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Solar Energy Research and Development: Program Balance

Annex, Volume 1

February 1978

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Prepared for

U. S. DEPARTMENT OF ENERGY
SOLAR WORKING GROUP

Under Contract No. EA-77-C-01-2693

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Prepared For

**U. S. DEPARTMENT OF ENERGY
SOLAR WORKING GROUP
WASHINGTON, D. C. 20545**

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PREFACE

In October, 1976, Robert Hirsch, then Assistant Administrator of ERDA for Solar, Geothermal, and Advanced Systems, asked the General Advisory Committee (GAC) to review the federal solar program to ensure that a reasonable balance existed between the R&D programs for each of the solar alternatives. The GAC, which has become the Solar Working Group (SWG) within the Department of Energy (DOE), contracted with SRI International (formerly Stanford Research Institute) to provide technical support for this evaluation and review. This report documents that support.

This evaluation and review examines the many solar options from various perspectives so that their roles in the U.S. solar R&D program can be assessed. The task is complex and difficult.

It was agreed at the outset that there is much more to consider in evaluating technology options than the number of "quads" of energy that some technology might produce several decades in the future. Considerable effort was expended in this investigation to evolve, in coordination with the SWG, a consistent methodology to systematically account for each technology's ability to meet specific goals: Can we expect it to make a significant contribution to the nation's energy supply? If so, when, and, in a relative sense, how much? Does it have a large resource base so that it could be depended on technically, even if it was not economical? Does it have specific environmental benefits compared with other solar options? Does it conserve oil and gas or does it conserve more abundant fuels? Is its commercialization sensitive to the level of federal R&D effort, or is its development self-sustaining within the private sector? Is it a research "long shot" that, although not currently feasible, could yield significant benefits if R&D were successful, or is it a technology that is relatively secure and not sensitive to R&D level? Might this technology yield unique benefits because of its decentralized nature? Might a significant export market develop for this technology that could justify a federal R&D effort?

This is clearly an imposing set of considerations; however, these considerations are essential to accomplish the stated goals.

At the outset, the limitations and boundaries on this study need to be strongly delineated so that this work can be seen in the context of similar efforts. Some of these limitations result from the many uncertainties of assessing technologies that might not be commercialized for several decades. Another serious limitation of this investigation is in the resources available for its conduct. Many previous investigations (e.g., Mitre, Office of Technology Assessment, and internal DOE planning

groups have devoted many times the resources to their efforts than were available for this work. The purpose in this work was not to duplicate these efforts but, where consistent with necessary independence, to build on them to develop a timely look at the major solar options to help determine a meaningful balance in the federal R&D program.

It is necessary to understand the boundaries of the areas of interest in this investigation. This effort has primarily been bounded by its objective of assessing the relative merits of the seven major solar technologies addressed in the federal solar program. Although it is possible to assess the solar technologies relative to nonsolar technologies, these comparisons are not made here, except where they are relevant to the issue of balance among the solar alternatives.

Evaluating a federal R&D program necessarily entails certain fundamental assumptions about the role of federal R&D programs. A solar advocate might claim that the federal role is to get solar systems into use at any cost, even to the point of having the government purchase the systems. Alternatively, some would say that the role of the government should be much more limited and that commercialization should occur through private choices in a free market. This investigation has attempted to frame questions whose answers are relatively unbiased on this issue. The SRI analysis has compared the solar energy systems in terms of the potential social benefits that could obtain through successes in research, development, and demonstration projects aimed at overcoming technical and economic barriers to the use of solar energy systems. Assessing these potential benefits has entailed assumptions and value choices; we have attempted to make these explicit and have described our evaluation methodology in detail to do so. However, the issue of whether the research, development, and demonstration should be carried out in the public or private sectors or in a combination of the two has not been addressed. This is a legitimate issue that undoubtably will be included in the final deliberations of the SWG and of others who wish to arrive at a judgment of priorities for federal solar R&D.

In summary, this study is an evaluation of federal R&D options on solar energy. It is not a definitive study of:

- Predictive market penetration
- Solar incentives
- The federal role in new technology development
- The comparison of solar with nuclear/fossil energy
- The merits of decentralized and centralized technologies.

However, this work does contain elements of all these items. Each item needs to be the focus of much additional work over the next decade.

Documentation of this work is in two volumes. Volume I contains the important overall conclusions and summaries of each technology

analysis. Volume II contains more detailed supporting data for the analyses presented in the first volume, as well as citations of selected references.

The reports contain contributions from a wide variety of SRI staff, including John A. Alich, Jr., deputy project leader responsible for benefits methodology; John P. Henry, Jr., project supervisor; Stephen M. Kohan, economic analysis and OTEC; Mark D. Levine, market penetration and ranking analysis; Partick J. Martin, energy storage; Paul C. Meagher, market penetration and ranking analysis; Katherine A. Miller, R&D analysis; Ellis E. Pickering, SHACOB; Meera Rao, computer programming; Frederick A. Schooley, biomass; Arthur J. Slemmons, wind and thermal power; James C. Snipes, R&D analysis; Nancy R. Teater, report coordination; Thomas E. Thompson, photovoltaics; and Jeffrey G. Witwer, project leader, market penetration and process heat. The core team, which was engaged in frequent presentations for and interaction with the SWG, consisted of John A. Alich, Mark D. Levine, and Jeffrey G. Witwer.

The willing cooperation of Dr. Henry Marvin, Dr. Lloyd Herwig, and the rest of the staff of the Division of Solar Energy (DSE) is also appreciated. Numerous DSE contractors and other solar researchers also gave important input to the study.

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CONTENTS

PREFACE	iii
LIST OF ILLUSTRATIONS	ix
LIST OF TABLES	x
I EXECUTIVE SUMMARY	1
II OVERVIEW OF METHODOLOGY AND RESULTS	5
Introduction	5
The Ranking Process	5
Prospects for Individual Solar Energy Technologies	10
Other Important Considerations	13
III BACKGROUND	17
Historical Review of the Federal Solar Program	17
Government Spending for R&D and Basic Research	34
IV TECHNOLOGY RESULTS	37
Introduction	37
Photovoltaic Devices	39
Solar Thermal Power Systems	54
Wind Energy Systems	60
Solar Heating and Cooling	67
Agricultural and Industrial Process Heat	79
Biomass Technologies	86
Ocean Thermal Energy Conversion	95
V EVALUATION METHODOLOGY	103
Introduction	103
Market Potential Methodology	104
Benefits Calculation Methodology	111
Technical Limit	116
Energy Supply/Demand/Price Scenarios	118

VI	APPLICATION OF THE EVALUATION METHODOLOGY TO THE ASSESS- MENT OF SOLAR ENERGY TECHNOLOGIES	125
	Introduction	125
	Potential Market Contribution of Solar Energy Technologies	126
	Potential Market Contribution: Sensitivity Cases	129
	Nominal Case Benefits Analysis	132
	Changes in Solar Technology Benefits at Reduced Solar Costs	133
	Sensitivity Cases	145
	Conclusion	147

ILLUSTRATIONS

1.	National Solar Energy Program Budgets	23
2	Federal Areas of Responsibility in the Solar Energy Program	29
3	National Solar Energy Research, Development and Demon- stration Program Structure	30
4	Trends in Federal Obligations for Basic Research by Agency	35
5	Trends in Federal Obligations for Development by Selected Agencies	36
6	Photovoltaic Development Schedule	42
7	Photovoltaic Array Cost as a Function of Concentration, Optical-Structure Costs and Cell Costs	45
8	Energy Displacement as a Function of Storage Capacity and Array Size for a Residential Site	49
9	Process and Equipment Technologies: Solar Heating and Cooling	70
10	Sensitivity of Solar Heating Unit Costs to Equipment Life and Interest Rates Space Heat Plus Hot Water	76
11	Biomass--Technology Overview	87
12	Conceptual Framework for Evaluating RD&D Plans	105
13	Equilibrium Market Share	107
14	Dynamic Market Response	109
15	Base Case U.S. Energy Consumption (1975, 1985, 2000, 2020)	120
16	Potential Solar Market Contribution: Base Case	130

TABLES

1	Relative Weights for the Values in the Benefits Calculation of the Nominal Case.	9
2	Solar Technologies Ranked by Total Benefits	9
3	NSR/RANN Solar Energy Program	21
4	NSR/RANN Solar Energy Budget.	22
5	U.S. Solar Energy Research Program Summary.	22
6	Federal Energy R&D Funding by Technology Area	22
7	Estimated Energy and Fuels to be Supplied in the U.S. by Solar Energy	32
8	Total Federal Basic R&D Expenditures.	33
9	Projected Nominal Unit Costs for Photovoltaic Systems . . .	43
10	Economics of Photovoltaic Systems for the Nominal Case. . .	46
11	Economics of Photovoltaic Systems for the Breakthrough Case	47
12	DOE's Photovoltaics Program, 1977	52
13	Development Schedule for Solar Thermal Power Systems. . . .	55
14	Economics for Solar Thermal Power Systems	57
15	Development Schedule for Wind Energy Systems.	62
16	Economics for Wind Energy Systems	64
17	Development Schedule for Solar Heating and Cooling	73
18	Projected Solar Heating and Cooling Unit Costs	74
19	Development Schedule for Biomass Conversion Processes . . .	90
20	Biomass Available for Fuel Use	91
21	Summary of Production Costs for Fuel From Biomass	92
22	Biomass Technology Risks and Potentials	94
23	Development Schedule for Baseload Electricity From Ocean Thermal Energy Conversion	96
24	Economics of Baseload Electricity From Ocean Thermal Energy Conversion	98
25	Market Penetration Parameters	110
26	Relative Weights for the Values in the Benefits Calculation of the Nominal Case	113

27	Base Case Primary Energy Consumption for the Total United States	119
28	Base Case Scenario Energy Demand Prices: End-Use Markets in Which Solar Energy Technologies Compete, 1985-2020	121
29	Comparison of Average Annual Growth Rate Assump- tions In the Base Case and High Electrification/High Demand Scenarios	123
30	Solar and Alternative Fuels Price Input into Market Penetration Model	127
31	Potential Solar Energy Market Contribution for the Base Case Scenario	128
32	Solar Market Potential in Sensitivity Case Scenarios . . .	131
33	Solar Technologies Ranked By Benefits for the Nominal Case	133
34	Ranking Values for Photovoltaic Devices	134
35	Ranking Values for Thermal Electricity	135
36	Ranking Values for Wind	136
37	Ranking Values for SHACOB	137
38	Ranking Values for Agricultural and Industrial Process Heat	138
39	Ranking Values for Biomass	139
40	Ranking Values for OTEC	140
41	Method of Estimating Change in Solar Technology Benefit Values with Changes in Solar Costs	141
42	Changes in Solar Technology Benefits Points from Nominal Case with 5, 10, and 20 Percent Cost Reductions - Near Term, 1985	142
43	Changes in Solar Technology Benefits Points from Nominal Case with 5, 10 and 20 Percent Cost Reductions - Intermediate Term, 2000	142
44	Changes in Solar Technology Benefits from Nominal Case with 5, 10, and 20 Percent Cost Reductions - Long Term, 2020	143
45	"Optimistic" Solar Cost Reductions from Nominal Solar Costs Based on Assumptions Derived from Current State of the Art	144
46	Changes in Solar Technology Benefits Points from Nominal Case with "Optimistic" Solar Cost Reductions . . .	144

I EXECUTIVE SUMMARY

Objective of the Study

The objective of the study was to provide support to the Solar Working Group of the Department of Energy in its assessment of the balance within the federal solar energy research, development and demonstration (RD&D) program.

Scope of the Assessment

The study contributed to the overall assessment of priorities in solar energy RD&D in two principal ways: by developing and applying a methodology that provided guidance to the Solar Working Group deliberations and by analyzing technical aspects of solar energy technologies.

Solar Energy Technologies Treated

The assessment treated seven groups of solar energy technologies. These are:

- Solar heating and cooling of buildings (SHACOB)
- Agricultural and industrial process heat (AIPH)
- Biomass
- Photovoltaics
- Thermal power
- Wind
- Ocean thermal energy conversion (OTEC).

Method of Approach

Because many factors are relevant to the assessment of solar energy RD&D options, there was a need to establish a framework for differentiating among the benefits of the solar energy technologies. SRI has chosen to use a concept of "benefit values" as an organizing principle for the study.

A procedure was developed, in concert with the Solar Working Group, to assess on a relative numerical scale the "benefit values" or social benefits that could be produced by each of the seven solar technologies.

The benefit categories deemed most important in assessing the solar energy technologies are:

- Relative energy contribution (market penetration value of the technology, based upon relative costs)
- Environmental qualities (environmental value)
- Potential contribution under adverse conditions of energy supply and price (insurance value)
- Conservation of oil and gas (conservation value)
- Potential for significant R&D breakthroughs (speculative value)
- Compatibility with decentralized systems (central/decentral value)
- Prospect for an export market (international value).

Results of Calculation of Benefits

The results of the benefits calculations were little changed under differing assumptions about the weights that should be ascribed to the benefits categories. The following results are contingent upon a continuing emphasis on solar energy RD&D.

In the near term (1985), three solar technologies contribute substantially more benefits to society than the others. These are:

- Solar heating of buildings
- Biomass
- Wind.

In the intermediate term (2000), the two leading contributors to benefits are:

- Solar heating of buildings
- Wind.

Biomass is also important in the intermediate term and photovoltaics could have a significant potential for making important contributions to social benefits in the intermediate time frame.

In the long term (2020), the analysis suggested that three technologies have the greatest potential for producing significant social benefits:

- Wind
- Solar heating of buildings
- Photovoltaics.

The sensitivity of these results to reduced costs through successes in research, development, and demonstration was assessed. Only those technologies already likely to contribute substantial benefits in the near term had a significant potential for increased benefits by 1985. In the intermediate term, the analysis suggested that two technologies might produce significant extra benefits under increased RD&D emphasis:

- Wind
- Photovoltaics.

In the long term, the solar technology that has the greatest potential of producing increased benefits under higher degrees of RD&D emphasis is:

- Photovoltaics.

Discussion of the Results

These results are meant to provide general guidance to the formulation of solar energy RD&D decisions. There are, however, additional factors that should be taken into consideration in evaluating the present program. As such, it is useful to summarize key insights that were gained about the seven solar technologies.

Solar Heating and Cooling of Buildings

The greatest need in the near term in solar heating of buildings is to promote the market acceptance of solar heating systems. Solar cooling is much less advanced than heating and needs considerable RD&D support before it can be expected to become commercial.

Wind

Wind energy conversion systems can play an important role in supplying electrical power. Both large and small units will find applications. The large wind systems have greatest potential because of economies of scale and their ability to effectively capture wind energy at prime sites. Additional RD&D can usefully be directed at obtaining better site data and supporting demonstrations to increase experience with wind systems under actual operating conditions.

Biomass

Both direct combustion of biomass and conversion of the biomass into fuels of a different form have considerable potential. RD&D can usefully focus on demonstration projects to better establish the viability of technologies for utilizing biomass.

Photovoltaics

Photovoltaic systems have been shown to have promise in the intermediate and especially the long term. As such, research is most usefully directed at this longer term potential. The most important areas for attention are new photovoltaic materials and less expensive fabrication processes.

Thermal Power

The high capital cost projections for thermal power systems are likely to limit the potential of these systems. RD&D that could enhance this technology include work on low-cost heliostats, high-temperature heat engine cycles, and total energy systems.

Ocean Thermal Energy Conversion (OTEC)

OTEC has barriers to commercial acceptance that will be difficult to overcome: the high capital costs of OTEC and the relatively low price of baseload electricity with which it competes. Key areas for federal RD&D emphasis are systems design, site specific data collection, and reliability in the marine environment.

Agricultural and Industrial Process Heat (AIPH)

Industrial uses of process heat must overcome siting limitations at industrial locations and the relatively high return on investment required by industry. Research and development can most usefully emphasize high-temperature collectors for industrial use and continued commercialization support for industrial hot water and selected agricultural applications.

II OVERVIEW OF METHODOLOGY AND RESULTS

Introduction

The assessment of the proper balance within the federal solar energy program requires an understanding of how each of the solar technologies could be developed to benefit the nation. Also required is an understanding of how progress in research, development, and demonstration of the solar technologies can contribute to the commercial acceptance of the technologies and the realization of their full potential.

A ranking process was developed to compare the solar technologies with one another on a figure-of-merit basis. The ranking process sought to achieve discrimination among the solar technologies in terms of several objectives and values that they might achieve. To carry out the comparison and ranking process, the solar alternatives were grouped into seven options:

- Solar heating and cooling of buildings (SHACOB)
- Agricultural and industrial process heat (AIPH)
- Biomass
- Photovoltaics
- Thermal power
- Wind
- Ocean thermal energy conversion (OTEC).

This section summarizes the conceptual development and results of the ranking methodology and provides specific comments on the prospects for each of the seven solar energy options.

The Ranking Process

Conceptual Development

As the technical evaluation of the solar energy systems progressed and monthly presentations were made by the SRI project staff to the SWG, it became clear that a carefully defined methodology was needed to provide a framework for the assessment. Within each of the seven areas in the solar program numerous opportunities could be found for useful research activities. But how were these opportunities to be judged against the overall energy needs of the nation? How could a procedure

be established that would structure the analysis and focus the attention of the participants on the key areas in need of discussion?

There exists no single way to answer these questions. But decisions had to be made that permitted an approach to evolve. The evolution of the approach can perhaps best be summarized by listing the major decisions that were made and the reasons for them:

1. There was a need to assess the social benefits of the different solar options. Without such an assessment, no clear framework for establishing priorities among solar RD&D options could be made available.
2. There was a need to decide what categories of benefits were of greatest importance in performing the assessment. After considerable discussion between the SWG and SRI, the following categories were chosen:
 - Relative energy contribution (market penetration value of the technology, based upon relative costs)
 - Environmental qualities (environmental value)
 - Conservation of oil and gas (conservation value)
 - Potential contribution under adverse conditions of energy supply and price (insurance value)
 - Potential for significant R&D breakthroughs (speculative value)
 - Compatibility with decentralized systems (central/decentral value)
 - Prospect for an export market (international value).
3. There was a need to develop a clearly defined and structured approach that recognized the importance of subjective judgments in assessing solar energy priorities. The decision was made to assign a numerical weighting to the different categories of benefits. The reasons for this decision are that such a numerical weighting system makes possible the explicit statement of values and permits the effects of these values on the analysis results to be tested through selected sensitivity runs.
4. There was a need to provide a relatively rigorous procedure for assessing the relative potential of the solar technologies to penetrate markets. The reason for this is that the benefits of a solar technology are of diminished importance if the technology has limited potential of coming into the marketplace. Furthermore, the economic projections performed on each solar technology (summarized in Section V) are useful only if compared with non-solar energy prices in the markets in which the solar technologies can compete.

5. There was a need to consider the role of solar technologies under a range of alternative energy futures. Considering a range of futures will not guarantee that the results of an analysis are correct, but it will at least allow the results to be more resilient than those that are predicated on a narrow view of future events.
6. There was a need to test the sensitivity of results of the investigation to key parameters and assumptions.

It was in response to these needs and the decisions resulting from them that the following analytic approach was developed.

Four scenarios showing energy supply and demand under different possible future conditions were developed. These four scenarios included a base case, designed to reflect a "consensus" view of the energy future; a high nonsolar energy price scenario, in which the solar technologies could have a significant potential for widespread use; a high electrification, high demand scenario, in which the solar electric options would be most favored; and a low solar price scenario, designed to indicate the full technological potential of the solar energy options over the long term. The details of these scenarios are explained in Section V of this volume and in the appendix to Volume II. These scenarios satisfy Point 5 above.

A model of the penetration of the solar energy technologies was constructed. This model included the time period between the present and 2020 (the end point of the technical and economic projections), seventeen end use markets in nine regions of the United States in which solar and nonsolar technologies can compete, and the four scenarios mentioned earlier. The model is described in Section V of this report and in Section X of Volume II. The solar penetration model satisfies Points 4 and 5 above.

Operational definitions of the benefits categories in Point 2 were established. The benefit values for each category were factored into two or more parameters, according to the logic that seemed most appropriate to describe them. Two examples describe the logic of the approach. To estimate the market penetration benefits of a solar technology in the near term (1985), the economic projections of the solar technologies were evaluated in three different scenarios. To assess the intermediate term (2000) market penetration benefits, uncertainty in the economic projection suggested that significant weight be placed on the overall technical (as distinct from economic) potential of the solar technologies. As such, 50 percent of the benefits weight was placed on the penetration results of the solar model (the total number of quads) and 50 percent was placed on the size of the market that the technologies could reasonably achieve (technical potential). For the long term (2020), two-thirds of the benefits weights were assigned to the technical potential. The method of estimating the magnitude of this technical potential is explained in Section V.

For the environmental benefits assessment, the assessment recognized that the overall benefits depend both on the inherent value of the solar technology for the benefit category of interest and on the fact that, without penetration, the benefits would not be realized. As such, the calculation of environmental benefits involved the multiplication of a factor representing the market penetration (or the technical potential for later time periods) and a factor representing the environmental benefits of the technology. These two factors were given approximately equal weight in the calculation. Details are presented in Section V. This approach was used also for the remaining benefits categories. Operational definitions of the other benefits categories are also presented in Section V.

These estimates of benefits points satisfy Point 2 above. They also partially satisfy Points 1 and 3.

The relative importance of the different benefits categories were specified. Table 1 presents the outcome of one evaluation of the weightings for the categories of benefits points. These weightings were arrived at jointly by SRI project staff and SWG members. Although these values are necessarily subjective, their rationale can be explained through a few examples. Market penetration is seen to carry less weight in the long term than it does in the near term, because knowledge of the economics and other market factors becomes progressively less certain with time. (The increasing use of the technical potential as a component of the market penetration benefits points also derives from the increasing uncertainty in the economic projections in later time periods.) Environmental benefits are given a greater value over time, under the assumption that cumulative environmental impacts will increase with time and with continued growth in resource development. Conservation of oil and gas were considered most important in the near term, under the assumption that replacements for them would ultimately be developed.

