for photovoltaic total energy systems in most regions of the United States.
Figure 15 — Washington, D.C. Townhouse.
8. FACTORS AFFECTING WIDESPREAD IMPLEMENTATION

Major questions in regard to widespread implementation of residential photovoltaic total energy systems relate to:

- Overall system cost needed to achieve viability
- The means of achieving these costs
- The timing associated with system introduction

The following topics will address these questions.

8.1 System Cost Versus Value

Figure 16 shows the relation of maximum system cost to insolation received, utilization of this energy by the load as determined by simulation, anticipated efficiency of conversion, and realistic estimates of the lifetime value of the energy received for systems with storage but without sellback. Balance-of-System (BOS) costs are also shown; they are based on very high volume projection of all subsystems. Thus, the maximum allowable installed array cost is the maximum difference between the two; the area at which this occurs is the optimized area for the photovoltaic system ($F_M$, not $F_M^{MS}$). The equation at the top of Figure 16 relating the factors involved in maximum allowable cost leaves little room for major variation. Insolation and efficiency are rather rigidly defined, and most proposals for viable systems aim at a substantial utilization of the energy received. This leaves only the value of the displaced energy as the variable that has resulted in widely disparate views of system viability. Suggestions that installed array costs alone can be of the order of $200/m^2$ and yet achieve viability are based upon exaggerated estimates of the value of the energy displaced. For a homeowner this could be considered in terms of percentage of the residence cost. A point to remember is that a high assigned value for $rM$ will result in reduced demand and a change in the economic elasticity from past estimates. BOS costs, on the other hand, depend greatly on production volume. At low volume they will be considerably higher than those shown.

The maximum allowable cost is based on insolation for an average site, a conservative projection of electric rates to the year 2000 (6.6¢ in 1975 dollars) and a realistic value for $M$. Maximum allowable costs would be higher for favorable regions and lower for regions with poorer insolation or less favorable load match. An approximation for Phoenix would add $60 to the maximum allowable cost; Boston would be reduced about $30.

The curve in Figure 16 is for an all-electric system as opposed to a combined module array that provides hot-water and space-heating thermally. Similar but more complex logic would be used for a combined array.
AVERAGE SITE - RESIDENTIAL APPLICATION - ALL ELECTRIC SYSTEM

\[ \theta/m^2 = (U \mu) (rM) \]

- \( \theta/m^2 \): Allowable overall system cost divided by Insolation area
- \( U \): Utilization Factor, \( U < 1 \) = Fraction of received energy used per year
- \( I \): Insolation received per square meter
- \( \mu \): Overall system efficiency
- \( rM \): A multiplier determined by the value of money, electric rates and rate escalation
- \( r \): Electric rate at time of installation (1975 dollars)
- \( M = \frac{1}{\exp((1 - I - 0.1)N)} \): Present Value Multiplier
- \( I \): Discounted mortgage rate
- \( f \): Fuel escalation (Above Inflation)
- \( N \): System life

For Curve: \( I = 1700 \text{kWh/m}^2 \), \( \mu = 0.10 \), \( (rM) = 0.94 \)

**Figure 16** — Allowable overall system costs: with storage.
Figure 17 is similar to Figure 16; it shows the modifications in utilization and BOS costs for a system without on-site storage or sell-back. The utilization curve is highly conjectural because of the uncertainty of the match of load to insolation even in an hourly simulation: without storage this must be complete. Because of the low utilization, non-storage systems are usually tied to sell-back of energy — a form of seasonal, infinite storage at no cost. Since the utility is unlikely to pay back the price it charges for residential energy, a fraction representing the sellback ratio must be used to evaluate a system of this type. This fraction, in effect, raises the utilization curve by its proportionate value in relation to the maximum allowable overall system cost for either a storage or non-storage system.

To a large extent, the sellback ratio (the amount the utility is willing to pay per kilowatt-hour divided by the amount it charges the residential customer per kilowatt-hour) depends upon the penetration of photovoltaic residences. Both the ability of the utility to use the energy and the relative economic importance of the sellback ratio in the overall utility operation influence its value. Therefore, the rate paid by the utility at very low penetration can be considerably higher than the rate at quite high penetration, for the particular utility. In fact, considering the seasonal aspect, the net value to the utility could be zero at high penetration.