Sensitivity tests on these weightings indicated that, over a reasonable range in the choice of these weightings, the results of the assessment were not significantly altered. Although changes in the weightings resulted in numerical changes in the benefits values of the solar technologies, no change in the relative positions of the technologies in terms of benefits resulted.

The weightings presented in Table 1 and the sensitivity cases run on them satisfy Point 3 and partially satisfy Point 6. The collection of all of the components of the methodology provides an overall framework for the assessment, as required in Point 1.

Results of the Ranking Process

The results of the ranking process, shown in Table 2, indicate that three technologies clearly stand out as offering the highest benefits to society between now and the end of the century: solar heating for

Table 1
RELATIVE WEIGHTS FOR THE VALUES IN THE BENEFITS
CALCULATION

Value	Near Term (1985)	Intermediate Term (2000)	Long Term (2020)
Market	37	30	28
Environment	19	25	28
Insurance	13	20	14
Speculative	--	5	10
Conservation	19	10	10
Central/Decentral	6	5	5
International	6	5	5
	100	100	100

Table 2
SOLAR TECHNOLOGIES RANKED BY TOTAL BENEFITS

1985		2000		2020	
System	Ranking*	System	Ranking*	System	Ranking*
SHACOB	79	SHACOB	86	Wind	90
Biomass	68	Wind	78	SHACOB	73
Wind	67	Biomass	49	Photovoltaics	65
Photovoltaics	21	Photovoltaics	36	Biomass	48
Thermal power	12	OTEC	17	OTEC	40
Process heat	10	Thermal power	16	Thermal power	35
OTEC	1	Process heat	11	Process heat	21

*The ranking, in which each technology could receive a maximum of 100 points, is based on a relative figure-of-merit comparison with the other solar technologies.

buildings, wind, and biomass. Beyond the turn of the century, photovoltaic systems join these three with high benefits.

Sensitivity cases were run to estimate the changes in benefits that could result from achieving substantial cost reductions in each of the solar technologies through research and development. These long term cost reductions were estimated using plausible but highly optimistic assumptions about the economic potential of each of the solar technologies. Two major observations have emerged from these sensitivity cases:

- The potential for increased benefits under optimistic assumptions about RD&D successes in the intermediate term appears greatest for wind and, possibly, photovoltaic devices.
- In the long term, photovoltaic systems appear to have the greatest potential for increased benefits. Achieving this potential, however, depends on uncertain technological achievements whose likelihood will have to be reassessed as research continues.

Because these benefits are relative, a technology might be low in this listing and yet merit strong research and development support, compared to technologies outside this set of solar technologies. Also, a technology that does not achieve a high benefits ranking might nonetheless merit strong support because of its stage of development in the RD&D process, its symbolic public importance, or its ability to conveniently fill some important energy niche. The appropriate use of the results of the methodology is as guidance in setting a baseline from which priorities can be established.

The relative ranking is but one set of information that is needed to evaluate RD&D funding, and it clearly is not meant to be the sole basis of funding alternatives. This study has found that, at least in part, because of strong public and political pressures, the federal solar RD&D program has stressed near-term demonstrations and commercialization. While this seems to be appropriate for some solar technologies, such as solar heating of buildings and combustion of biomass, the results of this investigation indicate that for other technologies, such as photovoltaics, overemphasis on near-term demonstrations could impede commercialization by delaying more innovative or fundamental research programs.

Prospects for Individual Solar Energy Technologies

The following discussion contains a summary of the key findings of the study for each of the seven solar energy technologies.

Solar Heating and Cooling

In the near and intermediate term, the highest benefits are from solar heating of buildings. This technology is attractive primarily because of its economics. In the longer term, it is surpassed in benefits by wind, only because the size of its potential (as opposed to projected) market is smaller than that of wind.

Because of the uncertainty of consumer acceptance in the near term, these building uses are likely to experience serious institutional barriers that are more amenable to government incentives and supports than to federal RD&D efforts. The most serious RD&D need in this area is for reducing the installed cost of collectors (on a cost per performance basis, not necessarily a cost per unit area basis). Solar air conditioning is much further from commercialization than solar heating; R&D is needed both to develop the technology and to improve its economic performance.

Wind

Wind systems also produce high benefits in all time periods. Wind is attractive because of its potential energy contribution, because it conserves oil and gas, and because its economics look relatively attractive. At least through the end of the century, wind systems will operate as "fuel savers", that is, full back-up by conventional units will be required. The cost of such units has been included in the analysis. Although this type of system would seem to be expensive because of its duplication of equipment, it would be the most effective way to use wind because of the even higher expense of energy storage. Larger scale (i.e., greater than 1 MWe) wind systems appear to be the most attractive, particularly in terms of total energy produced; however, smaller kilowatt-scale units can also be attractive, especially for off-grid uses.

Federal RD&D can do much to facilitate wind use by developing better site data (i.e., carefully mapping the resource), supporting demonstrations to accumulate operating experience, and facilitating industry RD&D in design and materials. The federal role is important because, although there are many potential hardware suppliers for wind systems, an integrated supporting industrial base is not now developed.

Biomass

Biomass has high benefits in the near term because of its potential energy contribution and because, as a fuel, it can save oil and gas. Its use in the near term will primarily be through direct combustion processes, while conversion to liquid or gaseous fuels is estimated to be competitive for some processes in the 1980s and for others not until 2000. The use of biomass as a source of energy can accelerate relatively rapidly, because most components of the technology are established and because incentives exist in some locations to use biomass residues as fuel to mitigate disposal problems.

In the near term, RD&D can most effectively concentrate on demonstration of both combustion and fuel conversion to reduce institutional inertia.

Photovoltaic Systems

Photovoltaic conversion devices are not likely to enter utility service on an economically competitive basis until after 2000; however, by this time, they could be an attractive option and experience rapid growth in use.

The successful technology is more likely to be an inexpensive thin film design than either concentrating or single crystal designs. The devices will provide peak and intermediate power and are likely to be dispersed on rooftops and connected to a central electrical grid. Off-grid uses by homeowners and others desiring "energy independence" could represent an important initial market after 1985; however, significant energy displacement will not occur until after 2000 when the utility application can be practical. The most important R&D efforts over the next decade will be in new photovoltaic materials and less expensive fabrication processes.

Thermal Power

Systems to produce electricity from solar driven heat engines do not score as many relative benefits as the previously described solar options. Significant commercialization would occur only under conditions of very high conventional energy costs, because prospects for major cost reduction in thermal power processes do not appear to be promising. The most attractive systems are likely to be advanced cycles (e.g., combined cycles) and/or hybrid designs that combine solar and fossil fueled heat inputs. Even with the advanced systems and hybrid designs, thermal power would be generally restricted in use to the Southwest where land costs are low and insolation is high. Total energy systems offer the potential for reduced costs, but the difficulties in matching heat demand and insolation are likely to restrict the number of these applications.

Key areas for fruitful federal RD&D that will enhance this technology are: low-cost heliostats, innovative design concepts (e.g., modular), high-temperature heat engine cycles (including combined cycles), and total energy systems.

Ocean Thermal Energy Conversion (OTEC)

OTEC scores low points in the near term because there is little prospect for its being commercially available by 1985. Its ranking moves up in the intermediate and long term because, under the conditions of very high nonsolar energy prices, OTEC could become a large source of solar energy. In this sense, OTEC could serve as "insurance".

Developing the commercial potential of power from ocean thermal gradients is made difficult by the technical uncertainties of reliability in the marine environment and the high initial cost of large

heat exchangers. Although the resource base is large, the reasonable market (baseload electricity in the South Atlantic, East South Central, and West South Central regions of the United States) is limited in size. OTEC is unique among the solar options in its ability to provide baseload power. Although this may seem to be an asset, it in fact means that OTEC must compete against nonsolar options that supply low cost baseload electricity. The baseload market will be a difficult one for OTEC to compete in. Similarly, the production of fuels (especially hydrogen) in OTEC plants will have to compete with many other advanced sources such as remote natural gas and synthetics from coal.

Key areas for federal RD&D emphasis are systems design, site specific data collection, and reliability in marine environment.

Agricultural and Industrial Process Heat (AIPH)

Process heat scores low relative benefits because of its low market potential. The available market is limited, because the largest industrial energy demands, those at very high temperatures and those that are very large in capacity, are virtually inaccessible to solar. In the near term, industrial systems would conserve oil and gas; however, near the end of the century, new applications would often displace coal, the anticipated marginal fuel for industrial process heat in the long term.

Institutional factors, some of which could be overcome with new policies, provide disincentives to process heat use. These include tax policies and other factors that require industry to seek a higher return on investment than, for example, utilities.

Although the total energy contribution of these AIPH applications will be small, selected applications will develop as economical systems. These include industrial water heating and, in the agricultural sector, grain drying. Federal RD&D programs in low-cost collectors, high-temperature collectors, and agricultural demonstrations will be most fruitful.

Other Important Considerations

Cost Estimating in Evaluating Solar Technologies

The analysis has focused on comparing the solar technologies with one another. Often, the study has encountered inconsistencies in the detailed economic and market penetration studies that are used to justify RD&D emphasis on particular programs. There seems to be an overemphasis on cost projections of conceptual technologies that are years, if not decades, from commercialization. In a world of cost/benefit analysis and zero base budgeting, this tendency to rely on economic projections is natural both within and outside the government. However, so many uncertainties enter into such analyses that it is unwise to depend on them as the only guide for policy making. This overemphasis on cost

projections simply becomes a game of "learning curves" and computer models in which the technology with the most quads wins. One effect of this has been to mislead the public on the outlook for new technologies. This problem is certainly not unique to the solar field. The technical difficulties and cost escalation in the now cancelled Coalcon Project demonstrate that cost estimates and technical projections are not even accurate for a short period of five years. The problem is rooted deeply in the whole decision-making process, which tends to reward over-optimistic cost estimating and penalizes more accurate costing.

Largely for these reasons, the project team developed and used a system for ranking that depends on both economic and noneconomic benefits so that at least part of this uncertainty can be removed. DOE contractor studies were heavily relied upon for the hardware cost estimates; however, SKI attempted to make these more consistent by using uniform estimates of interest during construction, contingencies, and other related expenses. The conclusions were based on analyzing a number of sensitivity cases. Conventional energy prices were among the important parameters that were varied. The size of the potential market by fuel type was weighed. Also considered were the relative impacts of factors such as variable market responses, dispersed versus central technologies, and international markets. This approach is certainly not the only way to improve these planning and evaluation processes.

Organizational Imbalances

The simple act of establishing an organizational structure inevitably lays the seeds for program imbalances. Evidence of this exists within the federal solar program.

In many parts of the country, passive techniques are the most effective way of using solar energy in new construction. Unfortunately, it is difficult to distinguish where conservation stops and where passive heating starts. Organizationally, this confusion is at least as great as it is technically, since passive heating seems to lie between the federal solar and conservation programs. An additional handicap that passive heating has faced is that, to the extent that it is considered "conservation", it cannot be measured in terms of quads of energy produced, which still seem better to many than quads of energy saved.

A wide variety of solar thermal power systems, ranging from large central towers to small, residential solar driven heat pumps, would greatly benefit from increased RD&D efforts into heat engines specifically designed for solar systems. Unfortunately, the responsibility for heat engine research within the federal government has been widely spread between conservation and transportation programs both within DOE and other departments. As a result, inadequate resources have been focused on heat engines for solar applications.

Solar concepts that have not been aggressively pursued are photochemical water splitting, solar thermal hydrogen production, and space power satellites. These range in requirements from basic research to very long-term engineering development. Without judging the merits of such schemes, one can at least suspect that their neglect has been due as much to the lack of an organizational home as to a lack of technical value.

Structural changes in the organization of the solar program undoubtedly can overcome many of these potential voids. The new structure of the DOE seems to recognize at least part of this by, for example, combining responsibility for building energy conservation and solar space heating. Time will be the judge of whether the other organizational changes of the solar program fill some gaps without opening new ones.

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III BACKGROUND

Historical Review of the Federal Solar Program

To place the current solar program in historical perspective, this section provides a summary of the early program's legislative basis, a look at its program basis in NSF and ERDA, and an indication of its relative significance in terms of the funding of and the historical reporting by the major agencies participating.

Legislative Basis

The national solar energy program is based on a series of public laws governing energy research, development, and demonstration described below.

Federal Energy Administration Act (PL93-275, May 7, 1974)

The Federal Energy Administration Act created the Federal Energy Administration as a temporary agency, transferred to it certain energy responsibilities from the Department of the Interior and the Cost of Living Council, and directed FEA to prepare a comprehensive energy plan (Project Independence), which included a solar energy section. The Act also directed the creation of a national energy informational data system.

Solar Heating and Cooling Act (PL93-409, September 3, 1974) and Solar Energy Research Development and Demonstration Act (PL93-473, October 26, 1974)

These two Acts are expressions of Congressional intent that the United States rely less on oil and accelerate development of alternative energy sources. The Solar Heating and Cooling Act authorized the spending of \$60 million over a five-year period to develop solar heating and cooling systems for buildings. The Solar Energy RD&D Act authorized \$75 million for solar energy research. Under the latter, the National Science Foundation (NSF) was assigned responsibilities for basic and applied research; the National Aeronautics and Space Administration (NASA), provision of management capability and technology development; the Atomic Energy Commission (AEC), technology development; the Department of Housing and Urban Development (HUD), fostering the utilization of solar energy for heating and cooling of buildings; and the Federal Power Commission (FPC), fostering the utilization of solar energy for generating electricity and producing synthetic fuels.

The Solar Energy RD&D Act also established a solar energy coordination and management project composed of six members, five to be representatives of the five agencies above and the sixth a member designated by the President. It provided for a solar energy resource determination and assessment program, scientific and technical education, establishment of a solar energy institute, and international cooperation in the solar field.

The Solar Energy RD&D Act specified that the areas of research would include direct solar heat, thermal energy conversion, conversion of cellulose and other organic materials, photovoltaic and other direct conversion processes, sea thermal gradient conversion, wind power conversion, solar heating and cooling of housing and commercial public buildings, and energy storage. It set forth the specific goals of a demonstration program and the criteria under which decisions on demonstration would be made. It provided for cooperative agreements between the responsible federal agency and other federal or nonfederal entities. Finally, it provided for the establishment of a solar energy information data bank (thereby creating a potential overlap with the energy information data system provided under PL93-275).

Energy Reorganization Act (PL93-438, October 11, 1974)

The Energy Reorganization Act abolished the Atomic Energy Commission and transferred its functions to two new agencies, the Energy Research and Development Administration (ERDA) and the Nuclear Regulatory Commission. In addition, it transferred several energy R&D programs to ERDA from the Department of the Interior, EPA, and NSF. Among functions transferred from NSF were solar heating and cooling development. The Act also transferred to ERDA the General Advisory Committee established pursuant to Section 26 of the Atomic Energy Act. Finally the Act established an Energy Resources Council in the Executive Office of the President to ensure communication and coordination among federal agencies with energy responsibilities, to advise the President on energy matters, and to prepare an annual report on national energy conservation activities.

Nonnuclear Energy Research and Development Act (PL93-577, December 31, 1974)

This Act established a ten-year, \$20 billion program for research and development of nonnuclear energy sources. Assigning most energy R&D programs to ERDA, it established broad policy guidelines for nonnuclear R&D.

Program Bases

National Science Foundation

The National Science Foundation established the Research Applied to National Needs (RANN) program in solar energy in 1971. Solar energy was one of many program areas within RANN. A solar energy panel, jointly funded by NSF and NASA under the auspices of the R&D Goals Committee of the Federal Council for Science and Technology, was organized in 1972 to assess solar energy technologies and propose a research and development plan. The general objectives of the RANN solar program, as recommended by the panel, were to:

- Provide the research and technology base required for the economic terrestrial application of solar energy and to foster the implementation of practical systems to the state required for commercial use.
- Develop at the earliest feasible time the potential of solar energy applications as large-scale alternative energy sources.
- Provide a firm technical, environmental, social, and economic base for evaluating the role of solar energy utilization in U.S. energy planning.

The panel's report, issued in December 1972, became the basis for a five-year program organized into six areas: heating and cooling of buildings, solar thermal energy conversion, photovoltaic conversion, biomass conversion, wind energy conversion, and ocean thermal conversion.

The objectives of each of these programs are presented in Table 3 and their budgets in Table 4. Table 5 shows the status of federally supported solar research projects in November 1974. Table 6 presents the total federal energy R&D funding by technology areas. Although solar research funding was relatively small in comparison with other technologies, it doubled in proportion and in total funds each year from 1971 when it accounted for 0.003 percent of the energy total. By 1974, the proportion had risen to 2.1 percent.

ERDA

In its national plan for energy RD&D, submitted to the Congress June 1975 in response to the Energy Research and Development Act of 1974,* ERDA recognized five national policy goals as a focus for energy policy; they were to:

- Maintain the nation's security and policy independence.
- Maintain a strong economy.

*ERDA 48, A National Plan for Energy Research, Development and Demonstration, June 1975.

- Provide for future needs so that life styles would not be limited by unavailability of energy.
- Contribute to world stability through cooperation in the energy area.
- Protect and improve the nation's environmental quality.

That report also presented the energy problem as one of altering the current use pattern of 75 percent of the energy consumption of the nation based on petroleum and natural gas, less than 20 percent on coal, and 2 percent on uranium, with solar energy providing a negligibly small percentage of our needs.

The plan called for moving from dependence on a narrow use of resources to a broader range of alternatives, including solar power. Solar sources constituted 5 of the 16 sources listed: crops, ocean heat, sunlight, tides, and wind power. However, the use of solar energy did not appear as a highest priority RD&D technology. Rather, its components were listed under the heading "other important technology" along with waste heat utilization, electric conversion efficiency, electric power transmission and distribution, electric transport, and energy storage. Solar items on this list included solar heating and cooling and fuels from biomass. The first was included in "underused midterm technologies," while biomass was a technology being explored for the long term.

The plan presented six scenarios in which solar played various roles, ranging from negligible to accelerated development. Under the program arising from these scenarios, the objectives for solar based technologies were as follows:

- Solar electric--an initial annual energy contribution before 1985, and a moderate contribution (up to 4.5 quads) by 2000. This would require one 10 MWe scale wind system in the 1979-82 period, lower cost photovoltaic elements (reduced to 0.1 percent of present cost) by 1985, and a 25 MWe ocean thermal power plant by the late 1980s.
- Fuels from biomass--a moderate annual energy contribution (up to 2 quads) by 2000. This entails operation of pilot plants under agriculture and wood plantation concepts in 1980-81 and under the marine biomass concept in 1982.
- Solar heating and cooling--an initial energy contribution before 1985 and a substantial annual contribution (4.5 to 9 quads) by 2000.

The economic analyses supporting the midterm stage (1985-2000) indicated that solar heating and cooling could become economically attractive along with second generation coal liquefaction and gasification plants, nuclear power, and use of waste heat in industrial processes. No solar technologies were included in the "economically attractive" lists for near-term or long-term implementation.

Table 3

NSF/RANN SOLAR ENERGY PROGRAM*

Process Element	Objectives
Heating and cooling of buildings	To establish the widespread utilization and availability of systems using solar energy for heating, cooling, and supplying the hot water needs for buildings in the United States to the degree that the systems applications are economically viable, technically feasible, and socially acceptable.
Solar thermal conversion	To prove the technical and economic feasibility of solar thermal conversion systems providing electrical or combined electrical and thermal service.
Photovoltaic conversion	To develop low-cost reliable photovoltaic conversion systems, capable of producing a significant amount of energy, resulting in widespread availability for terrestrial applications.
Biomass conversion	To prove the economic feasibility for large-scale conversion of waste, cultivated organic materials, and water to gaseous, liquid, and solid fuels using bio-organisms.
Wind conversion	To develop reliable, cost-competitive wind energy conversion systems capable of rapid commercial expansion on a significant scale.
Ocean thermal conversion	To establish system reliability and economic viability of large-scale power plants converting ocean thermal energy into electrical energy.

*Source: NSF-RA-N-74-062 Report and Recommendations of the NSF/NOAA Workshop on Solar Energy Data Requirements for Terrestrial Applications, 29-30 November, 1973

Table 4

NSF/RANN SOLAR ENERGY BUDGET
(Millions of Dollars)

Process	FY 71 (Actual)	FY 72 (Actual)	FY 73 (Actual)	FY 74 (Estimate)
Solar energy for buildings	\$ 0.54	\$ 0.10	\$ 0.40	\$ 5.60
Solar thermal conversion	0.06	0.55	1.43	2.20
Photovoltaic conversion		0.33	0.79	2.60
Biomass conversion	0.60	0.35	0.65	1.10
Wind conversion			0.20	0.80
Ocean thermal difference conversion		0.14	0.23	0.60
Workshops and progress assistance		0.19	0.26	0.30
Total	\$ 1.20	\$ 1.66	\$ 3.96	\$13.20

Table 5

U.S. SOLAR ENERGY RESEARCH PROGRAM SUMMARY

Process	Number of Projects			Total Projects	Total Funds Obligated (millions of dollars)
	NSF	NASA	HUD		
Heating and cooling of buildings	8	1	1	10	\$1.293
Solar thermal conversion	5	1		6	1.634
Photovoltaic conversion	9	5		16	1.578
Biomass conversion	9	1		10	1.641
Wind energy conversion	3			3	0.201
Ocean thermal conversion	3			3	0.313
Other projects	1			1	0.152
Technology assessments	1			1	0.267
Phase 0 - heating and cooling of buildings	3(est.)			3(est.)	1.533(est.)
Total	42	8	1	53	\$8.612

Table 6

FEDERAL ENERGY R&D FUNDING BY TECHNOLOGY AREA
(Millions of Dollars)

Process	FY 70	FY 71	FY 72	FY 73	FY 74
Coal	\$ 30.4	\$ 49.0	\$ 13.5	\$ 94.5	\$119.9
Oil and gas	8.8	11.5	12.9	12.8	9.1
Nuclear fission	283.4	295.2	358.0	412.0	475.4
Nuclear fusion	37.5	42.2	52.8	65.5	83.5
Geothermal	0.2	0.2	1.6	3.4	4.1
Solar energy		1.2	1.7	4.2	12.2
Control technology	22.1	19.8	23.6	38.1	47.5
Other		1.3	8.5	11.8	15.1
Total	\$382.4	\$420.4	\$532.6	\$642.3	\$766.8
Supplement					100.0
Total					\$866.8

* Appropriations Bill P. L. 94-355

FIGURE 1. NATIONAL SOLAR ENERGY PROGRAM BUDGETS

Before the legislation enacted in 1974, federal solar activities were based on more general charters authorizing research, development, and demonstration associated with the agencies' principal areas of responsibility. The historical significance of these activities and their position in national priorities can be assessed by reviewing the agencies' reports and federal budgets for the years during which energy matters became especially important to the nation. The degree of attention afforded solar energy in terms of coverage in the narrative portions and dollar value in the funding portions can be used as a rule of thumb in assessing the program's growth. Figure 1 presents the principal solar funding patterns over the period FY 1971-78.