An important point for the home-owner is a guaranteed sellback ratio over the life of the photovoltaic system. This means that in evaluating the ratio, the utility must consider the situation over a twenty-year period or longer, rather than just at the time of installation. It is our estimate that a realistic maximum sell-back ratio for modest penetration is 0.35; for the amount of penetration possible beyond 1990, the maximum would be 0.25. If early installations are made without storage, we suggest that provision be made for on-site storage to be added later. This would be satisfactory in some regions for the short term. This alternative will be considered in the discussion on precommercialization and backfit (Section 8.3).
Figure 17 — Allowable overall system costs: without storage or sellback.
In Table 5, allowable system costs for an owner in the 30% tax bracket are compared with likely costs for photovoltaic systems with storage and without storage. A sell-back ratio is assumed for systems without storage. The favorable Phoenix site and the relatively difficult Boston site are used as examples. Costs—both allowable and for an average system—are approximate and are used to illustrate implementation potential. Detailed simulations and computer summation of all system components are used to determine system Figure-of-Merit for specific sites and systems (described in Tables 1 through 4).

Near term is defined as the next 10 years; or alternatively, the near term ends when 200,000 units have been installed. Far term is the period beyond the near term to the end of the century; or whenever the volume reaches 5 million installed units. Ten thousand units is assessed as the volume achievable by 1986. The effect of volume, not only on the module costs but also on the Balance-of-System (BOS) costs, can easily be seen. The low costs associated with high volume production cannot be achieved if systems are viable only in favorable regions. Therefore, the photovoltaic system and its method of application must eventually be viable virtually nationwide if the desired widespread energy displacement is to be achieved.

The allowable cost listing compares allowable costs (for system viability) to the approximate actual system costs, in Phoenix and Boston, for the low volume assumed in 1986 and the high volume projected for 2000. Thus, in Phoenix in 1986, the projected allowable cost for the storage system is $180/m² whereas the projected actual cost is $208/m². When very high volume production is achieved, the situation is reversed: the allowable cost is projected at $230/m² (due to higher alternate energy costs) and the actual cost at $94/m². In Boston, the all-electric system would be viable for an owner in the 30% tax bracket; however, a combined system (as discussed earlier) would result in greater benefit.

Since the photovoltaic system will not be viable for this application anywhere in 1986, a means to achieve the high volume needed to initiate large-scale production must be found. A precommercialization program is suggested to accomplish this.
TABLE 5 — ALL-ELECTRIC SYSTEM VIABILITY

<table>
<thead>
<tr>
<th></th>
<th>CUMULATIVE VOLUME (NUMBER OF SYSTEMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10x10³</td>
</tr>
<tr>
<td>(1975 dollars)</td>
<td></td>
</tr>
<tr>
<td><strong>SUBSYSTEM COST (80m²)</strong></td>
<td></td>
</tr>
<tr>
<td>Installed Modules</td>
<td>$8400*</td>
</tr>
<tr>
<td>BOS — No storage</td>
<td>4200</td>
</tr>
<tr>
<td>BOS — With storage</td>
<td>8200</td>
</tr>
<tr>
<td><strong>SYSTEM COST (80m²)</strong></td>
<td></td>
</tr>
<tr>
<td>No storage</td>
<td>12600</td>
</tr>
<tr>
<td>With storage</td>
<td>16600</td>
</tr>
<tr>
<td><strong>SYSTEM COST ($/m²)</strong></td>
<td></td>
</tr>
<tr>
<td>No storage (with central air-conditioning/without)</td>
<td>158/183</td>
</tr>
<tr>
<td>With storage (with central air-conditioning/without)</td>
<td>208/233</td>
</tr>
<tr>
<td><strong>ALLOWABLE COST ($/m²) — For Owner in 30% Tax Bracket</strong></td>
<td>in 1986</td>
</tr>
<tr>
<td>Phoenix — No storage** (Actual average system cost)</td>
<td>120 (158)</td>
</tr>
<tr>
<td>— With storage (Actual average system cost)</td>
<td>180 (208)</td>
</tr>
<tr>
<td>Boston — No storage** (Actual average system cost)</td>
<td>80 (183)</td>
</tr>
<tr>
<td>— With storage (Actual average system cost)</td>
<td>115 (233)</td>
</tr>
</tbody>
</table>