Evaluation of Solar Priorities

The preceding discussion has described generally how solar, as a generic alternative, grew to take its place among the national energy options through a variety of legislative steps and programmatic changes. During these changes, the technologies among the solar options evolved relative to one another both through changes in budgetary emphasis of the dominant funding agency (NSF and later ERDA) and through interactions with federal agencies with overlapping jurisdiction. A more detailed examination of the lead agency plans and budgets, as they relate to solar energy, gives a better understanding of why some of the solar technologies have reached their present state of development.

National Science Foundation

The summary version of the federal budget for FY 1970 contained virtually no reference to the subject of energy research. The National Science Foundation Director's Program Review for FY 1970 mentioned three programs in the energy resource area and discussed the prospect of a large-scale national energy study. The ongoing work in 1970 included a look at hazards and biological consequences associated with energy (research done by Cornell University), work on thermal effects, power grids, plant siting criteria, and technological tradeoffs (Oak Ridge National Laboratory); and work on energy demand forecasting and long-range planning for energy utilization (RAND). No solar research was indicated.

There was a little more energy emphasis in 1971. The NSF's annual report for that year outlined an energy resources research program that included 26 awards for a total of \$5.1 million. The program included two general classifications:

- Surveys and analyses of energy resources and research
- Support of specific R&D projects that will have a direct impact on the energy problems of the nation.

Solar energy was included in the second category, but there was no specific information on the research involved. Information from other sources indicates that NSF's FY 1971 program included \$0.06 million for solar thermal research, \$0.54 million for solar heating and cooling, and \$0.60 million for biomass conversion research.

Funding for all advanced technology applications in the 1972 program amounted to almost \$19 million. This included a survey of current energy research and a resulting bibliography of 4,000 entries; a study of national energy problems summarized in a two-volume report, The U.S. Energy Problem; and a workshop on Energy and the Environment at Cornell. Work also was done on land use, power plant siting and power transmission, solar energy, and thermal energy storage. The solar program entailed a system aimed at the economical use of solar energy for generation of electric power, through a solar concentrator focused on a heat pipe with a selective optical coating (University of Minnesota). Direct formation of hydrogen using sunlight and photosynthesis of plants was under study at Case Western Reserve University.

In its report for FY 1973, the NSF acknowledged the need to expand the nation's energy resources. The RANN program placed emphasis on the development of definitive systems concepts involving energy, the environment, and productivity. The director cited as one example of the results of this program a technical breakthrough by which new optical coatings to trap solar energy have been improved by a factor of 2.

Of grants amounting to \$269 million in FY 1973, NSF provided just over 1 percent to solar-directed research. Product areas included heating and cooling of buildings, solar thermal conversion, photovoltaic conversion, wind energy conversion, ocean thermal conversion, photosynthetic production of organic materials, and conversion of organic materials (biomass) to clean fuels. Research was devoted principally to solar thermal applications (\$1.43 million), photovoltaic research (\$0.79 million), and biomass conversion research (\$0.65 million). The remainder was spread among ocean thermal and wind energy projects and workshops for program assistance.

By 1974, solar energy was solidly established as an important part of the NSF program. In his annual report, the director spoke of using the nation's scientific knowledge to replace the capital withdrawn from the earth's supply of finite resources. He cited as an example the potential ability to develop the means to use solar energy to replace the energy that would be depleted by the use of fission and fossil fuels. During that year, NSF established an office of energy-related research and identified 45 areas for priority support from the Foundation. By this time, the energy crisis had stimulated energy emphasis throughout the Foundation; in addition to RANN, the Scientific Research Project Support, Science Education, National and International Programs, and policy and planning activities all included energy facets. A separate NSF division was established to direct the energy research and technology program. The Foundation initiated a series of workshops of energy experts to outline research opportunities in the 44 areas of energy-related research

identified as relevant to energy problem solutions. International programs included a series of visits by U.S. scientists to countries exploring alternative forms of energy. In addition, binational and international seminars on energy research, especially solar and geothermal, were initiated.

In research applications, solar heating and cooling activities included three feasibility studies, an experimental solar house, two laboratories, a national workshop, and the construction and operation of experimental solar energy systems to augment heating in four public schools. Design of a large wind energy system was begun. Studies in biomass conversion economic and engineering feasibility were completed. Work also included research in photovoltaic and ocean thermal power conversion.

More than 200 of NSF's 615 research applications studies in FY 1974 concerned energy. Of the \$76 million spent in research applications, \$28 million was for energy projects. Total NSF funding for the solar program in FY 1974 was \$13.2 million. Almost \$6 million of this was for heating and cooling research, approximately \$2 million each for thermal and photovoltaic, and \$1 million each for wind energy and biomass conversion.

In FY 1975, with the formation of ERDA, a comprehensive RANN research program in the energy field was transferred to the new agency along with experienced staff. However, RANN continued a strong energy research program, refocusing it toward more advanced, longer range, high risk, high payoff research.

Part of the responsibility NSF transferred to ERDA was the lead responsibility for solar energy and thermal energy research. ERDA was given funds of \$51.7 million and 45 staff additions for the task. NSF contributed strongly in the field, providing the technical background for a request for proposal for a 10 MW(e) proof-of-concept experiment and similar studies for a solar thermal conversion system test facility, as well as studies on wind characteristics, feasibility studies of the closed cycle thermal conversion system (in support of the ocean thermal program), and work on photovoltaic energy conversion. NSF's RANN organization was responsible for preparation of the Project Independence blueprint section on solar energy. However, by FY 1976, RANN virtually concluded its energy research with the transfer to ERDA of an additional 125 projects with a funding level totaling over \$21 million. Thereafter, NSF's resource application work was directed at nonenergy resources.

Atomic Energy Commission

The report of the Atomic Energy Commission (AEC) for FY 1973 describes that organization's response to the energy challenge and its work on projects to increase the amount of energy available to the nation through nuclear and nonnuclear sources. Solar work included the design of a five-year development program, leading to a solar community

demonstration project and an evaluation of the program's system design and component requirement. To provide perspective, other energy research included the demonstration of the subterranean, a promising method of excavating tunnels and boring deep holes more efficiently; a lithium/sulfur battery storage system; a field demonstration of the feasibility of extracting geothermal energy from dry hot rock; and work on the use of multiple nuclear explosives to stimulate natural gas production.

During FY 1974, solar research concerned the development and comparison of solar collectors. These projects were transferred to ERDA along with other AEC activities in FY 1975.

Department of Housing and Urban Development

Under the provisions of PL93-409, HUD was assigned the responsibility of implementing the residential demonstration portion of the solar heating program. Besides the residential demonstrations themselves, this function entails the development of performance criteria and certification procedures for solar heating and cooling equipment, market development to encourage acceptance of solar technology by the housing industry, and information dissemination of the program. In FY 1974, HUD and ERDA jointly developed a program plan for demonstrating the commercial feasibility of solar energy for residential use. In 1975, requests for proposals for the first cycles of demonstrations were issued, beginning the five-year \$44 million program of awards and grants. HUD also began working with the National Bureau of Standards to develop performance standards and criteria for solar energy systems, including those to be incorporated into HUD minimum property standards. The first step in developing performance standards was the publication of Interim Performance Criteria in January 1975. Subsequently, HUD published a draft on minimum property standards for solar heating and domestic hot water systems. In response to the HUD standards, professional associations in the materials and construction field have worked to develop standard test methods, properties, and specifications necessary for publication as definitive performance criteria. Other work by HUD includes the study of public barriers to solar acceptance such as building codes; the study of land use regulations and property taxes assessment; work on potential financial incentives to encourage installation and use of solar energy systems; and work to develop appropriate system warranties, design of building and maintenance manuals, training programs, and interface arrangements between utility companies and solar energy system users.

Under an interagency agreement, HUD budgets only the cost of its solar staff, while ERDA provides funds by transfer for the demonstration projects themselves.

Other Federal Agencies

While the majority of the effort in the solar program is being undertaken by the agencies discussed above, other agencies are also

involved. Figure 2, taken from ERDA-49, Definition Report of the National Solar Program (June 1975), gives an overview of responsibilities for solar energy by major activity and agency. The principal activities not previously described are:

- NASA--Through the Marshall Space Flight Center, the Lewis Research Center, and the Jet Propulsion Laboratory, NASA provides support to the heating and cooling demonstration in the areas of instrumentation, data gathering, and performance analysis; and developing, testing, and evaluating wind energy components. It also manages the low-cost silicon solar cell development program.
- Department of Commerce--The National Bureau of Standards has developed (for HUD) interim performance criteria for solar heating and cooling systems and residential dwellings, and will keep these criteria updated. The National Oceanic and Atmospheric Administration's responsibility is to make an inventory of all solar energy resources associated with federal lands (and in some cases nonfederal lands), conduct regional surveys, and publish maps and other documents developed from the survey.
- Department of Defense--DOD participates by providing sites and buildings for applications of solar technologies.
- Department of Agriculture--DOA supports the program by managing demonstrations of crop drying, greenhouse heating and cooling, and animal shelter heating and cooling through solar systems. It also supports programs of terrestrial biomass production and conversion.
- Other--GSA, Department of the Interior, and the Postal Service programs include solar demonstrations in buildings under their control. The Small Business Administration's function is to provide loans and management support for small businesses taking part in the program. HEW is identifying school and hospital buildings for utilization of solar systems. FPC (now the Federal Energy Regulatory Commission) and FTC are participating in their normal regulatory roles. The Department of State is concerned with international agreements on solar matters.

The ERDA/DSE Program

Since ERDA's inception, the federal solar program, within the Division of Solar Energy (DSE), has had a more unified and coherent thrust. Although it has undergone minor restructuring throughout its existence, the Division has maintained a basic structure oriented toward the six major solar classifications identified in the 1972 report of the NSF/NASA Solar Energy Panel: heating and cooling of buildings, solar thermal power, photovoltaic power, fuels from biomass, wind, and ocean thermal energy conversion. DSE also added technology support programs as shown in Figure 3, which was taken from its Definition Report of 1975

	ERDA	FEA	HUD	NASA	NSF	STATE	DOD	DOC	USEA	GSA	USPS	HEW	FPC	FTC	TREASURY
Direct Thermal Applications															
Solar Heating and Cooling of Buildings	X	X	X	X	X		X	X		X	X	X			
Agricultural and Process Heating	X				X				X						
Solar Electric Applications															
Wind Energy Conversion	X			X	X		X		X						
Photovoltaic Energy Conversion	X			X	X		X								
Solar Thermal-Electric Conversion	X				X		X								
Ocean Thermal Energy Conversion	X				X		X								
Fuels from Biomass	X				X		X		X						
Technology Support and Utilization															
Solar Energy Resource Assessment	X		X	X	X		X	X	X						
Solar Energy Research Institute	X														
Technology Utilization and Information Dissemination	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Regulation of Energy	X	X											X	X	X
Energy Policy Analysis and Development	X	X	X		X			X						X	X
Program Definition	X	X	X	X					X						
Manpower and Training	X				X							X			

SOURCE: ERDA-49 Definition Report of the National Solar Program, June 1975

FIGURE 2. FEDERAL AREAS OF RESPONSIBILITY IN THE SOLAR ENERGY PROGRAM

FIGURE 3. NATIONAL SOLAR ENERGY RESEARCH, DEVELOPMENT AND DEMONSTRATION PROGRAM STRUCTURE

(ERDA-49). From the standpoint of solar energy this Definition Report is an important document, because it presents one of the first public statements by the federal government of how the various solar technologies could fit together to contribute to the national energy supply. The estimates of future solar energy supply, shown in Table 7, have been widely quoted in the popular press as predictions of what solar will do, although they were based only on early analysis and have been more accurately described as goals than predictions.

If there is a dominant factor in Division of Solar Energy (DSE) since its founding, it is high and continuous growth, which has averaged more than 100 percent per year through 1977. An unusual aspect of this growth has been that it has at times exceeded DSE's own plans in that congressional appropriations have exceeded DSE budget requests. This has undoubtedly made the planning of a coherent RD&D program more difficult by making long-range budget plans obsolete.

The Public Impact on the Federal Solar Program

A discussion of the evolution of the solar program would be incomplete without including the role of the public. Probably no other element of the federal energy program has been reviewed and evaluated by as many organizations inside and outside the government, including the Office of Technology Assessment, the General Accounting Office, and numerous public interest groups. The federal solar program is shaped not only by the results of these studies but also by a requirement to be under continuous investigation.

This public interest in the program is simply the logical expression of public interest in solar energy. Numerous surveys have shown that the public at large has an extremely favorable picture of solar energy and is optimistic about its becoming a significant source of energy in the future. The political pressures favoring solar are real and diverse.

High public expectations have clearly made an impact on the federal solar program. It has been frequently claimed, and this study seems to bear out the claim that the federal solar program to date has emphasized near-term applications of technologies that are state of the art rather than more basic R&D that would advance the state of the art. This result could be expected since, with such high public expectations, the failure to deliver early demonstration systems would be construed as foot-dragging at best, or subverting at worst.

Spending by the federal government for all forms of R&D has grown steadily since 1960, as shown in Table 8. Although this growth appears substantial, more careful examination shows that, because of inflationary pressures during this time, R&D expenditures expressed in constant dollars actually fell 20 percent between 1965 and 1977. In FY 1977, ERDA received about 14 percent of the total federal R&D budget.

Table 7

ESTIMATED ENERGY AND FUELS TO BE SUPPLIED
IN THE U.S. BY SOLAR ENERGY*

	1985	2000	2020
Direct thermal applications (in units of quads per year= 10^{15} Btu per year)			
Heating and cooling	0.15	2.0	15
Agricultural applications	0.03	0.6	3
Industrial applications (process heat)	0.02	0.4	2
Total	<u>0.2</u>	<u>3</u>	<u>20</u>
Fuels from biomass	0.5	3	10
Solar electric capacity (in units of thousands of megawatts, GWe) [†]			
Solar thermal	0.05	20	70
Photovoltaic	0.1	30	80
Wind	1.0	20	60
Ocean thermal	<u>0.1</u>	<u>10</u>	<u>40</u>
Total electric capability	1.3	80	250
Equivalent fuel energy [‡] (quads)	<u>0.07</u>	<u>5</u>	<u>15</u>
Overall energy equivalent in quads	1	10	45
Total projected U.S. energy demand (quads)	100	150	180

*These categories and numbers are not identical to those used in the ERDA-48 analyses for 1985 and 2000. They are, essentially, the same within the accuracy of such estimates.

[†]These numbers represent estimated equivalent rated capacities of conventional plants which are operating at a load factor of 0.6 (5,200 hours per year) for 1985 and 0.7 subsequently. They are provided for comparison.

[‡]Assumes a conventional electrical generation efficiency of 32 percent.

Source: ERDA 49

Table 3.

TOTAL FEDERAL BASIC R&D EXPENDITURES
(Millions of Current Dollars)

	<u>1960</u>	<u>1965</u>	<u>1970</u>	<u>1971</u>	<u>1972</u>	<u>1973</u>	<u>1974</u>	<u>1975</u>	<u>1976</u>	<u>1977</u>
Basic	\$ 610	\$ 1,690	\$ 2,042	\$ 2,132	\$ 2,411	\$ 2,420	\$ 2,465	\$ 2,146	\$ 2,345	\$ 2,519
Applied	1,331	3,164	3,555	3,942	4,146	4,080	4,708	4,783	5,223	5,331
Development	<u>5,611</u>	<u>9,760</u>	<u>9,743</u>	<u>9,490</u>	<u>9,955</u>	<u>10,321</u>	<u>10,265</u>	<u>12,115</u>	<u>14,056</u>	<u>15,637</u>
Total	\$ 7,552	\$ 14,614	\$ 15,340	\$ 15,564	\$ 16,512	\$ 16,821	\$ 17,438	\$ 19,044	\$ 21,624	\$ 23,487

Percentage of Total

Basic	8.0 %	11.6 %	13.3 %	11.4 %	14.6 %	11.9 %	14.1 %	11.3 %	10.8 %	10.7 %
Applied	17.6	21.6	23.2	23.9	25.1	23.3	27.0	25.1	24.2	22.7
Development	74.4	66.8	63.5	64.7	60.3	64.8	58.9	63.6	65.0	66.6

Government Spending for R&D and Basic Research

Basic research can play an important role in the development of some solar technologies. For example, the major expense of many solar systems is the material used in fabrication. For this reason, basic research in materials and materials fabrication could be an important boost in the commercialization of some solar technologies. Because of this importance, the federal support of basic research needs to be examined.

The National Science Foundation, whose major responsibility is the funding of the federal basic research program, defines the goals of basic research as:

- Providing an expanded knowledge of our physical world to give society a more accurate picture of the natural setting and boundaries in which it operates.
- Improving our resource base and the economics of resource utilization.
- Understanding nature's way of using her resources to sustain the varied systems of life on earth.

Funding of basic research has been between about 11 and 15 percent of total R&D funding since 1965. It remained stable on a constant dollar basis to 1973 and has declined slightly since that time.

Funding of basic research by agency is shown in Figure 4. HEW has led this funding category since 1967. Since 1974, ERDA has shown increased support for basic research. In 1977, about 11 percent of ERDA's RD&D budget was allocated to basic research. This ERDA-supported research is directed toward improving energy conversion technologies and toward high-energy physics.

The ERDA basic research that was specifically identified in briefings to the Solar Working Group as being solar-related represents about 2 percent of the ERDA-DSE budget. This is far below the ERDA basic research to total ERDA research relationship of about 10 percent.

Funding of all applied research has fluctuated between 21 and 27 percent of total R&D spending since 1965. On a constant dollar basis, applied research funding in 1977 is at the 1967 level. DOD has been the leading agency for applied research throughout the last decade. ERDA currently has 8.6 percent of the applied research budget; most of this was transferred from the NSF-RANN and AEC programs.

The majority of the R&D budget, 60 to 67 percent in the last decade, has been spent for development. The 1977 budget increase for development is a record high and will run ahead of inflation for the second consecutive year. However, on a constant dollar basis, this funding is 26 percent less than the 1967 level.

^a Prior to 1974 AEC data were used.

^b Prior-year data for fiscal years 1968, 1970, 1972, and 1974 are not currently available on a comparable basis pending revision by NASA of basic research totals for those years.

SOURCE: National Science Foundation

FIGURE 4. TRENDS IN FEDERAL OBLIGATIONS FOR BASIC RESEARCH BY AGENCY

DOD, NASA, and ERDA accounted for 92 percent of the development effort in 1977; this is a decrease from the 1967 level of 96 percent. ERDA funds for development have increased rapidly since 1974, as shown in Figure 5. ERDA funds in FY 1977 constitute 16 percent of the development budget. Development activities are found in almost all ERDA programs.

^a Prior-year data for fiscal years 1968, 1970, 1972, and 1974 are not currently available on a comparable basis pending revision by NASA of development totals for those years.

^b Prior to 1974 AEC data were used.

SOURCE: National Science Foundation

FIGURE 5. TRENDS IN FEDERAL OBLIGATIONS FOR DEVELOPMENT BY SELECTED AGENCIES

IV TECHNOLOGY RESULTS

Introduction

The following discussion provides summaries of the results of the technical and economic analyses of the seven solar energy technologies: photovoltaic, thermal electric, wind, solar heating and cooling of buildings (SHACOB), agricultural/industrial heating, biomass, and ocean thermal energy conversion (OTEC). These summaries discuss pertinent information to describe the state of the art of the technologies, to provide the results of the economic projections, and to explain the factors considered in developing these projections. Also included are brief discussions of environmental factors, international opportunities, and present priorities in the research, development, and demonstration activities for each solar energy technology. A more complete discussion of the technologies, with full documentation of the economic projections, is contained in Volume II.

To reduce the likelihood of confusion, the economics of all the solar energy technologies are expressed both in units that are commonly used in the literature and in a set of consistent units. Because the description of costs is least uniform for the solar electric options, we first discuss these options and then explain the consistent units used in this section.

The commonly used units to express capital costs for photovoltaic systems are dollars per peak kilowatt (\$/kW-pk) or cents per peak watt. The capital costs of wind energy conversion systems (WECS), thermal power systems, and ocean thermal conversion systems (OTEC) are commonly presented in dollars per rated kilowatt (expressed in this report as \$/kW). Peak kilowatts are units that express the maximum power of the energy facility. Rated kilowatts refer to the sustainable power of the energy facility under the specified operating conditions and over the lifetime of the facility. The rated power (also referred to as the nameplate rating) is less than the peak power.

The capacity factor for these solar electric options is the ratio that converts peak kilowatts (for photovoltaic) or rated kilowatts (for the other solar electric technologies) into average kilowatts. The latter term is expressed in this report as kW_{av}. The capacity factor is defined as the actual energy output of the facility for one year divided by the energy output that would have obtained if the facility were performing at its rated capacity (or peak capacity for photovoltaic) for one year.

To avoid confusion between these different terms for expressing the capacity of the solar electric systems and also to facilitate comparison of the electric and nonelectric options, the economic estimates

for each solar technology are also presented as specific capital costs (SCC). These units are not to be confused with capital costs. The specific capital cost is the total facility capital investment divided by the annual energy output of the energy facility. It is expressed in this report in dollars per annual kilowatt hour (\$/annual kWh) or dollars per annual million Btu (\$/annual 10^6 Btu). The estimates of initial capital investment include both the direct costs (e.g., plant equipment) and indirect costs (e.g., labor, interest costs).

One other term is commonly used in this report for discussing the economics of the solar energy systems: the capital **recovery factor** (CRF). The CRF is the annual cost of the total capital investment^{*} in the energy facility divided by the total capital investment. Thus, multiplying the specific capital cost of a facility by the capital recovery factor yields the annualized fixed cost per unit of energy (expressed as either \$/kWh or \$/ 10^6 Btu). Adding operating and maintenance costs to the product of CRF and SCC gives the total annualized cost per unit of energy.

The economic analysis in this section reports all costs in constant 1975 dollars. The capital recovery factors that were used in our analysis were 0.10 for the residential/commercial sector, 0.17 for the utility sector, and 0.24 for the industrial sector, current dollars. The capital recovery factors were converted into constant dollar values for use in the analysis.

* The cost of capital investment includes the cost of depreciation, interest on debt, return on equity, taxes, and insurance.

Photovoltaic Devices

Introduction

Photovoltaic devices convert light (photons) directly to electricity. When sunlight falls on a semiconductor, some of the photons in the light beam create pairs of electrons and holes in the semiconductor. If these oppositely charged particles are in the vicinity of an electric field (such as that produced at a p-n junction, or a metal-semiconductor barrier), they will move in opposite directions, producing a net electric current. The process is totally electronic, requiring no moving parts. It works at ambient temperatures and pressures and produces no by-products except the heat from the sunlight that is not converted to electricity. Photovoltaic cells, consequently, are quiet, easy to operate, and extremely reliable.

The photovoltaic effect, first observed by Becquerel in 1839, can occur in gases, liquids, and solids; but acceptable levels of efficiencies have been observed only in solids. The first photovoltaic cell to convert solar energy into electrical energy with an efficiency greater than 1 percent, discovered in 1953, consisted of a silicon p-n junction. Since that time, silicon solar cells have been extensively studied and developed as energy sources for the space program. More than 500 satellites currently in orbit around the earth depend on silicon solar cells as their primary energy source. As an example, Spacelab uses a 20-kW photovoltaic system with silicon solar cells which have efficiencies between 10 and 15 percent.

With the growing concern for the world's energy problems, increased effort has been put into developing solar cells for terrestrial energy sources. This approach seems feasible when one considers, for example, that the yearly average of solar energy incident on the face of the United States is many times greater than the current annual U.S. energy use.

Cost is the main hindrance to the use of photovoltaic cells as terrestrial power sources. A complete solar panel is currently available for about \$420, which will produce 19 volts dc at 1.3 amps with peak noon-time sunshine (1 kWh/m^2). The cost equates to approximately \$17,000 per kW-pk for this 12 percent efficient silicon array. If the panel were to be used continuously for 20 years with no further costs incurred, the electricity produced would cost nearly 50 cents per kilowatt-hour, compared with the current utility rate of about 3-1/2 cents per kilowatt-hour for domestic electricity. However, even at this high rate, many currently economically viable terrestrial applications are available for photovoltaic arrays. These include such remote location uses as battery chargers for mountaintop weather stations, radio repeater stations, forest lookout towers, warning lights for offshore structures and channel buoys, and cathodic corrosion inhibitors for pipelines.

The following discussion is based on information gathered from the general technical literature, public documents, and discussions with individuals in industry, universities, and government agencies.

Generic System Types

The three types of systems chosen for the economic analyses are: small systems that might produce power from several watts up to 10 kilowatts, termed residential; intermediate-sized systems from 10 to 500 kilowatts, as might be used to power a school or shopping center; and central power stations, which could produce 1 megawatt (MW) or more.

Within each of these generic categories, capital costs per unit of energy are expected to be comparable since the type of equipment and its deployment would be similar. For instance, the installation of solar cell panels for residential systems will not entail expense for land. The owner could be expected to routinely maintain the system, much as home appliances are currently maintained. Tracking systems would be inappropriate for residential use. On the other hand, a central power station would have its own dedicated land, have its own technical, operating and maintenance staff, and would require special high voltage and switching equipment for connecting into the transmission network.

Both the intermediate-sized system and the central power station would be of sufficient size to warrant a minimum dedicated staff commitment (either operating, maintenance, or technical).

Solar cells made of several different materials are discussed in this section. Silicon cells, now generally available as single crystals, are the most common type of solar cell for photovoltaic systems at present. Gallium arsenide cells, which are more efficient and more expensive than those made of silicon, are considered for application with high powered concentrator systems. Cadmium sulfide cells are perhaps the most advanced for application as thin films, although research to produce thin films from other materials--including silicon--is actively being pursued. Section II of the second volume discusses the variety of types and applications of solar cells for use in photovoltaic systems.

Development Schedule

Photovoltaic solar energy converters for terrestrial use are currently commercially available. In 1976, over 350 kW-pk of silicon cells were sold and the projected 1977 sales will be over 750 kW-pk. Ten manufacturers currently produce silicon solar cells in the United States. Two pilot plants for the production of cadmium sulfide cells are being set up. The Motorola Corporation has invested over \$3 million in a silicon cell assembly line.

A recent study by the BDM Corporation for DoD indicates that photovoltaic devices are currently economically competitive for a large number of remote military uses. The market size was estimated to be at least 100 MW per year. The military and other governmental sectors are now experimenting with the use of photovoltaic solar energy converters for normal daily use.

A schedule for likely commercialization along with various development stages is presented in Figure 6. Concentrating systems will probably become commercial in the early 1980s but will be phased out in favor of either more advanced systems or cheaper silicon cells by the end of the 1990s.

Economics

A solar electric energy system using photovoltaics will consist of an array of solar cells, a support structure, perhaps an optical system to concentrate the sunlight, usually a storage system, and usually power conditioning to convert the dc from the cells to ac and to switch and interface with the system that uses the electricity. Table 9 shows the unit costs for these components.

Four rows of array costs in four time periods are presented; silicon (Si) and thin film cells are seen to be in the competitive range after 1985. Gallium arsenide (GaAs) cells are included because of their application to high concentration. Breakthrough arrays refer to the possible low costs attendant to significant technological advances. Different possibilities for breakthrough arrays are discussed in Volume II. The cost for silicon cells is based on our assessment that ERDA's goals (e.g., \$500 per kilowatt-pk in 1986) may be too optimistic unless a major commercialization thrust is made.

Several types of systems have been considered, ranging from simple tilted flat panel construction to tracking systems with optics that concentrate the sunlight by a factor of 1,000. The designs and therefore the costs of such systems are still being developed. The numbers presented in Table 9 are typical of those found in the recent OTA report on solar energy.

Analysis of the unit cost projections indicate that low concentration systems using inexpensive materials are more cost-effective than the high concentration systems with expensive, though efficient, cells.

Consider a concentrating solar array with a geometrical concentration factor, K , a cell efficiency, E , and a unit cost $CELL$ (\$/kW-pk) and the support structure and optical concentrating system cost $OPTIC$ (\$/m²). The optical efficiency of the concentrator system is taken to be 85 percent. Therefore, for peak solar radiation of intensity 1 kW/m², the required collector area is $(0.85E)^{-1}$ m² to produce 1 kW of output. The optics and support will cost $OPTIC/(0.85E)$ dollars per kilowatt of output. The cell

FIGURE 6. PHOTOVOLTAIC DEVELOPMENT SCHEDULE

Table 9

PROJECTED NOMINAL UNIT COSTS FOR PHOTOVOLTAIC SYSTEMS

	<u>1975</u>	<u>1985</u>	<u>2000</u>	<u>2020</u>
Cell array (\$/kW-pk)*				
Si (12%)	\$25,000	\$1,500	\$500	\$200
GaAs (20%)	200,000+	45,000	15,000	10,000
Thin films (7%)	---	1,500	500	200
Breakthrough (40%)	---	1,200	250	75
Support structure (\$/m ²)				
Nonconcentrating	\$15	\$15	\$15	\$15
5x concentrating nontracking	--	60	40	25
1,000x concentrating	150	120	100	80
Power conditioning (\$/kW)	\$200	\$150	\$ 70	\$50
Storage (\$/kWh)	80	55	30	30

* Cell conversion efficiencies are shown in parentheses.

cost will be reduced by the optical concentration factor $0.85 K$ (allowing for the inefficiency of the concentrator) and will cost $CELL/(0.85K)$ dollars per kilowatt of output. Allowing an installation labor cost of 10 percent of the structure cost, the formula for the array cost per peak dc output array (dollars per kilowatt) is:

$$\text{Array} = \frac{1.1 \text{ OPTIC}}{0.85 E} + \frac{\text{CELL}}{0.85 K}$$

The above equation and the range of unit costs presented in Table 9 are used to show array costs as a function of concentration in Figure 7. Low-cost cells (\$500 and \$1,500/kW-pk) are assumed to have efficiencies of 12 percent and high-cost cells (\$10,000 and \$45,000/kW-pk) are assumed to have efficiencies of 20 percent. The shaded areas of Figure 7 represent a range of structure and optics costs. For low concentration, the range of costs for the optical concentrating system is from \$30 to \$60/m², and for high concentration, from \$80 to \$150/m².

The information presented in Table 9 and Figure 7 suggests that by 2000, low-concentration systems using low-cost cells will have lower array costs (\$/kW-pk) than high-concentration systems. The installed costs in 1985 will be about the same for both systems. However, when increased operating and maintenance requirements of a high-concentration tracking system are considered, low-concentration systems with inexpensive cells and without tracking may be economically more attractive. This important result is the key to much of the following economic analysis.

Because tracking was shown to be uneconomical for intermediate-sized systems, the residential and intermediate-sized systems will have similar economics because of their common nontracking structures and operating and maintenance costs. These two systems are combined into one category called a distributed system. The central power station, which has the added expenses of land, special structures, and switching gear, is considered separately.

Table 10 shows total installed costs for the most cost-effective systems. Cell costs were obtained from Table 9. If the "breakthrough" costs presented in Table 9 were attained, the lower installed costs shown in Table 11 would result.

All these costs are for electrical energy delivered to the generator terminals. Transmission and distribution costs would be additive if required.

The amount of energy that is actually used from a particular photovoltaic system depends on the phasing between the solar insolation and the demand, with a lag factor supplied by storage. The photovoltaic displacement of electric utility energy will depend in a complicated way on geographical location, system design, and the individual load. The optimum design from the standpoint of economics must be found separately for each system.

FIGURE 7. PHOTOVOLTAIC ARRAY COST AS A FUNCTION OF CONCENTRATION, OPTICAL-STRUCTURE COSTS AND CELL COSTS

Table 10

ECONOMICS OF PHOTOVOLTAIC SYSTEMS FOR THE NOMINAL CASE

	Estimated Total Installed Costs			
	1975	1985	2000	2020
Distributed system, residential, or intermediate power system				
Without storage				
Dollars per annual kWh	\$ 21	\$ 0.85	\$ 0.46	\$ 0.25
Dollars per annual 10^6 Btu	6,100	250	140	74
O&M				
Mills per annual kWh	5.4	5.4	5.4	5.4
Dollars per annual 10^6 Btu	\$ 1.6	\$ 1.6	\$ 1.6	\$ 1.6
Central power station				
Dollars per annual kWh	21	0.91	0.52	0.31
Dollars per annual 10^6 Btu	6,100	270	150	91
O&M				
Mills per annual kWh	3	3	3	3
Dollars per annual 10^6 Btu	\$ 1	\$ 1	\$ 1	\$ 1

Insolation: Phoenix, Arizona

Lifetime: 20 years

Load factor: 0.21

Table 11

ECONOMICS OF PHOTOVOLTAIC SYSTEMS FOR THE BREAKTHROUGH CASE

	Estimated Total Installed Costs			
	1975	1985	2000	2000
Distributed system, residential, or intermediate power system				
Without storage				
Dollars per annual kWh		\$ 0.65	\$ 0.24	\$ 0.14
Dollars per annual 10^6 Btu		192	71	40
O&M				
Mills per annual kWh		5.4	5.4	5.4
Dollars per annual 10^6 Btu		\$ 1.6	\$ 1.6	\$ 1.6
Central power station				
Dollars per annual kWh		0.71	0.30	0.19
Dollars per 10^6 Btu		\$ 208	\$ 88	\$ 57
O&M				
Mills per annual kWh		3	3	3
Dollars per annual 10^6 Btu)		\$ 1	\$ 1	\$ 1

Insolation: Phoenix, Arizona

Lifetime: 20 years

Load factor: 0.21

For the distributed system, installed costs were presented for systems without storage. Five hours of storage are estimated to add about \$36 per annual million Btu output in 2000 and thereafter, under an assumption of significant progress in reducing costs of electricity storage. The degree and type of storage selected will depend on the profile of energy demand. The central power station has been considered as a peak daytime source only and does not use storage.

The numbers in Tables 10 and 11 assume an insolation appropriate for Phoenix, Arizona. The installed costs per unit of energy output will vary with location. For the nine SRI solar zones, the costs are higher by the following factors:

<u>Region</u>	<u>Factor</u>
New England	X 1.61
Middle Atlantic	1.61
South Atlantic	1.27
E. S. Central	1.37
E. N. Central	1.59
W. S. Central	1.20
W. N. Central	1.45
Pacific	1.37
Mountain	1.20

The economic analysis for photovoltaic systems was done on a conceptual basis, with little or no detailed design to support the results. Therefore, a number of additional factors, such as individual utility load characteristics, must be considered before a high degree of precision can be ascribed to the costs of photovoltaic systems as discussed here.

Potential Applications

As described, photovoltaic systems directly provide power during daylight hours. As a result, considering them to be peak, intermediate, base, or fuel saving units depends on the design details of the specific system.

Thus, both size of the photovoltaic array and the amount of storage will determine the percentage of total demand displaced by solar energy. This displacement will also depend on the insolation and demand curves. An example of a displacement calculation is that presented in an Aerospace Corporation report prepared for NSF. Using weather bureau records for the insolation of Phoenix and demand curves provided by the utility company, the displacement was calculated as a function of array and storage size. The results are shown in Figure 8. The residential demand in the Aerospace model was an average of 3.47 kilowatts with a peak demand of 8.19 kilowatts. Figure 8 shows that for a given array size a maximum storage size is associated with a given array area.

LOCATION: PHOENIX, ARIZONA
 DEMAND: ARIZONA RESIDENTIAL,
 3.5 kW_{AV}

COLLECTOR: FLAT PLATE, TILT
 ARRAY EFFICIENCY (20 C): 0.1125

⊙ = OPTIMUM POINT

LEGEND: THE INTERSECTION OF A LINE ON THE CHART INDICATING ARRAY SIZE WITH A LINE INDICATING STORAGE CAPACITY GIVES THE ENERGY DISPLACEMENT

FIGURE 8. ENERGY DISPLACEMENT AS A FUNCTION OF STORAGE CAPACITY AND ARRAY SIZE FOR A RESIDENTIAL SITE

In its report, Aerospace Corporation determined the most cost-effective system to be one with 8.1 hours (28.5 kWh) of storage with an array size of $32.6 \text{ m}^2/\text{kW}_{\text{av}}$. (114.1 m^2). (Denoted by a 0 in Figure 8.) This system resulted in a 60.7 percent solar displacement, requiring a utility backup capacity of 2.1 kilowatts.

The applications that can be expected from photovoltaic energy systems depend highly on the ability of technological advancements to reduce the production costs of photovoltaic devices. A major breakthrough allowing a large cost reduction would permit these systems not only to compete very well in distributed applications but also to capture a share of the electric power market as peak and intermediate load central station power systems. Less dramatic cost reductions could limit the installation of photovoltaic devices to distributed applications.

In comparison with the other electricity-providing solar technologies, photovoltaic systems are inherently well suited to distributed applications. This is due to the potential economic viability of these systems even in very small sizes and their very low maintenance requirements.

Photovoltaic systems have an advantage over several other solar energy technologies in that they are able to use indirect sunlight. Solar thermal power stations, on the other hand, require direct insolation for operation. This is an important consideration that may allow photovoltaic energy contributions in areas where other solar technologies cannot compete because of the problem of frequent cloud cover.

The amount of displacement will depend on the insolation profile. For a site such as Cleveland, it may be reduced to about half of the displacement in a site such as Phoenix.

Environmental Considerations

Since photovoltaic systems have no moving parts or products other than heat (which would normally be transferred to the earth), relatively few environmental problems are associated with this technology.

The main environmental questions are associated with the supply and toxicity of the materials that constitute the cells, such as arsenic and cadmium. Since there has been no widespread commercialization of photovoltaic devices, many of these factors can only be estimated.

Cadmium is a highly toxic poison believed to increase cancer risk, heart disease, and birth defects and to accelerate aging. Present controls on cadmium release may be inadequate. However, its use in solar arrays would not result in a large increase in the amount of cadmium entering the environment. Both gallium arsenide and arsenic are highly toxic and are recognized carcinogens. However, it has been estimated that the amounts of arsenic material used per square meter of 1,000 times concentrating array is 250 to 1,500 times smaller than the concentration

of As_2O_3 recommended for weed control by the USDA. These statements are made to describe the uncertainty of these problems and not to minimize their important nature.

ERDA has drawn up an environmental development plan. To be investigated are the effects of Cd, CdS, GaAs, and As release during production and into the environment in general, as well as effects caused by doping compounds such as phosphine gas and boron trichloride. Consumer and utility relationships as well as the regulation of solar industries and land use also are items to be investigated.

International Potential

There are communities in many parts of the world that are not reached by an electrical grid. This is particularly true of rural communities in developing countries. Currently, if electricity is needed for a school, health center, or tourist center in such a community, it is supplied by a gasoline generator or batteries. Photovoltaic electrical energy sources can make a significant impact on the electrical use in such areas.

For a remote location in a developing country, the cost of electricity from a gasoline generator varies from \$4 to \$8 per kWh, depending on the price of gasoline, and battery sources are two to three times more expensive. Photovoltaic sources currently appear to be economically favorable with costs near \$1 per kWh. The main reasons why they have not yet made an impact in these areas are the higher initial investment cost and the lack of engineering and marketing.

The international market is expected to be a driving force for commercial development of solar cells in the near future. For example, the need for remote photovoltaic sources to power educational TV sets in the Ivory Coast, Malaysia, and India, a rather modest demand, is estimated at 1/2 MW (peak), of the same magnitude as the 1977 world solar cell production of 3/4 MW (peak).

RD&D Programs

As much as 90 percent of the financial investment in terrestrial solar photovoltaic energy RD&D is that administered through ERDA's Division of Solar Energy (DSE), reorganized into the Conservation and Solar Applications Division of the Department of Energy. DOE's stated objectives are to demonstrate by the mid-1980s that solar electric energy can have a significant contribution to the projected national energy needs by the year 2000. Its strategy is to (1) stimulate industries' manufacturing function through selected development projects, (2) recommend and develop incentives to alleviate barriers in the marketplace, and (3) create aggressive RD&D activities. The photovoltaics program was allocated \$62 million in FY 1977 to carry out its part of this program. An outline of DOE's activities along with program funding levels is shown in Table 12.

Table 12

DOE'S PHOTOVOLTAICS PROGRAM, 1977

Silicon Technologies Branch (\$25 million)

Low-cost silicon materials
Processing (slicing, annealing)
Ribbons; sheets; films

Advanced Materials Branch (\$8 million)

CdS, GaAs, Amorphous Si, etc.

Outside Programs (\$13.3 million)

- A. Mission and systems analysis and engineering (\$4.1 million)
- B. Test and applications (\$6.7 million)
- C. Concentrators (\$2.5 million)

Silicon has been the basic constituent in solar cells for the past 20 years, and approximately 70 percent of the photovoltaics budget has been directed toward silicon-related projects. DOE seeks to reduce the cost of silicon cells in large scale manufacture to 50 cents per peak watt. The activities of the Silicon Technologies Branch along with at least half of the outside programs are designed to meet this goal.

The cost of silicon cells is presently much higher than this cost goal. The current cost for the starting single crystal material alone is nearly 2 dollars per peak watt. A major emphasis of the research and development effort on silicon cells is directed to improving manufacturing processes for the silicon cells.

Silicon will not necessarily remain the most cost-effective material for future cells. Another approach to reducing cell costs is to develop cells with materials that are either inherently more efficient energy converters or require less expensive, simpler processing methods. This work is being directed through the Advanced Materials Branch. Materials considered good candidates for junction cells are GaAs, InP, CdS, ZnS, CdSe, CdTe, Cu₂S, AlGaAs, AlCdS, and CuInSe₂. The number of possible junction types is limited only by imagination. To date, five types of junction solar cells have been made with efficiencies greater than 10 percent: Si, AlGaAs/GaAs, InP/CdS, CuInSe₂/CdS, and Cu₂S/CdZnS.

The great majority of silicon projects is being pursued by commercial companies. Most of the outside programs are being contracted through Sandia Laboratory. Also, NASA's Jet Propulsion Laboratory monitors a good share of the low-cost silicon projects. Research contracts on advanced materials have been awarded mainly to universities. In FY 1977, the University of Delaware received \$2 million, mainly for research on cadmium sulfide-related cells.

The ERDA photovoltaics program to date has been conservative, even though its management has constantly tried to be receptive and responsive to change and new ideas in technology. A major problem with the structure of DSE seems to be the inability to respond quickly to unsolicited, potentially innovative proposals. Perhaps the recently initiated "inventors program" will relieve this.

Solar Thermal Power Systems

Introduction

Solar thermal power systems use the energy from the sun by collecting the sun's rays, concentrating them, converting them to heat, and converting the heat to electricity. Many means of achieving each of these sequential steps are technically feasible, and their reduction to practice has already been demonstrated in various combinations. What remains is to develop and demonstrate systems that will be competitive with other electricity producing systems.