* Based on $500/kWp, 16% nominal cell efficiency.
** With estimated sell-back ratio in 1986 of 0.35, and in 2000 of 0.25.
***(70) and (94) costs assume cumulative $5 x 10⁶ installations; this requires viability beyond favorable areas.
8.2 Need for Precommercialization Program

The overriding importance of high volume production of all system components — not just the photovoltaic material — has been stressed throughout this discussion. Figure 18 illustrates the degree of system viability as a function of time and institutional action for systems that could eventually be viable. The problem is that even if the 1986 goals of $500/kWp material are achieved, the system will cost far too much because of low volume for all system components. This is not alleviated by considering only favorable insolation areas because they are not ordinarily sufficient to achieve the volume required for all sub-systems.

The suggested solution to this problem is a precommercialization program that allows the selected systems to proceed on a national scale. The program should be based upon guaranteed buys, at rates that reduce as volume increases over about a five-year period. There are, of course, many variations and extensions of this basic concept (which we have covered in previous studies) but incentive to manufacture and facility expansion are basic and essential. If the solar energy systems are viable, they continue to improve (as indicated in Figure 18). The curve is based on an average site and system.
Figure 18 -- Basis for viable cost estimates.
8.3 Near and Far Term Potential

Beyond the accomplishment of the 1986 National Photovoltaic Program goal of $500/kWp, large-scale implementation of photovoltaic systems will require that:

- The application will consist of small on-site systems
- A viable electrical storage system will be available
- A precommercialization program will be implemented to achieve high-volume production of all sub-systems

It is also necessary to start now to consider all of the institutional problems associated with small on-site systems. This includes such diverse items as local building codes; federal-state-local government actions; and the necessity of providing the complete storage/electrical-transfer subsystem with minimum mark-up — preferably as a single pre-tested package.

As shown in Figures 19 and 20, implementation will be hastened dramatically by a program that starts now to encourage the design of residential buildings to accept photovoltaic systems (backfit), because retrofit of arbitrarily constructed and oriented residences is considered impractical. This will probably require some incentive to the prospective purchaser and/or developer.

Backfit capability will result in:

- Rapid accomplishment of high volume production
- Large available market in favorable regions, awaiting only the capability of increased module production
- Reduced precommercialization costs and earlier completely commercial market
- Larger and earlier solar energy displacement; a displacement that would not be available over the lifetime of the buildings that were made available for backfitting

The increased rapid penetration made available by the backfit potential virtually eliminates the need for consideration of sell-back to the utility, even for the near term. The impracticability of sell-back for high volume photovoltaic penetration has already been discussed.

Finally, on-site buildup is a slow but relentless process. Once viability is achieved, it progresses for over half a century, when an estimated seventy million units will be solar powered.
Figure 19 — Annual new photovoltaic residences.

Figure 20 — Cumulative photovoltaic residences.
SUMMARY

- Sites representing most regions of the United States have been used to examine on-site photovoltaic total energy residential systems.
- The better systems for each region have been selected through detailed computer simulation.
- If high volume production of all subsystems can be attained, photovoltaic total energy systems will be economically viable in most regions of the country.
- In some favorable regions, viability can be achieved within 10 years.

To attain widespread on-site residential photovoltaic penetration, it is necessary to:

- Achieve the $500 per peak-kilowatt of the National Photovoltaic Program.
- Develop a single-package electrical subsystem, including storage.
- Plan a precommercialization program designed to achieve high-volume production.
- Build test bed facilities now, and habitable dwellings for test purposes in the near future.

Early high-volume implementation will be greatly accelerated if buildings constructed from 1980 on are designed so that they can be backfitted with photovoltaic systems. This will also substantially reduce the cost of precommercialization. Once precommercialization is completed, there will be a steady increase in the number of solar powered units installed — approaching one-million per year — until about 60% of the annual residential load is supplied by the sun.