Recent developments initiated under the auspices of the NSF and further developed under ERDA have addressed many of the technical problems associated with the thermal conversion of solar energy to electricity. However, the economic problems have yet to be solved. As with many other forms of solar energy use, the energy source is not constant; consequently, the complex collection equipment and conversion systems must include storage equipment or be idle most of the time. The effort to compensate for this variability of the source has emphasized storing energy in the form of heat. One of the attractive features of thermal power systems is that, although such heat storage is currently expensive, it is much less costly than storage of electricity as is necessary, for example, with photovoltaic devices. In spite of the promise of practical heat storage systems, the current state of development is such that solar thermal power comes closest to being economically competitive when it is used as a conventional fuel saver only during the sunniest part of the day, i.e., to give the solar unit itself no capacity credit and to provide full backup capacity with conventional generating units.

Three categories of solar thermal power options are:

- Large centralized plants
- Small decentralized plants
- Individual homeowner plants.

The large centralized solar thermal power plants have received the greatest RD&D dollar priority and are the closest to being economic. The design considered most practical is one that provides intermediate load power during the day rather than base or peak load power. The smaller decentralized power plants have their greatest potential as total energy systems, providing both electrical power and heat that would otherwise be rejected to the environment. In addition, the siting flexibility inherent in the smaller plants could save transmission and distribution costs of electricity. The individual homeowner solar thermal power plants are currently the least economic, because these plants do not benefit from economies of size.

Technology Description

Three generic technologies have been chosen to represent the potential applications of solar thermal power: central receiver, total energy, and irrigation. The central receiver system used for comparison is the "power tower" concept. Although other central receiver concepts, both large and small, are currently under development that could potentially lower power costs, this concept was chosen because it has received the greatest funding and because detailed cost estimates are currently available. The total energy technology was selected because of its potential for lower costs. The irrigation technology was chosen as an example of a small sized solar thermal power application. This application has the greatest load factor penalty because it is used only during part of the year.

Development Schedule

An estimated development schedule for these technologies is shown in Table 13.

Table 13

DEVELOPMENT SCHEDULE FOR SOLAR THERMAL POWER SYSTEMS

<u>Generic Technology</u>	<u>Concept</u>	<u>Design</u>	<u>Pilot</u>	<u>Demonstra- tion</u>	<u>Commercial</u>
Central receiver	1964/Ind.	1974/Ind.	1985/1990	2000/2020	2020/Ind.
Total energy	1975/Ind.	1974/Ind.	1977/Ind.	1985/2000	2000/Ind.
Irrigation	1915/Ind.	1976/Ind.	1977/1980	1980/2000	2000/Ind.

Ind. = Indefinite

Schedule Start Date/Schedule End Date

These schedules depend on technical progress in several areas such as heat engines and storage devices. The central receiver and solar irrigation concepts are old, although meaningful U.S. effort in these technologies is rather recent. Design and pilot plant activities for all were initiated in the 1970s. Development of all the technologies should continue indefinitely; the initiation and completion dates are shown for concepts currently under development. For each technology, these schedules could be stretched out over time to permit further development--thus lower cost--of key components such as engines for higher cycle temperatures, improved and lower cost collection systems, and so

forth. This would avoid the disappointment from failing to meet Congress' and the people's high expectations for solar energy. Emphasis on research until the economics look favorable will probably result in earlier large scale commercialization.

Economics

The estimated costs for the generic systems as currently being developed are shown in Table 14. The 1985 estimates are based on published information, either DOE estimates or DOE contractor estimates. For the total energy system, a reduction in operating and maintenance costs is shown for various credit values of the by-product hot water. Finding a potential use for this water and matching its availability to insolation and power production can be difficult. The irrigation system cost is for mechanical power at the engine shaft. It has a reduced power capacity factor because of the seasonality of irrigation demand. The other system costs are for intermediate power at the bus bar.

The estimates for the cost of electricity are based on the system's use in the southwest United States. The capacity factor shown will normally decrease for other parts of the United States and the cost of electricity from the system will be higher.

The continued development of these technologies will necessarily require emphasis on the reduction of costs for the line-focus single-axis system and the improvement in the efficiencies of the energy collection and heat conversion to electricity for the point-focus two-axis systems. For thermal power to receive capacity credit, strong emphasis and funding will continue to be required to reduce the cost of storage. Higher temperature systems with improved conversion efficiency offer the greatest promise to reduce the cost of electricity. For total energy application, low cost and efficient roof-top collector systems should be emphasized to reduce the land cost component of these systems in populated areas.

Potential Applications

Thermal power is an attractive option because, if it could be demonstrated to be economically practical, it would find many applications. The emphasis on central station, utility-type systems recognizes the importance of focusing development on major markets in which a large "quad impact" could be made.

Total energy systems are attractive because they can permit more efficient use of the expensive collected solar energy. One of the drawbacks of total energy systems is that they require careful individual engineering design for each installation since almost each installation will be unique. Fossil fueled total energy systems have found few applications at least in part because of the difficulty of integrating two

Table 14

ECONOMICS FOR SOLAR THERMAL POWER SYSTEMS
(1975 Dollars)

Generic Technology	1985	2000	2020	Comments
Central receiver				
Capital cost (\$/kW)	--	\$ 2,900	\$ 2,100	Capacity factor = 0.5
O&M (mills/kWh)	--	3.3	2.4	
Total energy				Nominal size = 12 MWe
Capital cost (\$/kW)	\$ 6,800	\$ 6,000	\$ 5,500	Capacity factor = 0.55
O&M (mills/kWh)				By-product hot water
By product hot water				Rate = 340×10^9 Btu/Yr.
Credit at \$0/MM Btu	13.0	11.5	10.4	
Credit at \$0.50/MM Btu	10.1	8.6	7.5	
Credit at \$1.00/MM Btu	7.2	5.7	4.6	
Irrigation				
Capital cost, \$/kW	\$20,000	\$11,000	\$11,000	Capacity factor = 0.42
O&M (mills/kWh)	109	60	60	

independent energy demands for electricity and heat. The design of solar total energy systems will be even more complex because three independent energy flows (electricity and heat demands and insolation) must be coordinated.

The pumping of irrigation water could be an important application of thermal power systems, although not large from the viewpoint of total national energy use. Water pumping has several technical features which make it appealing. Unlike the production of utility electricity, water pumping does not require instantaneous availability on demand so that storage is not so critical. Furthermore, simple storage in ponds can be provided. Because many irrigation sites can be located far from an electrical or gas supply, the conventional energy source can be expensive to supply. Finally, land requiring irrigation is generally flat, open, and inexpensive, so siting the collector field should be no problem.

Environmental Considerations

The solar thermal energy systems all have the advantage of producing power without directly producing emissions. The collection system requires large areas without trees or shade creating structures. A potential safety problem is associated with the concentration of light, but this can be solved with appropriate procedures for operating personnel. Since the two-axis tracking systems usually have a stagnation temperature higher than the melting point of steel, there is a potential hazard of receiver boiler failure with the failure of control mechanisms. This would be avoided with the atmospheric-pressure hot gas receivers now under development. Microclimate impacts should not be important.

International Potential

The potential for export of solar thermal energy equipment and technology is uncertain. It depends in large measure on the eventual economic viability of solar thermal power systems. A large portion of the plant costs are for on-site construction and conventional equipment (pumps, piping, electrical generators, condensers, cooling towers, and so forth); the United States is not notably competitive in exporting these factors of production at the present time. Some potential does exist for licensing agreements and for U.S. firms having foreign subsidiaries.

R&D Programs

Increasing the R&D budget for solar thermal power systems would allow for the concurrent development of alternative concepts. The solar thermal energy program was initiated by taking advantage of conventional heat engine technology. Standard steam cycles and low-temperature organic working fluid Rankine cycle turbines are being used for demonstrations and pilot plants. For example, the central receiver pilot plant planned

for Barstow, California, uses conventional steam turbine technology. An alternative to increased funding for solar thermal power systems would be to use the available funds for new higher temperature and more efficient heat engine development (such as combined cycles) and lower cost storage development. The use of the available time "window" for the development of systems using more efficient engines and higher storage temperatures, higher temperature organic fluids, or chemical generation/storage equipment should not delay widespread commercialization, since this is not likely anyway until after the end of the century. Interim emphasis on the inherently lower cost single-axis systems could develop a technology base for rooftop total energy systems used as fuel savers and thereby bypass the use of expensive industrial land for collector fields.

The demonstration plant for Barstow represents a major commitment for this program (more than \$100 million). The principal benefit that will be gained from this demonstration is the experience of integrating and operating a large solar power plant with a utility grid. Commercial installations are not likely to result from this demonstration because of the high cost inherent in its design.

Wind Energy Systems

Introduction

For centuries wind machines, such as the slow speed Dutch windmills, have been converting indirect solar energy (in the form of wind) into useful work. Within the last 50 years, the development of electrical machinery has led toward generating electricity with high-speed wind turbines, commonly called wind turbine generators (WTG). When the WTG is used with storage or is tied into an electrical grid, it is called a Wind Energy Conversion System (WECS).

Three major candidates for the conversion of wind energy have evolved; (1) the horizontal axis, two- or three-bladed propeller, (2) the vertical axis Darrieus or "eggbeater" wind turbine, and (3) the vertical axis Savonius, or curved plate wind machine. Alternative wind machine designs using augmentation of the free air stream velocity or other blade shapes and arrangements are currently being evaluated or developed.

Horizontal axis turbines may well be economically practical today. Large-diameter WTGs located in areas of moderately high mean wind speed possibly may produce electricity at a cost competitive with electricity from fuel oil. With increasing oil costs, shorter payback periods may be possible and wind turbine applications in areas with lower wind velocities may become practical.

The Savonius turbines have power coefficients (ratio of power of absorption to power available) approximately one-half those of the horizontal axis systems. Without an ability to feather in high winds, the Savonius turbine's high profile requires a design of great strength. The rotor and tower weights required to withstand the high loads are comparatively high. For these reasons, the horizontal wind turbine appears to have greater potential.

The Darrieus rotor can have a power coefficient higher than the Savonius, but still not as high as a two-blade or three-blade horizontal axis rotor. Although it has the advantage of not requiring a wind direction tracking mechanism, the Darrieus rotor has two major problems. The first problem is that it is not self-starting. However, it may be possible to use the generator itself as a starter motor. The second problem, which is structural, is more serious. The structural problems of a Darrieus rotor result from the cyclic nature of the aerodynamic loads placed on the blades and the required flexibility of the long curved blades. Research is continuing on this type of rotor, and it may yet develop into a practical wind turbine.

Technology Description

The three WTG generic technologies selected for evaluation as the most likely candidates for economic generation of electricity are:

- A 1.5-MW two-bladed horizontal axis WTG (similar to the Model II design of DOE)
- A 200-kW Darrieus vertical axis WTG
- A 15-kW three-bladed horizontal axis WTG.

Horizontal machines represent a proven technology and can be constructed to take advantage of economies of scale. (The power available varies as the diameter squared.) The large machines do have an upper economic size limit, but according to current estimates this limit may even be somewhat greater than the 1.5-MW Mod II size now under development. The economics of wind machines depends heavily on mean wind velocities, since the power available varies as the wind velocity cubed. For example, a very large 1.5-MW WTG may be economic at a mean wind speed of 15 miles per hour (at about 200 feet above the ground, the approximate height of the wind system axis). In locations with higher mean wind speeds, WTGs of a smaller physical size can be deployed that achieve similar economies.

The vertical axis 200-kW Darrieus WTG was chosen for comparison because it is the most likely economic competitor with horizontal WTGs. The Canadian government is currently constructing a 200-kW Darrieus turbine on the Magdalen Islands in the Province of Quebec. Since the average annual wind speed at this site is 8.5 meters per second (19 mph), this isolated location appears favorable for the use of a WTG.

The third WTG system considered produces about 15 kW. This represents the size of a unit that is now commercially available as well as the size an individual farmer or homeowner might purchase. It is rated at 15 kW at 11.8 meters per second (26 mph) and 3.5 kW at 6.8 meters per second (15 mph). The current economic viability of these small units has yet to be firmly established, but the opportunities for a significant reduction in price may be high because of the large potential market.

Development Schedule

The estimated development schedule for these three generic technologies is shown in Table 15.

Numerous recent studies have suggested that megawatt-scale WTG units could be economically attractive today if utilities had sufficient experience with wind to understand system integration issues and if at the same time, capable supply channels were developed. The schedule for the Darrieus WTG is based on the present rate of funding and the expectation that these funding levels are sufficient to overcome technical problems. The development schedule for the 15-kW WTG is based on the history of WTGs in Denmark and the western United States where electricity from steam-electric plants and rural electrification subsequently made WTGs uneconomic. Sales of 3-kW WTGs in the United States during the early

Table 15

DEVELOPMENT SCHEDULE FOR WIND ENERGY SYSTEMS

<u>Generic Technology</u>	<u>Concept</u>	<u>Design</u>	<u>Pilot</u>	<u>Demonstration</u>	<u>Commercial</u>
1.5-MW horizontal axis WTG	1940/1980	1976/1980	1977/1980	1980/1985	1985/Ind.
500-kW Darrieus vertical axis WTG	1920/Ind.	1970/1985	1980/1985	1985/1990	1990/Ind.
15-kW 3-blade horizontal axis WTG	1890/Ind.	1910/1980	1910/1980	1910/1980	1914/Ind.

Notes: Ind. = Indefinite

Schedule Start Date/Schedule End Date

1930s until the mid-1950s approached \$50 million. At least ten different design 15-kW WTGs are commercially available today. Significant market penetration of these machines will be a function of future alternative fuel costs for electric power generation as well as the public sector incentive mechanisms that may be applied. The technical barriers to the implementation of the schedule are minor in the case of the 1.5-MW horizontal axis WTG. Some difficulty has been experienced with the location of the turbine blades downwind from the structural steel supporting tower. Refined tower design or the location of the blades upwind could alleviate this problem. Wind shear (the difference in wind velocity between the top and bottom of the rotor) in the large-diameter turbines is a problem, but it does not appear to be insurmountable even in the case of two-bladed turbines. The use of three blades could help alleviate the wind shear problem with some increase in cost.

The structural problems associated with the Darrieus rotor also do not appear to be insurmountable, although the solution may increase costs, either through a reduction in performance that may be required to ensure reasonable equipment lives or by the increased cost of a satisfactorily high performance turbine structure.

Economics

The estimated costs for the generic wind systems are shown in Table 16. The system costs in this table are based on a location with a 6.8 meter-per-second (15 mph) average wind velocity. At such a site, a capacity factor of 0.5 could be expected. The costs for the 1.5-MW horizontal WTG are based on average costs of production runs of 2,500 units. Excluding costs for blades and hubs, these average production unit costs represent 89 percent of the first production prototype unit cost for the 1.5-MW units. The capital cost of the same systems in locations having a higher mean wind velocity will be less than shown.

The cost of the 500-kW Darrieus WTG has been estimated at 20 to 25 percent less than an equivalent power horizontal axis WTG, assuming the technological problems can be solved at reasonable blade cost. Costs for the 25-kW unit are based on information received from industry. All costs include any power conditioning necessary to produce utility quality power.

Although the cost of WTGs will be reduced because of the learning curve, the best available sites will be used first, so that as the number of installations increases, the associated lower wind velocities will require larger machines for the same power. This could tend to keep the cost of electricity constant. The Darrieus WTG may have a later market penetration and could have a cost reduction because of a greater number of smaller units being manufactured.

Table 16

ECONOMICS FOR WIND ENERGY SYSTEMS
(1975 Dollars)

<u>Generic Technology</u>	<u>1985</u>	<u>2000</u>	<u>2020</u>
1.5-MW horizontal axis WTG			
Capital cost, \$/kW	\$ 870	\$ 830	\$ 820
O&M, mills/kWh	6.0	5.7	5.6
500-kW Darrieus vertical axis WTG			
Capital cost, \$/kW	\$ 1200	\$ 1100	\$ 1050
O&M, mills/kWh	8.2	7.5	7.2
15-kW 3-blade horizontal axis WTG			
Capital cost, \$/kW	\$ 1200	\$ 1200	\$ 1200
O&M, mills/kWh	8.2	8.2	8.2
1.5-MW horizontal axis WTG			
Specific capital cost \$/annual MM Btu	\$ 58	\$ 56	\$ 55
O&M, cents/MM Btu	176¢	167¢	164¢
500-kW Darrieus vertical axis WTG			
Specific capital cost \$/annual MM Btu	\$ 80	\$ 74	\$ 70
O&M, cents/MM Btu	240¢	220¢	210¢
15-kW 3-blade horizontal axis WTG			
Specific capital cost \$/annual MM Btu	\$ 80	\$ 80	\$ 80
O&M, cents/MM Btu	240¢	240¢	240¢

MM Btu = Million Btu

O&M = Operating and maintenance cost

*All systems are based on a mean wind velocity of
7 meters per second and a capacity factor of 0.5.

Potential Applications

The mechanical power which WTGs produce can be used directly for mechanical tasks (e.g., to pump water) or can be simply and efficiently converted into electricity or heat. Two of the most attractive applications appear to be utility electricity and agricultural water pumping.

The introduction of wind generated electricity onto an electrical grid can give rise to several concerns. Because it is not possible to accurately predict when wind energy will be available, it is usually not practical to assign capacity credit to wind units. An exception to this situation could occur on a utility system in which abundant storage was available. Because of the high current cost of storage devices, this situation is likely to exist only at those few utilities with significant pumped storage and/or hydroelectric facilities. For the majority of utilities, it will be necessary to provide conventional generating facilities as back-up so that the economic value of the WTG becomes simply the savings of fuel, operating, and maintenance expenses due to the reduction in operation of the conventional units. This is commonly referred to as a "fuel saver mode" of operation.

Some studies have indicated that, in spite of the unpredictable nature of wind, WTGs might merit some capacity credit (e.g., 10 percent) depending upon the region. For this analysis, the conservative approach has been taken and so zero capacity credit is allowed. Thus, the cost of electricity from wind units is compared only to the fuel cost of conventional units to assess market potential. This cost of conventional fuel is a composite value approximating the fuel mix between peak, intermediate, and base electricity in the United States.

An additional concern with utility integrated WTGs is the instabilities that could be introduced into the system by the continuously varying output of numerous WTGs. The importance of this factor will vary with each utility depending upon the characteristics of its generating mix. Although, typically, this should not be a problem unless WTG installations exceed 15 percent of installed capacity. (The market penetrations subsequently discussed are well below this on a national average.)

There is wide experience in the use of small wind units for off-grid applications, such as water pumping. These units were in common use in the U.S. several decades ago but fell out of favor largely due to the availability of federally supported, low cost electricity. Many of these units are now being refurbished due to increasing costs of electric power. These water pumping applications can be attractive for many reasons. Storage of pumped water in ponds or tanks is simple so that wind fluctuations can be accommodated. Providing either electrical power or combustible fuel to a remote well can be very expensive so that the economics can be favorable.

Off grid electrical applications of small WTGs can also be attractive where wind speeds are high and transmission distances are great. However,

the cost of this power will be considerably greater than grid-supplied power because of the high cost of electrical storage and because of the higher cost (per unit of capacity) of smaller WTGs.

Environmental Considerations

The wind energy systems produce electrical power without the production of atmospheric emissions. WECS will be located in windy areas, which can coincide with scenic hills and mountains. For this reason, the aesthetic impacts of large wind energy systems may cause difficulty in site selection for WECS. The disruption of TV reception in the proximity of a WTG is a problem that can be alleviated through the use of cable TV in populated areas or nonmetallic WTG blades. The TV problem could cause special difficulties in the siting of small, 5 to 50 kW, WTGs which are likely to be sited near populated areas.

International Potential

There is a potential for the export of WECS. However, the technology is such that many countries have the required technical and industrial resources and are now building WECS. For example, small WTGs are already being imported into the United States. The import/export ratio will be strongly shaped by the development of internal markets that can support an export effort. The international aircraft industry is an example of how the megawatt WECS international market industry might develop. The international automotive industry is an example of how the 5 to 50 kW WTG industry international market could develop. The United States could capture the major portion of both markets, since government funding could provide a head start. A liberal foreign patent policy could also encourage United States industry to initiate the foreign sales and service program investment necessary for the development of an export market.

R&D Program

The R&D program for the megawatt WECS could be accelerated by multiple awards to various segments of the aircraft industry. This need not be a duplication in the program, since many variations are possible within each of the three major generic technologies. For instance, the 1.5-MW Mod I is a downwind machine, whereas the tower shadow is reduced with an upwind machine. The 1.5-MW Mod I has a two-bladed rotor, whereas a somewhat more expensive system with a three-bladed rotor tends to mitigate the vibration from wind shear and off-axis wind direction. The implementation of a more dispersed and larger research program can benefit from the increase in opportunity for innovation as well as the acceleration of the commercialization of cost-effective WECS.

Solar Heating and Cooling

Introduction

General Description

Solar heating and cooling refers to the process of using the sun's radiant energy to provide space heating, space cooling, and hot water heating for application to a complete range of building types. Other purposes are swimming pool and greenhouse heating. In the present context, it does not include provision of energy for process heat in industrial or agricultural applications, which is treated separately in this report, although the processes and equipment will generally be similar.

A fundamental characteristic of solar heating and cooling processes is the relatively low temperatures required compared with other uses such as electric power generation. Applications include space heating, space cooling, hot water heating, or various combinations, and thus replace or supplement conventional heating, cooling, and hot water heating systems. Although solar energy is free, the equipment necessary to convert it to useful heat is considerably more expensive than that required for conventional heat. Thus, the total annual cost of delivering solar energy includes a rather large equipment amortization component compared with conventional systems.

Another limiting factor applying to solar heating and cooling systems arises from the mismatch of radiant energy availability and space conditioning energy requirements and the random nature of climatological phenomena. These problems generally limit the economical sizing of solar energy equipment to somewhat less than what would fulfill the total energy demand of the application. Therefore, conventional systems are required to back up or supplement the solar system. The economical degree of solar energy supplied, or solar dependency, is a complex function of climate, energy demand, cost of solar equipment, equipment durability, cost of capital, and present and future costs of supplemental or alternative energy. Optimum solar dependencies are generally found in the range of 30 to 80 percent.

A solar heating or cooling system generally consists of a radiant energy collection subsystem, an energy storage subsystem, an energy application subsystem, and one or more energy transfer and exchange subsystems. In the case of cooling, an energy conditioning or conversion subsystem is also included.

Solar heating and cooling systems may be categorized as active, passive, or hybrid. The primary feature of an active system is the use of a moving energy transfer medium (a liquid or air) between the point of collection and the point of application. A passive system is generally characterized by the combination of the collection and storage subsystems into one body and nondependency on mechanical systems to transfer energy

to the point of use or for other purposes. A hybrid system combines elements of solar and nonsolar systems, such as the use of a heat pump to extract heat from a solar generated heat store and move it to the point of application. Other hybrid systems would include water- or air-cooled photovoltaic electrical systems in which the heat produced in the cooling fluid is used for space heating or absorption cooling. These categories are not precise. For example, small fans may be used in a passive system to transfer heat by forced convection from a storage body to the point of use. Additionally, mechanically operated shades or insulation panels are applied in passive systems to regulate the collection and/or rejection of solar energy by the collector/storage body.

History

The theory of application of radiant energy for heating and cooling purposes has long been well known, and sporadic applications appeared in the latter portion of the 19th century and the early portion of this century. The earliest substantial applications were for heating of hot water in areas where alternative energy supplies were not available or were expensive. In this country, such applications were made as early as World War I with hot water heating for army training camps in California. Later, residential-type solar hot water heaters were used in substantial quantities in Florida and southern California. These applications were largely eliminated by the introduction of low-cost electricity and natural gas distribution systems. Hot water heating by solar energy has also enjoyed substantial application in other countries where cheap alternative energy sources are not available. These include Israel, Australia, and Japan where substantial applications have taken place and remain. The present state of technology of solar hot water heating in this country, in fact, can be related directly to developments in Israel and Australia.

Although earlier research and development took place, the current state of technology in solar space heating is based on fundamental analytical and developmental work performed at MIT from 1939 to 1959. This work established the fundamental principles and techniques for collection and application of solar energy for space heating, which have not been greatly advanced up to the present time. In the interim, the technology was kept alive and further developed by a small but persistent body of pioneer researchers, engineers, and amateur solar enthusiasts. These include Telkes, Bliss, Bridgers, Löf, Whillier, Tabor, Yellott, Hay, Trombe, Thomason, Jordan, Farber, Morse, Böer, and Daniels.

In the area of space cooling, early development work with solar driven absorption refrigeration equipment at the University of Florida by Farber established a base for further development.

Passive heating and cooling systems have also received attention in the past by Trombe (Trombe Wall) in France, and by Hay and Yellott (Skytherm System), and Baer (Drumwall-Beadwall system) in the United States.

Current Status

The technological base for space and hot water heating may be classed as well advanced, with further evolutionary advances coming about through further research and development, and more particularly, through manufacturing and process developments. Such systems are in an early stage of commercialization with some 500 enterprises involved in system and component manufacture in some degree. Design, distribution, and installation enterprises are also being established at a rapid rate.

The present state of commercialization has been accelerated by federal demonstration programs for residential and commercial systems. Also, large numbers of individual owners are installing heating and hot water systems at their own expense. The systems installed and being installed, however, are not necessarily economically viable compared with alternate means--in fact, most are not.

Problems remaining that affect commercialization are high capital costs, the lack of standards, low reliability and durability of equipment, and the lack of technological dissemination throughout the heating and cooling industry, particularly at the contractor level. These problems will be reduced with time and as the industry gains maturity.

Although a substantial number of solar cooling installations have been made, commercialization cannot be said to match that of space and hot water heating. The existing cooling systems use rather high cost absorption-type refrigeration machinery, which is not economically viable compared with alternative conventional cooling systems.

Passive systems have received increased attention recently because of their substantial economic potential. However, they are hindered by architectural and aesthetic considerations, as well as by a general lack of understanding of their principles and applications. Massive application of passive systems will require a reeducation of the architectural and building professions and some change in living habits of building occupants. Government demonstration programs can hasten the acceptance of these systems.

Technological Description

The technology of solar heating and cooling may also be considered on a generic basis as to end use or application. The generic technologies considered include solar space heating, solar service water heating, solar space cooling, and combined applications. These may be further subdivided by type of process and equipment used. The basic processes are collection or rejection, storage, transfer/conditioning, and application. A variety of equipment types is available for each process, thus providing alternative system approaches or "paths" to each generic technology. The available approaches are illustrated in Figure 9, with

TYPICAL GENERIC TECHNOLOGY PROCESSES

- FOR SPACE COOLING SYSTEMS A COOL STORE MAY ALSO BE INCLUDED OR SUBSTITUTED. IN THIS CASE, THE PATH IS FROM HEAT STORE TO CONDITIONING, TO COOL STORAGE TO APPLICATION
1. FLAT PLATE LIQUID COLLECTOR SERVICE HOT WATER; WATER STORAGE
 2. FLAT PLATE LIQUID COLLECTOR SPACE HEATING AND SERVICE HOT WATER, WATER STORAGE
 3. FLAT PLATE AIR COLLECTOR SPACE HEATING AND SERVICE HOT WATER, ROCK STORAGE
 4. EVACUATED TUBE COLLECTOR, ABSORPTION SPACE COOLING, WATER STORAGE
 5. SINGLE AXIS TRACKING, CONCENTRATING COLLECTOR VAPOR COMPRESSION COOLING, WATER STORAGE
 6. FLAT PLATE LIQUID COLLECTOR, SOLAR ASSISTED HEAT PUMP SPACE HEATING/COOLING, GROUNDWATER STORAGE
 7. FLAT PLATE AIR COLLECTOR, DESSICANT/EVAPORATIVE SPACE COOLING, PHASE CHANGE STORAGE
 8. PASSIVE HEATING AND COOLING USING BUILDING MASS AS COLLECTOR/STORAGE, NIGHT RADIATION COOLING

FIGURE 9. PROCESS AND EQUIPMENT TECHNOLOGIES: SOLAR HEATING AND COOLING

several typical paths identified. Although several alternative approaches to each generic technology are technically possible, they are limited by practical and economic considerations. For this report and the time range under consideration, generic technologies and their primary features to be considered hereafter are limited to:

Active Systems

Hot Water Heating--Flat plate liquid collectors with direct flow or heat exchanger application for service hot water or swimming pool heating.

Space and Hot Water Heating--Flat plate liquid, flat plate air, evacuated tube and concentrating nontracking collectors with water, rock or phase-change material storage and direct-flow or heat exchanger applications. Service hot water heating will be considered as included.

Space Cooling--(1) Flat plate liquid, evacuated tube and concentrating nontracking collectors with water storage and absorption type chillers; (2) concentrating nontracking and single-axis tracking concentrating collectors with water storage and steam or organic fluid Rankine vapor compression-type chillers; and (3) these systems in combination with hot water and space heating where climate is appropriate.

Passive Systems

Space Heating and Cooling--Trombe, Hay, Böer, or similar systems.

Hybrid Systems

Space Heating and Cooling--Solar assisted heat pump systems with hot water heating included.

Limitation of the generic technologies to these few types will not have a substantial effect on the overall outcome of this study, i.e., on the comparative economics or ranking of the various technologies.

Development Schedule

The equipment and processes in Figure 9 are in various stages of development, ranging from the rather well developed flat plate collectors used for space and hot water heating to Rankine cycle space cooling chillers which may be classed as being in the laboratory research stage. In all cases, the theory or concept is well established. Major breakthroughs are not expected because of the nature of the processes involved and the relatively long past period of research and development. Gains are expected to come about, however, through advancements in collection and application efficiencies and cost reductions.

The estimated development schedule for the several generic technologies is shown in Table 17. The indicated dates are by no means precise events, and considerable overlap among development stages is to be expected. For example, solar hot water heaters are already being sold in significant quantities; however, development work continues toward cheaper, more efficient and more durable collector systems.

There are no significant technical barriers in the way of development of the listed systems. The primary measure of development at any stage is the economic viability of the system compared with both other solar and conventional alternates. However, there is uncertainty in the eventual economic viability of the various systems within a generic technology, and for this reason various alternative paths are included. In summary, full development does not necessarily mean commercialization and free market sales.

Economics

The economics of solar heating and cooling systems are complex functions of load, climate, system capital costs, efficiencies, and durabilities; the cost of capital, taxes, and other financial considerations; and the price of alternative energy sources and escalation rates. As previously noted, because solar heating and cooling systems do not provide 100 percent of requirements on a practical basis, the price of auxiliary energy becomes an important factor in economic analyses.

The approach to economic analyses requires the establishment of an optimum system size and solar dependency as affected by the many variables listed above and the calculation of the unit cost of energy produced on an annual basis, including the cost of auxiliary energy. This unit cost is compared with that accruing to alternative conventional systems to determine the economic viability of the solar system.

Estimates of the costs of various solar heating and cooling generic technologies are listed in Table 18 for present and future periods. These estimates are based on national averages and midrange interest rates and equipment durabilities.

The cost estimates are also based on rather low building heat loss rates because reduction of such rates through added insulation and other factors will often be more economical than solar energy system applications.

The costs are affected quite strongly by regional and site-specific factors. For example, the cost of installation varies quite widely between systems installed with new building construction and systems installed in existing buildings (retrofit). Although not taken into direct consideration here, the solar costs are also affected by the availability of alternate/auxiliary energy sources in the various regions.

Table 17

DEVELOPMENT SCHEDULE FOR SOLAR HEATING AND COOLING

<u>Generic Technology</u>	<u>Stage of Development</u>					<u>Commercial Application</u>
	<u>Theory or Design Concept</u>	<u>Laboratory Scale R&D</u>	<u>Subsystem Development</u>	<u>Pilot Plant Testing</u>	<u>Demonstration and Testing</u>	
Hot water heating	Currently established	Substantial work completed in the past; however, work is continuing.			1976-1980	1975-1980
Space heating	Currently established	Substantial work completed in the past; however, work is continuing.			1976-1980	1975-1980
Space cooling	Currently established	Absorption process; substantial work completed, development continuing.			1976-1980	1980-1985
<u>Rankine and Other Processes</u>						
Passive heating and cooling	Currently established	N.A.	1976-1980	1976-1980	1976-1980	1980-1985
Solar assisted heat pump heating and cooling	Currently established	N.A.	1975-1980	1976-1980	1976-1980	1980-1985

Table 18

PROJECTED SOLAR HEATING AND COOLING UNIT COSTS
(National Averages)

Generic Technology	Capital Costs (dollars per annual million Btu)									
	1975		1980		1985		2000		2020	
Hot water heating	New	Retro	New	Retro	New	Retro	New	Retro	New	Retro
Nominal	128	167	98	137	83	122	69	108	69	108
Low forecast	---	---	78	110	67	98	62	97	62	97
O&M costs	2.50		1.95		1.68		1.36		1.36	
System life (years)	10		12		15		20		20	
Space and water heating	New	Retro	New	Retro	New	Retro	New	Retro	New	Retro
Nominal	162	238	121	178	81	119	61	89	61	89
Low forecast	---	---	97	143	68	95	55	80	55	80
O&M costs	3.28		2.46		1.64		1.23		1.23	
System life (years)	10		12		15		20		20	
Space cooling	Alone	W/Heat	Alone	W/Heat	Alone	W/Heat	Alone	W/Heat	Alone	W/Heat
Nominal	609	305	457	254	367	203	229	127	229	127
Low forecast	---	---	366	203	312	173	206	114	206	114
O&M costs	5.78	2.91	4.34	2.43	3.54	1.94	2.17	1.21	2.17	1.21
System life (years)	10		12		15		20		20	
Passive heating	New		New		New		New		New	
Nominal	86		86		86		86		86	
Low forecast	---		65		65		65		65	
O&M costs	0.86		0.86		0.86		0.86		0.86	
System life (years)	25		25		25		25		25	
Solar assisted heat pump*	New	Retro	New	Retro	New	Retro	New	Retro	New	Retro
Nominal	218	273	189	236	160	200	146	183	146	183
Low forecast	---	---	151	189	136	170	131	165	131	165
O&M costs	3.70		3.31		2.60		2.32		2.32	
System life (years)	5		10		15		15		15	

* Heating and cooling.

The reduction in cost over time is a result of developments in efficiency and manufacturing costs as well as improvements in durability.

Differences between these results and those published elsewhere are primarily due to equipment lifetime (durability) assumptions. Most previous economic analyses have assumed equipment lifetimes at least equal to 20 years. SRI does not believe this assumption is realistic, particularly in the light of the equipment warranties available today and from comparisons with similar equipment. Durabilities and associated warranties will improve with time through development and increasing industry maturity. The sensitivity of solar unit costs to both lifetime assumptions and interest rates is shown in Figure 10.

The estimated costs are not expected to improve appreciably as a result of complementary research in such areas as storage, application equipment, or basic research.

Potential Applications

The basic market potential for solar heating and cooling equipment is associated with the residential building sector and low-rise commercial and institutional buildings that have the space necessary for deployment of the rather large collector arrays required. For solar service hot water equipment, an additional potential market is present in medium- and high-rise multifamily residential and commercial buildings where the relatively smaller collector area requirements can be accommodated.

Actual market penetration, however, will be a function of the economic viability of solar systems compared with conventional alternative systems. While it is true that some portion of the population will procure and install solar equipment having a negative economic viability (as witnessed from the present market activity), massive applications will depend on a favorable viability resulting from substantial cost reductions in equipment, rapid rates of escalation in the price of alternate energy supplies, or most likely, both. Government subsidies in the form of tax credits and the like have the effect of reducing equipment capital costs and therefore favoring market increases.

The most important market potential for solar heating and cooling technologies is associated with the single-family housing segment of the building sector. Some 60 million single family houses exist in the United States, with only about 1 million being constructed each year. The existing stock represents a substantial potential; however, installation costs will be higher and efficiencies lower as a result of poor orientation, lack of available space, and other factors. New construction can be designed for solar, thus decreasing installation costs and improving efficiencies compared with existing buildings.

The market potential is affected by several regional considerations. The most important of these relates to the availability and cost of alternative energy. For example, where only high-cost electric energy

FIGURE 10. SENSITIVITY OF SOLAR HEATING UNIT COSTS TO EQUIPMENT LIFE AND INTEREST RATES SPACE HEAT PLUS HOT WATER

is available for space and hot water heating, solar systems are already economically viable, or soon will be with modest equipment cost reduction and increased lifetimes. On the other hand, areas where cheap electrical energy is available (such as in the Northwest) solar prospects are poor.

Other regional factors affecting economic viability, marketability and potential energy contribution include solar energy availability (insolation) versus heat or cooling demand (in terms of degree days heating or cooling). These factors have been taken into consideration in the estimates in Table 18.

Although the maximum potential energy contribution in terms of existing and new building volume is rather large, several practical factors tend to provide a substantial reduction. These include siting, orientation, and space limitations for existing buildings as previously described. Economical factors, including capital availability, also could tend to retard the overall potential. Thus, there will be both technical and economic limits to the use of solar heating systems in buildings.

Environmental Problems

The substitution of renewable solar energy for fossil fuels has a substantially positive benefit to the environment through a net reduction in air and water pollution. Offsets in this regard are primarily related to aesthetic considerations, although the energy requirements for equipment production are also a factor.

International Potential

The potential for exporting the technology and products in the solar heating and cooling area is considered to be limited. The area is one of rather low technology, and shipping cost will offset the advantages of mass production, at least in part. This is particularly true for the industrialized countries, including Europe and Japan; however, potential markets may exist in Asia, Africa, Mexico, Central and South America, and the Middle East. Competition in these areas by the industrialized countries is expected to be severe. Export markets for the basic materials (glass, plastics, copper aluminum, steel) and appurtenances (pumps, valves, controls) may exist, particularly for basic materials in semifinished form.

RD&D Programs

Past and present RD&D programs sponsored by the federal government (and some state governments) have improved the technology and application potential. At least as important is the dissemination of the technology over a wide spectrum of the academic, professional, research, and industrial and trade communities. The present RD&D program policy

(as contained in the National Program Plan for Research and Development in Solar Heating and Cooling) is comprehensive and adequate. The plan was developed in coordination with a cross-section of knowledgeable academic, professional, research, and industrial contributors.

The primary objective of the plan is to stimulate the development of industrial, commercial, and professional capability for producing and distributing solar energy systems. Major problem areas identified are (1) improvement of cost-effectiveness, (2) the relatively lower state of technology for solar cooling, (3) complexity of application analysis resulting from climatic zone differences and other factors, and (4) the requirement for development of cost-effective retrofit systems. Another major problem area is related to the requirement for development and demonstration of passive systems, although it is noted that passive system research is included in the details of the R&D plan.

Demonstration programs are perhaps more important in reaching cost-effectiveness goals, considering the existing state of technology. Such programs provide standardization, industry development, quantity cost reduction, and other benefits even though individual installations are not economically viable. The demonstration program is still in progress and is expected to be amplified. It appears increased emphasis on the retrofit and passive areas in future projects may be desirable.

At least as important, if not more so, are R&D activities conducted at their own expense by manufacturing companies. In this regard, it is encouraging to note the entry of large companies having not only cost reducing mass production capabilities but also the distribution, marketing, and service capabilities required for eventual national mass application.

No direct association may be drawn between RD&D funds expended and benefits in terms of market volume and overall energy contribution. Certainly, expending RD&D program funds may produce benefits, but a quantitative assessment is not possible. In the case of solar heating, the primary agent is economics, particularly with respect to alternative energy costs and availability. For solar cooling, improvements in technology and economics are required.

Agricultural and Industrial Process Heat

Introduction

Industry accounts for about 40 percent of the energy consumed in the nation. If nonsubstitutable electricity use and feedstocks are subtracted, the fraction is about 30 percent. Agriculture (defined basically as on-farm activities) consumes about 2 percent of the national energy. Although differing greatly in size, these demands are both attractive targets for solar energy use: industrial applications because of their large size and agricultural applications because of their frequently modest temperature requirements.

The use of solar energy in these sectors is not a new concept. Solar distillation processes have been used in the United States and abroad for many years to concentrate minerals and to purify water. High concentration solar collectors have been used for high-temperature materials research. These uses have been small from the standpoint of the national energy budget.

In the agricultural sector, solar uses were much more pervasive in the past. For example, leaving grain in the field to field dry is a use of solar energy that fossil fuel heated dryers have replaced. Leaving animals in unheated buildings caused them to rely on feed for warmth. The trend toward heated buildings has essentially replaced feed (solar produced biomass) with fossil fuel.

In the agricultural sector, the most promising uses of solar heat are for grain drying and building heating. These uses consume only about 10 percent of the energy used on farms, the remainder being used primarily for irrigation pumping and motor fuel. Although this represents a modest market, it is attractive from a technical and economic viewpoint. (The use of solar energy for irrigation pumping is described in the thermal power section.)

The most attractive uses for solar heat in industrial processes are those that require hot water and low-temperature ($\leq 350^{\circ}\text{F}$) steam. These uses represent about one-third of the energy required by industry.

The use of solar energy to provide industrial and agricultural process heat is in the demonstration stage. The hardware necessary for these solar uses is available, and the remaining constraint to its widespread use is economical because of the high cost of the solar collectors. The federal program recognizes this and has focused its efforts accordingly.

In the industrial sector, most current demonstrations focus on providing hot water, for example, in a textile mill and in a commercial laundry. The hardware for these uses is essentially the same flat plate collectors as are used for building space heating and domestic water heating. The production of industrial steam is less advanced because the

required collectors are somewhat less developed. For these higher temperatures, either evacuated tube or concentrating collectors are required. The designs are generally adaptations of ones originally posed for either building heating or steam turbine powering.

In the agricultural sector, demonstrations have been focusing on grain drying and building (including greenhouse) heating. In these applications, low-cost collectors and clever system designs (e.g., passive heating) have been demonstrated. However, here the barrier to widespread use continues to be economic.

In addition to these demonstrations, the federal program has made assessments to develop better data on the agricultural and industrial markets. This effort has resulted in unique information on energy requirements, by quantity and temperature, of a wide spectrum of U.S. industrial practices.

Technology Description

Three generic systems were selected to represent the wide variety of possible uses of solar heat in the agricultural and industrial sectors: industrial hot water, industrial low-temperature steam, and low-temperature agricultural drying. While spanning the spectrum of desirable solar end uses, these systems are also typical of the range of solar hardware that will be used.

Industrial hot water is of interest because it can be supplied by state-of-the-art flat plate collectors. Hot water demand is largest in the textile and food processing industries. (These two industries require about 0.035 quads out of a total demand of 0.07 quads for industrial hot water.)

To produce low-temperature steam (less than 350°F) higher performance collectors, such as concentrating or evacuated tube, are required. Although the collectors are more complicated, the market is more attractive because of its much larger size (about 1.2 quad). This demand is spread throughout many industries, including chemicals, paper, petroleum refining, and textiles.

The selection of these generic technologies excludes a large fraction of the industrial market. Over 6 quads of energy (nearly three-fourths of industrial heat use) is used in industrial processes at temperatures above 350°F. Because solar systems that can supply these temperatures are generally more expensive than those that supply lower temperatures, the approach has been to first consider the less expensive, low-temperature applications. Only if these are attractive would the more expensive high-temperature systems need to be examined in detail.

Solar grain drying has been selected as representative of a solar system that could supply low-temperature agricultural heat. Several recent studies have shown that this could be an attractive option. The analysis is based on a bin-wall collector system that can be installed

on new storage bins or retrofitted onto existing ones. This is compatible with the growing trend toward more on-farm storage and drying.

Development Schedule

Each of these generic technologies is in or near the demonstration or commercialization phases as indicated below.

	<u>Concept</u>	<u>Design</u>	<u>Pilot</u>	<u>Demonstration</u>	<u>Commercial</u>
Industrial hot water	--	--	--	1975	1975
Industrial steam	--	--	--	1980	1985
Agricultural drying	--	--	--	1960s	1975

These dates are somewhat arbitrary, since undoubtedly there were earlier uses than those shown. For example, solar drying of fruits has been common practice for hundreds of years, although recent trends have seen sunlight replaced with combustion dryers.

The current federal program has focused on demonstrating systems that are more or less commercially available in an effort to promote more widespread use. Some commercial installations of both industrial hot water systems and agricultural drying (grain drying) have been made without governmental assistance. For example, Anheuser-Busch is installing such a system in its brewery in Jacksonville. Solar grain dryers are commercially available, for example, the Kuss Soloron unit.

Industrial steam is less developed because of its higher cost. ERDA has conceived one of its water heating demonstrations (a commercial laundry in El Centro, California) to be expandable to produce steam, should that appear attractive. The demonstration date of 1985 represents the period where suitable concentrating collectors should be available commercially and when successful demonstrations will have produced reasonable consumer confidence.

Economics

Because these technologies will be available in the near term, their costs can be estimated with reasonable accuracy. These estimates make no provision for storage. The evolving consensus is that storage for anything except short-term buffering is not reasonable, given the high cost of storage and the inevitable need for standby heat to maintain reliability. The costs, shown below, are dominated by the collection cost. Reductions in cost are produced by a combination of

reduction in unit cost in dollars per unit and an increase in performance (efficiency). Shown below is the process heat capital cost in dollars per annual millions of Btu:

<u>General Technology</u>	<u>Product</u>	<u>1985</u>	<u>2000</u>	<u>2020</u>
Industrial hot water	Hot water	\$56	\$45	\$40
Industrial steam	Steam	86	69	55
Agricultural drying	Hot air	39	39	39

The costs shown are for the Southwest. Solar industrial and agricultural heat costs in some other regions increase as the total insolation decreases. The industrial steam costs change as a function of the direct beam radiation, since steam is generally produced by a concentrating collector.

Site specific factors can influence these costs. For example, because no allowance has been made for land costs, the assumption is that these systems are placed on rooftops or on surplus land. There is some economy of scale in assembling large industrial facilities, compared, for example, with smaller industrial systems.

The most important complementary research will be improvements in collector performance and life time. This includes the areas of selective coatings, high performance glazings, and materials for absorbers. Storage research, while helpful, will not have a large impact on these applications, since back-up systems will generally be needed anyway.

Potential Applications

Although the industrial heat sector is a large consumer of energy, about 10 quads of end-use energy (roughly 15 quads of primary energy), only about one-third of this is at low enough temperatures (less than 350°F) to be technically attractive for solar heat. The higher temperatures are problematic. They would require substantially more sophisticated solar systems. Furthermore, the industries that use these higher temperatures, such as petroleum refining, glass, cement, and steel and iron, are so energy-intensive that they would require unreasonable land areas to support their heat requirement entirely with solar energy. Furthermore, many of these largest energy users are located in the industrial Northeast and Midwest where land costs are high and solar insolation is lower. Putting all these factors together suggests that over the next 50 years technical considerations alone will limit solar use to at most one-third of the industrial heat market. In contrast, most agricultural systems suffer from few of these barriers, so that their use can be more widespread even though the market itself is much smaller.

One factor that facilitates solar use in these applications is that, because these solar systems operate as fuel savers, installations do not need to depend on growth in demand to generate a solar market. Because the solar system is only saving fuel, an existing system can be left in place to serve as backup.

Since more than 90 percent of the industrial fuel that could be displaced by current use of solar systems would be oil and gas, these systems could have considerable benefit to saving these scarce fuels in the near term. However, because coal will be more widely used to meet these demands in the years ahead, coal will likely be the principal alternative by the end of the century.

In the agricultural sector, the principal alternatives are LPG and electricity. Because of recent scarcities of LPG, the use of electricity is likely to continue growing.

In addition to the previously discussed technical barriers to solar use, the industrial sector has some serious institutional barriers to solar energy use. Fuel costs are deductible expenses as incurred, whereas a solar system is an expense that is depreciated over some period of years (e.g., 20). This difference in tax treatment has the effect of increasing the cost of solar relative to combustible fuels. Furthermore, the cost of capital is usually higher for industry than for utilities or, in some cases, residences, because of the higher risk associated with private ventures. Again, this acts as a barrier to the solar applications in industry.

Environmental Considerations

The use of solar heat in industrial applications will yield definite environmental benefits. The principal fuels displaced will be oil and gas in the near term and coal in the long term. For this reason, these uses will directly reduce CO₂ production as well as the fossil fuel residuals. Perhaps a more important factor is that this reduction will occur in industrial areas that experience the worst environmental problems. Because most industrial solar systems will be on building rooftops and because they will be professionally maintained, no adverse impacts should occur.

International Potential

The widespread use of solar heat in U.S. industry is not likely to lead directly to important export markets. As with residential systems, the hardware will be generally labor-intensive to manufacture, so that a favorable product position is unlikely. At the same time, little of the technology is unique, so it will be difficult to gain a proprietary capability. Some agricultural systems (such as grain drying and building heating) can be modest cost, labor-intensive systems that

can aid developing countries in improving their agricultural productivity; developing these systems can promote international good will even if not export markets.

RD&D Programs

The 1977 budget for the Agricultural and Industrial Process Heat Branch was \$7.8 million, less than 3 percent of the entire DSE program. Most of the programs have been directed toward demonstrating industrial hot water and agricultural drying systems. In addition, several studies have been made to survey potential applications.

The long-term prospects for solar process heat use are probably fairly insensitive to RD&D program efforts, because in the long term, use will be determined by solar cost. This solar cost will be determined primarily by collector development, which depends heavily on the success of collector manufacturers. Thus, in the long term, the most effective role of the federal program would seem to be supporting the more fundamental research (for example, in materials and surfaces) that can eventually lead to reducing collector costs.

Conversely, in the near term, the important factor is to support early suppliers so as to build industrial experience and customer confidence on which to later build substantive expansion. For this reason, this early federal program can be important to developing the industrial base on which long-term energy contribution will be established. The current program seems to recognize this by relying on demonstrations in the near term.

Significant increases in RD&D effort in process heat could most effectively be directed toward high-temperature collectors. Although significant results in this area will be difficult to achieve, they will be important to furthering those uses, because the potential market increases greatly as the temperature capability of the solar collector increases.

Storage, particularly high-temperature storage, is frequently mentioned as a key to facilitating solar heat use. This investigation has found that such storage is not important. Since most industrial processes require very high reliability of energy supply to avoid idle capital and labor, a conventional backup system is usually needed anyway. Thus, storage capability is not likely to eliminate the backup expense. Furthermore, many industries are so energy-intensive that supplying their instantaneous energy demand with a solar system of reasonable size can be difficult; consequently, collecting enough solar heat to recharge a storage system for nighttime use only adds to the difficulty.

In summary, the process heat RD&D program as it is currently directed can be depended on to provide systems at the costs described earlier. The program appears reasonably balanced. Reduction in this RD&D program

would delay the availability of systems by retarding commercial acceptance. Conversely, increasing the RD&D program, if directed toward demonstrations, would speed commercialization of low-temperature systems without greatly changing the eventual level of use. Alternatively, an increased program aimed at development of higher temperature collectors would increase the eventual level of use, although the chances of such a program's success might not be great.

Biomass Technologies

Introduction

As used in this analysis, and as organized in the federal solar program, the biomass classification includes aggregation or production of biomass as well as conversion of biomass to useful products. Biomass considered in this study includes all forms of plant materials, both those grown on land (terrestrial) and those grown in or on water (aquatic). It includes forest and crop residues, crops grown for their energy content, and animal manures. It does not include conversion of municipal solid waste or industrial wastes.

An overall view of biomass technologies is shown in Figure 11. The five conversion technologies evaluated are: (1) direct combustion to produce process steam and electricity; (2) anaerobic digestion to produce intermediate- and high-Btu gases; (3) fermentation to produce liquid fuels and petrochemical feedstocks; (4) fermentation to produce thermochemical products, including gasification, and (5) liquefaction to produce useful fuels and petrochemical substitutes. Biomass production technology was also assessed, including both terrestrial and aquatic energy farming.

Biomass offers a significant potential for reducing national dependence on fossil fuels through the conversion of a renewable energy source to useful liquid and gaseous fuels, electric energy, and petrochemical substitutes. Conversion of residues such as wood to electric power and steam is currently carried out at competitive costs in several parts of the United States. Biomass supplies electricity to many U.S. industrial facilities and in some cases supplies power to local communities from industrial or central conversion sites.

Technology and Product Descriptions

Many technology options could be applied to the conversion of biomass to energy or chemicals. These range in stage of development from laboratory scale to commercially proven processes.

Direct Combustion

Combustion can be one of the most efficient methods of using the energy potential of biomass. Thermal efficiency is limited only by the heat recovery equipment downstream of the combustion chamber. For direct-fired furnaces and steam boilers, thermal efficiencies as high as 85 percent can be achieved. Generally, biomass with moisture content below 30 percent can be combusted directly, while those with higher moisture content may have to be predried or fired with supplementary fuel, either of which requires expenditure of additional energy and lowers the efficiency of the process.

FIGURE 11. BIOMASS -TECHNOLOGY OVERVIEW

The successful use of the combustion process option will depend on the cost of power from new coal or nuclear plants in a given area. The relative simplicity of the process will tend to make it more attractive for certain sites than some of the other options.

Thermochemical Gasification and Liquefaction Processes--

Pretreated biomass may be converted to useful products by gasification to make synthesis gas, methane, methyl fuel, and others, or by liquefaction to make fuel oil. For example, cellulosic materials such as wood can be reacted with hydrogen and carbon monoxide to give oils equivalent to fuel oil from petroleum. High temperature and pressure are required and the feed must be well subdivided.

Thermochemical technology comprises a wide range of processes that depend on thermal decomposition of organic matter to produce other usable fuels. The types and the amounts of fuel produced depend primarily on the temperature used in the process. Thus, low temperatures (those generally under approximately 1200°F) produce large quantities of char and oil together with lesser amounts of fuel gas, while high temperatures (greater than 1800°F) produce primarily fuel gas, possibly some char, but no oils. Wood or other biomass can be reacted with oxygen and steam to produce a low- or medium-Btu gas or a synthesis gas that can be upgraded to SNG, methanol, ammonia, or hydrogen.

Anaerobic Digestion

Anaerobic digestion consumes biomass directly to produce methane without first breaking it down to sugars. Almost any material from biological sources can be digested by anaerobic microbial processes to yield carbon dioxide and methane.

The technology is currently commercial and is in common application today as a means of waste treatment for removing organics and destroying harmful microorganisms in domestic and industrial wastes. The process takes place at essentially ambient conditions (15 to 65°C) and works best on substances with high moisture content (80 percent or greater). Product gases, consisting mainly of methane and carbon dioxide, can be burned directly or can be upgraded to SNG by removal of the carbon dioxide.

Hydrolysis and Fermentation

Thus far, the ERDA (now DOE) program has concentrated on hydrolysis of cellulose to sugars and their subsequent fermentation to ethyl alcohol, an excellent motor fuel. Ethanol is an interesting product because it can be blended with gasoline to extend supplies or used directly in modified internal combustion engines on an almost one-for-one replacement basis for gasoline.

Cellulose can be converted by chemical and biological hydrolysis to glucose (sugar), molasses, or derived single-cell protein. Both chemical and biological (enzymatic) hydrolysis of cellulosic raw materials to produce sugars and ethanol have been demonstrated.

Low yields are obtained by direct fermentation, and therefore acid hydrolysis is often carried out under pressure before fermentation. This system usually requires phosphoric or nitric acid as a catalyst, which cannot easily be reclaimed and therefore must be disposed of after neutralization with lime. Careful control of reaction times, temperatures, and acid concentrations is required.

Development Schedule

Specific development schedules for selected conversion processes are projected in Table 19. The demonstration and commercialization start dates in all cases are not the same as those proposed by ERDA because of variations in assumed plant operating costs and competitive product market prices.

The Economics of Production and Conversion

Both the economics of feedstock production on energy farms and the economics of feedstock conversion to useful fuel and petrochemical substitutes are addressed in Volume II.

The type of analysis that yields the best indication of future biomass value (and ultimate utilization) is a study of the expected prices of competing energy feedstocks. For this analysis it was assumed that regardless of the ultimate energy product (e.g., electricity, gas) the major competitive feedstock would be coal. Table 20 is SRI's estimate of available residues and potential energy farm production of biomass.

The economics of feedstock conversion to useful fuels, based on the technologies described earlier, are shown in Table 21. This table lists the most important products expected to be produced from biomass, their projected date of commercialization, and their expected cost range.

Potential Applications

Because many combustion processes are currently economic and others will soon become economic, the potential applications of biomass energy products will be limited by feedstock price and supply. Unlike other solar energy technologies, biomass conversion allows for wide flexibility, since numerous fuel products can be produced, depending on the process used. Many substitutes for fuel products currently in wide use can be produced directly with biomass technologies. For example, methanol or ethanol from biomass conversion could substitute directly for gasoline.

Table 19

DEVELOPMENT SCHEDULE FOR BIOMASS CONVERSION PROCESSES

	<u>Concept Study</u>	<u>Design</u>	<u>Pilot</u>	<u>Demonstration</u>	<u>Commercial</u>
Anaerobic digestion to produce SNG (various feedstocks)	1965	1967	1973	1978	1985
Fermentation to produce ethanol	1960	1978	1980	1985	1990
Pyrolysis to produce medium-Btu gas	1960	1975	1980	1984	1990
Pyrolysis to produce boiler fuel oils	1960	1977	1983	2000	2020

Table 20

BIOMASS AVAILABLE FOR FUEL USE
(Estimated Millions of Dry Tons and Btu)

	<u>1973</u>	<u>1975</u>	<u>1985</u>	<u>2000</u>	<u>2020</u>
Residues (tons)					
High	--	--	260	195	190
Mid	28	43	215	161	114
Low	--	--	170	92	38
Biomass crops (tons)					
High	--	--	15	195	640
Mid	--	--	7.2	130	320
Low	--	--	--	10	100
Total biomass (tons)					
High	--	--	275	390	830
Mid	28	43	222.2	291	430
Low	--	--	170	102	138
Total Btu 10 ¹²					
High			4,125	5,325	12,450
Mid	420	645	3,333	4,365	6,450
Low	--	--	2,550	1,530	2,070

Other widely used biomass fuel products are process steam, methane, electricity, oil for direct combustion, ammonia, acetic acid, hydrogen, and intermediate-Btu gases. A significant advantage of producing a fuel, compared with substituting for an end-use conversion device as many solar applications do, is that introduction of the solar technology is not constrained by replacement rates of existing hardware.

Environmental Problems

The environmental impacts of the biomass program are not a major constraint. Nevertheless, special attention to the following environmental issues are necessary:

- Land and water availability
- The potential for erosion and depletion of soil organic content if too many residues are removed
- Secondary impacts associated with large-scale farming and conversion operations
- Particulate emissions from direct combustion
- Disposal of residuals from conversion processes.

Table 21

SUMMARY OF PRODUCTION COSTS FOR FUEL FROM BIOMASS

Generic Technology	Product	Potential Product Costs*			Expected Commercialization Date
		1985	2000	2020	
Acid hydrolysis and fermentation of woody crops	Ethanol	\$17.7	\$16.8	\$15.8	1990
Pyrolysis of wood	Fuel oil	6.1	5.8	5.5	2030
Catalytic conversion of medium-Btu gas	Methanol	6.8	6.5	6.4	1990
Anaerobic digestion of cattle manure	SNG	2.7	2.5	2.3	1979
Pyrolysis of woody crops	Medium-Btu gas	3.3	3.1	2.8	1990
Pyrolysis and methanation of woody crops	SNG	5.0	4.7	4.5	2025
Direct combustion of gin trash or wood	Process steam	1.9	1.9	1.9	1977
Shift conversion of medium-Btu gas from wood	Ammonia	4.6	4.2	4.2	1985
Cents per kWh (baseload)					
Direct combustion technology	Electricity	3.2¢	3.0¢	3.0¢	1985

*1977 dollars per million Btu.

These impacts are significant compared with impacts from other solar technologies.

International Potential

Many of the technologies relevant to the fuels from biomass production problems have been in use in Europe and other countries for many years. Several of the early bioconversion and thermochemical conversion processes were first developed and implemented commercially in other countries. Therefore, the probability of exports of U.S. developed processes and conversion equipment to the more advanced countries of Europe and Asia is remote. However, the export of U.S. conversion knowledge and exchange of information on new techniques and methods is highly probable. The possibilities for technology transfer programs and the trade of production knowledge is excellent. In addition, the sale of equipment and the licensing of conversion processes to underdeveloped countries that import large quantities of petroleum products seem a definite possibility.

Several foreign countries have put a high value on the achievement of energy independence and have been willing to subsidize local energy conversion industries. Where the problems of international finance and foreign exchange can be overcome, significant technology exports by the United States to Latin American, African, Indian, and Asian countries can be accomplished.

RD&D Program

The current program of the Fuels from Biomass Branch is directed at specific RD&D goals in both the biomass production and conversion areas. It is likely that increased RD&D funding could result in increased potential for energy production over the near term as well as long term. In both areas, processes and technologies exist in which there is near-term potential to accelerate commercialization, given increased funding levels. If funding levels were held constant, a reallocation and development of incentive systems to encourage private development of biomass resources and fuels conversion activities could result in greater near-term impacts. Volume II contains a description of current program RD&D objectives and discusses possible changes in emphasis. To reallocate funding it is necessary to examine: (1) the near-term potential for the technology, (2) the probability of process development success, and (3) the long-term market potential. These factors are evaluated for specific technologies in Table 22.

The current budget for the Solar Energy Division Fuels from Biomass Branch is \$20.7 million in FY 1978. This budget is expected to increase to \$35 or \$40 million in FY 1979. SRI believes that an increase in fiscal year 1979 funding could significantly accelerate commercialization of biomass conversion technologies.

Table 22

BIOMASS TECHNOLOGY RISKS AND POTENTIALS

<u>Technology</u>	<u>Near Term Potential*</u>	<u>Risk of Process Development Failure†</u>	<u>Long Term Market Potential</u>
Terrestrial energy farming	High	Low	High
Aquatic energy farming	Very low	High	Very high
Anaerobic digestion	High	Low	Low
Direct combustion to steam or electricity	High	Low	Moderate
fermentation	Low	Moderate	Moderate
Gasification	Low	Low	High
Liquefaction	Low	Low	High

* Potential capability to stimulate or increase near-term energy production in the United States.

† Probability of failure in achieving commercialization.

Ocean Thermal Energy Conversion

Introduction

In 1881, d'Arsonval proposed the possibility of extracting energy from fluids having thermal gradients, and early experimenters such as Claude in 1930 used an open-cycle concept in which seawater was the working fluid. The relative quantity of energy available from ocean thermal sources is said to far exceed that available from other sources. The resource may certainly be large, and the current thrust of DOE's OTEC program is in making the products extracted from this resource competitive with alternatives.

Products from OTEC installations include electricity and a variety of energy-intensive products from industrial complexes that would use this electricity in their manufacture. Current research concerning OTEC, which began in the early 1970s under the sponsorship of the National Science Foundation program administration, was subsequently transferred to ERDA's Division of Solar Energy and currently exists as a program in DOE.

OTEC technology uses the temperature variation between warm, surface ocean waters and cold, deep ocean waters to generate electric power, using either an open thermodynamic cycle or a closed, binary fluid thermodynamic cycle. Since current cycle efficiencies for this concept tend to be between 3 and 5 percent, the movement of large quantities of seawater (both warm and cold) is involved in the generation of electric power in the 100 MWe to 200 MWe range. Since the ocean acts as a vast heat reservoir, the technology would be capable of baseload operation with no storage.

Technology Description

The generic OTEC technology considered here uses a closed cycle with shell and tube heat exchangers. Open cycles are candidates for second generation concepts, as are plastic heat exchangers and plate heat exchangers. The closed cycle generic system was selected because its concepts are closest to commercial practice. It is believed that significantly more development time would be required for second generation systems.

The generic OTEC technology operates in tropical or subtropical waters on thermal temperature differences of 38°F minimum. The net electric power output is about 200 MWe, generating baseload power with no storage. It operates from a moored location, 20 to 200 miles offshore, delivering electric power to an on-shore utility grid by a high voltage AC or DC submarine transmission cable.

Ocean Energy Industrial Complexes (OEIC), either moored or grazing, are also candidates for a generic technology category. However, because of the variety of possible products from OEICs (inorganic and organic chemicals, metal products; desalinated water, ammonia, hydrogen, and others), each of which tends to serve a different end-use market, no generic description of OEICs are attempted here.

Development Schedule

As seen from the OTEC program summary (ERDA 76-142) and from announcements of recent contract awards, DOE has activities under way in a great many areas related to OTEC development. Major contractors exist in 12 to 15 major program areas and are too numerous to list. Original ERDA timetables show the OTEC demonstration program beginning in 1984. This date may not be achievable for several reasons:

- The OTEC program currently lacks significant private sector (not contractor) technical involvement.
- The present OTEC program structure does not exhibit strong mission-oriented approaches or strong approaches involving the assessing of the benefits of OTEC RD&D.
- The original OTEC program plan does not chart the elements of the entire program, show their interaction, or make provision for alternative strategies or timetables because of uncertain outcomes from experiments. Insufficient time is allowed between the completion of a series of experiments and the incorporation of these results on the design concepts for the next program phase. Some of these problems may be procedurally remedied by appointing a prime contractor for the OTEC program.

Table 23 is a proposed development schedule for the OTEC program which incorporates the above considerations. Commercialization may not be realized until after 2000, and the development of Ocean Energy Industrial Complexes ("grazing" installations) may lag OTEC development by ten years or more.

Table 23

DEVELOPMENT SCHEDULE FOR BASELOAD ELECTRICITY FROM OCEAN THERMAL ENERGY CONVERSION

	<u>Concept</u>	<u>Design</u>	<u>Pilot</u>	<u>Demonstration</u>	<u>Commercial</u>
OTEC	1972/ind.	1980/1980	1982/1990	1988/1995	1997/ind.

Notes: ind = indefinite

Schedule Start Date/Schedule End Date

Economics

Economic projections are presented for OTEC installations producing electricity. Capital cost estimates for OTEC installations are likely to increase with time as system construction, operation, safety, and maintenance requirements become better defined. Large uncertainties exist regarding costs and performance of heat exchanger components, the cold water pipe, and recovering systems. The cost projections for OTEC are subject to these uncertainties.

Table 24 shows OTEC capital costs in 1975 dollars. Initial costs for the first production unit were obtained from Lockheed and adjusted from a 36.5°FΔT to a 38°FΔT. Costs were increased by applying a 100 percent contingency factor to the mooring system and cold water pipe because of the uncertainty in these systems and by applying a 30 percent contingency factor to the heat exchanger to account for design unknowns. Many pumps, new exchanger bundles in the case of aluminum material, and like items need to be replaced after about fifteen years of use. We have discounted these costs to present value to represent current value of this expense. Additional costs represented the owners' costs and interest during construction. The resulting costs of the initial production units in Table 24 range from \$2,700 to \$2,800, with negligible differences between titanium and aluminum. This is attributed to the larger costs of the 15-year investment for aluminum compared with titanium, which tends to offset the lower initial cost for the aluminum alternative.

Learning curve effects were assumed to decrease the cost of OTEC installations by 10 to 12 percent over a 20- to 25-year period. A portion of this learning may be attributed to standard shipyard learning regarding hull fabrication and the balance to the fabrication of other equipment items (e.g., heat exchangers, turbines).

Because of a lack of definition of basic requirements for maintenance, O&M costs were assumed to be about 6 mills per kWh. The cost of electricity transmission to shore was assumed to be 8 to 10 mills per kWh, assuming an average plant location of 80 to 120 miles offshore. The cost of electricity transmission to shore was assumed to decrease slightly with time to account for learning for cable manufacturing, development, and the like.

The capacity factor for an OTEC facility was assumed to be 0.8. This suggests that the availability factor for OTEC might be 0.85 to 0.90. Because of current unanswered questions concerning OTEC operability and the effects of biofouling, corrosion, seasonal derating, exchanger cleaning, and the like, the 0.8 capacity factor may be considered as a technology goal.

Potential Applications

The market served by electricity-generating OTEC installations will be the baseload electric power market. The electricity will enter the

Table 24

ECONOMICS OF BASELOAD ELECTRICITY FROM OCEAN
THERMAL ENERGY CONVERSION
(1975 Dollars)

	2000		2020	
	Titanium	Aluminum	Titanium	Aluminum
Capital cost* (\$/kW)	\$2,775	\$2,675	\$2,470	\$2,380
O&M cost (mills/kWh)	6	6	6	6
Transmission to shore (mills/kWh)	10	10	8	8
Specific capital cost [†] (\$/annual MM Btu)	\$ 116	\$ 112	\$ 104	\$ 100
O&M cost, ¢/MM Btu	175¢	175¢	175¢	175¢
Transmission to shore, ¢/MM Btu	292¢	292¢	234¢	234¢
Demand Regions 3, 4, and 6				

*Not including cable to shore.

[†]At 0.8 capacity factor.

market at coastal locations and will be further transmitted and distributed to demand regions. Competition exists for this market from commercial and advanced coal technologies, nuclear technologies, and geothermal technologies, as well as other solar-related technologies. Since OTEC technologies operate with zero "fuel costs," potential dates of market viability for OTEC installations are often characterized as functions of assumed escalation rates in the costs of fossil (coal) or nuclear fuel. The probabilities of the dates of OTEC market viability are difficult to characterize when viewed from this perspective, because future fuel escalation rates are uncertain and are subject to supply/demand elasticities as well.

Potential markets for OTEC installations include the states comprising the Southeast and South-Central regions of the United States.

OTEC capital, operating, and energy product costs may vary from location to location. These differences are not characterized here because the technology is at an early stage of development. Factors contributing to capital cost variation include fabrication location (e.g., domestic versus foreign), the design temperature differentials, the availability of dedicated fabrication facilities, and the design specifications required by sea conditions at specific sites. Factors affecting OTEC availability at rated capacity are also site specific and include biofouling, corrosion,

operating the facility at off design conditions because of seasonal de-rating or other factors, and the frequency of forced maintenance outages. Such factors have not been adequately characterized for potential OTEC sites.

As an alternative to coal-based generation of electricity, OTEC installations will avoid constraints in the availability of skilled mining personnel, coal transportation to site, and the requirements for opening large numbers of coal mines. By the same token, the development of an OTEC industry will place other demands on the concrete, aluminum or titanium, shipbuilding, and similar primary and supporting industries.

Many institutional constraints face the development of an OTEC industry. These include the lack of demonstrated electric utility interest to date, the lack of industrial experience with and acceptance of this type of technology, jurisdictional issues, liability and accountability issues, hazard issues regarding maritime safety, environmental impacts (both short and long term), and numerous issues regarding conflicts of ocean use.

Ocean Energy Industrial Complexes (OEIC) produce energy-intensive products from moving or "grazing" platforms. The costs of these products depend heavily on the cost of electricity. When assessing U.S. markets for OEIC-produced ammonia or methanol (or for energy-intensive metals such as aluminum), a principal alternative appears to be the production of such commodities from remote natural gas (or, in the case of metals, the production of these materials from regions of the world having very low-cost electric power such as hydropower). Such a comparison, including commodity shipment to the United States, would highlight the risks of the OEIC venture when compared with low-cost alternatives.

Very preliminary net energy analyses concerning OTEC installations suggest that high lifetime performance factors and very short payback times may be possible. However, the materials of construction, as well as the quantities of these materials committed to an OTEC installation, are being continually reevaluated.

Environmental Considerations

OTEC and OEIC concepts are rapidly evolving. Work regarding bio-fouling and corrosion is far from complete, as are concepts for materials of construction, technology design, and technology operability. As a result, the environmental consequences of a decision to install an OTEC or OEIC facility are far from being completely understood.

Generally speaking, the environmental consequences of installing OTEC or OEIC facilities, based on current thinking, may be relatively benign compared with alternatives (such as baseload coal and nuclear power plants) that have been studied more completely and are commercially available. This picture may change as more becomes known about OTEC and OEIC.

Air pollution may not be a major concern in the construction of OTECs or OEICs. Certain emissions may be possible during the operation of OEICs, and these have been discussed by some investigators. OTEC installations producing electricity may be considered to pose air pollution hazards only from the inadvertent release of the working fluid or during periods of the transfer of the working fluid to the closed cycle.

Minimal water pollution problems should exist during the construction of OTECs or OEICs. Potential thermal pollution and salinity gradient impacts are common to the operation of these facilities, and procedures may be developed to minimize such impacts. A variety of opinion exists concerning the fate of the cold water brought to the ocean surface from below. For example, will this water sink due to density differences or mix with warmer surface waters? Since key questions of system operability and nutrient dispersion depend on the fate of the cold water, this issue should be clarified by site research when possible.

International Potential

Numerous potential OTEC sites may be available in countries lying in the thermal belt region within $\pm 15^\circ$ of the equator. A recently completed study prepared by the University of Southern California suggests nine countries with high potential: Puerto Rico, Singapore, Brazil, Mexico, India, the Philippines, Indonesia, Australia, and Malaysia. Because of the capital intensiveness of OTEC installations, the debt-financing of these ventures through well-known international agencies such as the Export/Import Bank and the International Development Agency may be necessary. Also, OTEC markets may exist in certain lesser developed countries for sizes smaller than the 100 to 260 MWe net installations currently considered as reasonable sizes for the future domestic U.S. market.

Besides restrictive home equity rules in most of the above nine countries, as well as political instabilities in certain of these countries, several other considerations emerge that may impede OTEC growth abroad:

- For Australia, the potential OTEC zones are geographically distant from demand regions.
- For Brazil, coastal OTEC electricity will have to prove competitiveness with relatively inexpensive transmitted hydroelectric power from interior regions.
- Both Indonesia and Malaysia are currently enjoying an abundance of oil and natural gas, which may deter interest in alternative energy sources.

The economics of OTEC installation abroad may depend heavily on site-specific characteristics (biofouling, corrosion, seasonal derating), which have yet to undergo analyses.

RD&D Program

Increased RD&D funding (e.g., budget doubling) would permit parallel efforts to be pursued in the areas of heat exchanger R&D (laboratory, bench scale) to more adequately define geometries, fluid distribution, cleaning techniques, and the like; the conduct of site-specific investigations in several geographic areas to more adequately characterize normal and extreme variables in the environment in which OTEC or OEIC installations will operate; and heat exchanger component testing at several possible sites. Additionally, under certain budget levels, scaled heat exchangers in the 1 MWe to 8 MWe size range could be fabricated and tested at several sites simultaneously.

Such program changes would permit more time for site testing than is shown on current OTEC program schedules. A greater variety of information would be obtained earlier in the program from site tests, permitting improved criteria for decision making and a more realistic characterization of the environment in which OTEC installations would operate.

If the budget for OTEC were cut in half, this would permit only limited hardware-related studies for the foreseeable future and probably delay the OTEC demonstration plant until after the year 2000.

The following suggestions are offered:

- Maintain a record of cost goals for principal alternative technological options, including electricity costs, inorganic chemicals costs, and organic chemicals costs attributable to OTEC competitors, and continually update this record as technologies evolve. If it is clear that a cost goal for an OTEC product can never be achieved, eliminate the product from further consideration.
- Develop realistic estimates for assessing the benefit streams that will flow from the operation of an OTEC installation. This would be helpful in establishing appropriate OTEC missions. Additionally, seek technical input from industry concerning the desirability of alternative OTEC missions.

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V EVALUATION METHODOLOGY

Introduction

Many considerations must be included in an evaluation of solar alternatives. One approach involves assessing the relative value of expected "net social benefit" from a solar technology and comparing this with alternatives under various scenarios. The total "net social benefit" would be defined to include a spectrum of benefit values such as reduced energy import, favorable economic and environmental imports, and so forth. From this information, estimates could be made of the changes in the probability of achieving the value of benefits as a function of the level of RD&D support. Rigorous application of these considerations would result in relative budgets for solar technologies, based on maximizing the discounted value of expected benefits less RD&D costs. The current state of development of the solar technologies, the forecast period of their market penetration (window), and the accuracy of data available suggest that rigorous application is not appropriate. However, the technology evaluations provide the input necessary to develop the desired recommendations using a subjective figure of merit-type "benefits" calculation with RD&D budget alternatives considered subsequently. The benefits assessment is based on seven considerations or "values" that SRI and the SWG determined to be important in distinguishing between solar alternatives. These are:

- Market potential. Under several price/demand scenarios, which solar technologies would contribute the most to national energy supply?
- Environment. Which solar technologies have the least adverse environmental impacts themselves and which replace the most environmentally adverse alternatives?
- Insurance. Which solar technologies can be relied on to provide energy to the nations under conditions of extremely high alternative prices that could result, for example, from limits on availability of conventional energy supplies or severe environmental constraints on conventional energy supplies?
- Speculative. Which solar technologies have the possibility of supplying major fractions of our national energy needs because of their simultaneous meeting a major energy demand and utilizing a large solar resource base?
- Conservation. Which solar technologies directly conserve oil and gas, the conventional fuels with the smallest national resource base?

- Central/decentral. Which solar technologies are decentralized in use so that the potential benefits of small-scale applications could be realized?
- International. Which solar technologies might lead to significant export markets either of hardware or of services?

Operational definitions of these values are given later. To carry out the desired comparison between the solar alternatives, a ranking process was developed to combine the seven values into a numerical "benefits" score. This benefits ranking, then, is a relative comparison of the solar alternatives based on these seven values. It needs to be stressed that the resulting ranking is relative to this particular grouping of solar technology options and that being high or low within this list might mean little about how a particular solar technology compares with some alternative outside this set of options.

Figure 12 is a conceptual diagram of such a review process. It incorporates a conceptual evaluation of the considerations described above. This section briefly describes the methodology of this process; the results of the process, as well as sensitivity analyses for alternative solar and alternative fuels inputs, are presented in Section VI.

Market Potential Methodology

A long-term market penetration analysis for solar technologies is a difficult and uncertain task, because it considers competition between products that will be produced by technologies competing with other technologies that have not been demonstrated. The potential of a solar technology to penetrate a market depends on a large number of variables that, in turn, depend on other variables. Some of the more important variables are the cost of energy delivered to the end use by the technology relative to alternatives; the magnitude and growth of the market under consideration; institutional barriers and incentives for the new technology (e.g., governmental taxes and/or subsidies, zoning restrictions, depreciation schedules, interest rates, and decisions in the investment community); environmental laws and regulations; and a host of social and consumer variables that are likely to influence the actions of the market's decision-makers. Examples include a desire to conserve resources or limit energy imports or a preference for known sources of supply or decentral technologies.

The present state of development of market penetration models makes it unwise to claim that a single estimate is predictive of what in fact will happen. Too many factors, particularly regarding the response of markets to new, unique technologies such as solar, are unknown. For these reasons, market penetrations for this assessment are based on a set of four scenarios derived from different assumptions of solar and alternative energy costs. The penetrations are most meaningfully interpreted as showing relative contributions of the solar alternatives and are not absolute projections. The following is a brief description

FIGURE 12. CONCEPTUAL FRAMEWORK FOR EVALUATING RD & D PLANS

of the fundamentals of the market penetration model. Details are found in Volume II.

Based on past work, SRI has found that it is possible to estimate the market response to a new energy commodity from three major variables: relative prices, energy market size (demand), and a set of market response parameters. The SRI Solar Penetration Model (SPM) combines these pertinent variables to allow systematic studies to be carried out on the marketability of new energy products and technologies. The SPM can be used to help estimate the market share that could be expected for the solar technologies under consideration and to provide a framework for sensitivity analysis.

As an idealization, the share of a particular market that can be attained by a new technology at any particular time under equilibrium conditions can be represented by the curve shown in Figure 13 and given by:

$$\text{Equilibrium Market Share to Solar Technology} = \frac{1}{1 + \left(\frac{P_s}{P_a} \right)^\gamma}$$

where P_s and P_a are the equivalent prices of the solar technology and alternative fuels, respectively.

This static representation says that, at equal prices and under equilibrium conditions, the market will be shared equally. The gamma parameter is a measure of market imperfections, price variations, and consumer preferences. In this representation, average prices are used for both the solar technologies and alternative fuels, although there are significant individual variations from the average. For example, continued governmental intervention might introduce significant disparities into the future prices of pipeline natural gas. Also, other sources such as LNG imports and various high-Btu synthetic products will be introduced at yet different prices, causing an even wider distribution of prices about our assumed average.

In addition to these price impacts, decision-makers influence market share. Even if the solar technology is somewhat more expensive than the alternative, some fraction of purchasers will select it, perhaps because of environmental or "energy-independence" considerations. Alternatively, some fraction of purchasers will continue to use their familiar fuel source even if economic considerations dictate a change to a new one. Imperfect price information also affects the market share curve. The application of this market share curve prevents the unrealistic result of an entire market shifting to a new technology simply because its estimated price is slightly lower than other alternatives.

FIGURE 13. EQUILIBRIUM MARKET SHARE

All these variables are aggregated into the one parameter, gamma. In a perfect market with high price sensitivity and none of these real world effects, gamma would be infinite.

The market share curve of Figure 13 is a static representation of real-world variations from average. To assess the dynamics of market penetration, a "market penetration curve" is used to describe how fast the current market will move toward the static price-determined market share curve as a result of real-world behavioral response. We call this the "behavioral lag" effect.

The curve, given by:

$$\frac{1}{1 + \left(\frac{h}{n}\right)^\alpha}$$

is shown in Figure 14 where h = half life (time required for one-half the market to respond to the entrance of a new commodity)
n = years since new commodity introduction
α = response parameter

The curve combines two important effects that tend to slow the introduction of a new technology. The first factor is the time it takes decision-makers to accept and switch to new fuel sources, especially those that are based on unfamiliar processes. Second, this curve considers the combined difficulties entailed in bringing a new technological venture to full commercial development. Factors such as component production capabilities, plant lead times, and plant construction and starting difficulties would inhibit market penetration for a period of time.

To find the share of the particular market captured by a new technology in any particular year, the equilibrium market share and dynamic market response curves are multiplied. This is done for each year, resulting in a cumulative market share for the new technology as a function of time.

Table 26 shows the response parameters that were used in the base case market penetration analysis. Sensitivity cases were also run to determine the effects of these assumptions on the market penetration results.

These values are subjective; there are as yet no valid data to determine accurately a predictive model of, for example, how rapidly utilities will install thermal power plants.

The values used here (i.e., h = 10 and α = 4 for central thermal power) indicate an assumption that once economic viability is demonstrated, utilities will respond more rapidly than homeowners/communities

FIGURE 14. DYNAMIC MARKET RESPONSE

Table 25

MARKET PENETRATION PARAMETERS

	Market Share Parameter (γ)	Behavioral Lag Parameters		Behavioral Lag Starting Date
		Half-life (h)	Response Parameter (α)	
Photovoltaic				
Central	25	10	4	1985
Dispersed	10	15	4	1985
Thermal electric				
Central	25	10	4	1985
Dispersed	10	15	4	1985
Wind				
Central	25	15	4	1980
Dispersed	10	15	4	1980
SHACOB				
Water heating	10	10	4	1980
Space and water heating	8	10	4	1980
Space cooling	8	10	4	1985
Industrial indirect heating	10	15	4	1980
Biomass	--	15	4	1975
OTEC	25	15	4	1985

($h = 15$, $\alpha = 4$ for dispersed thermal power) because utilities are more directly driven by economic choices. The variations in the market share parameter, α , simply say, for example, that there will be less variation in the cost of OTEC plants, as installed, ($\alpha = 25$) than in the costs of residential space heating systems ($\alpha = 8$). Residential space heating systems show wide cost variations because of do-it-yourself installations, passive systems, and so forth. The absolute results of a single penetration estimate are sensitive to these assumptions; however, by basing the market penetration benefits value on different market penetration estimates, the sensitivity to the parameters α , γ , and h is reduced. Again, for this study, the important issue about these parameters is their relative values, not their absolute value. It is the market penetration of one solar technology relative to that of the others that enters into the benefits calculation.

Benefits Calculation Methodology

The figure of merit benefits calculation methodology was developed subjectively through discussion with the SWG. Based on these discussions, it was decided to calculate benefits for each of the seven solar technologies through the following value categories:

- Market penetration
- Insurance
- Conservation
- International.
- Environmental
- Speculative
- Central/decentral

Rather than using a discounting approach, benefits in each category are calculated for three periods: near term--1985; intermediate term--2000; and long term--2020. For each category, the method for calculating benefits and the relative weights changes for each period. This reflects changing priorities and uncertainties in the data. Assessing benefits for the three periods permits assigning an appropriate fraction of each year's research budget based on each of the three benefits calculations, the sensitivity analysis, and the RD&D implications described in Section V. Throughout the discussion of the methodology, three terms are used to describe market components of the solar technologies. These are:

- Market forecast--the forecast market penetration (e.g. in quads) based on output of the solar penetration model.
- Economic potential--the forecast market penetration assuming no behavioral lag, institutional limitations, or other deterrents which slow down the introduction of the new solar technologies. It is the equilibrium market share.
- Technical limit--lesser of practical product market size (i.e. number of quads that could be realistically satisfied by the solar technology due to the finite size of the applicable market) or practical resource potential (i.e., number of quads that could

be practically produced). These values were developed subjectively and include economic limitations.

The relative weights of each of the seven values, as used in the nominal ranking process, are shown in Table 26. These values are, obviously, subjective and are the result of extensive deliberations between SRI and the SWG and within the SRI project team. It is not practical to document all of the reasoning behind each of these numbers, because that would require a comparison of each of these twenty-one numbers, one with another (i.e., 231 comparisons). Rather than to attempt this, which would not be wholly satisfying anyway, a few illustrative comparisons will be made.

The market value is given less weight farther out into the future because the accuracy of such projections becomes increasingly unsure over longer time periods. Environment becomes more important over time under the assumption that environmental considerations become increasingly important as total energy demands grow and resources become limited over time. Conservation (of oil and gas) is most important in the near term because, as time goes on (past 2000) these fuels will become less important. Each value as well as the method for calculating benefits in terms of each value is described below. It should be understood that the relative weights of the values in Table 26 are subjective and that sensitivity calculations using different weightings have been performed.

The market penetration value is intended to reflect the increased energy availability and economic benefits which would be associated with the commercial use of a new energy source, in this case solar. The market penetration value is derived by comparing the penetration of a given solar technology with that of the solar technology achieving the highest penetration for each of five scenarios: the base case market forecast, the high electrification market forecast, the low solar price economic forecast, the base case economic forecast, and the base case technical limit. Different weights are applied to the penetration (or "quad factors") derived from the scenarios in each of the three time periods.

To keep the total weight associated with the market penetration value consistent with those shown in Table 26, the "quad factors" must be multiplied by normalizing factors. These normalizing factors are equal to the maximum benefits points available for a given scenario divided by the largest quad factor that any solar technology achieved in this case. (The normalizing factors assure that the solar technology with the highest penetration in any relevant scenario receives the maximum benefits points and that the benefits points of the other solar technologies are scaled to this maximum.) Finally, the actual benefits points for each solar technology are calculated by multiplying the normalizing factor by the particular technology's quad factor. In narrative form, this is likely to sound confusing, but an example will illustrate the process.

The near term (1985) market penetration value is derived from three cases: market forecast (base case), market forecast (high electrification)

Table 26

RELATIVE WEIGHTS FOR THE VALUES IN THE BENEFITS
CALCULATION OF THE NOMINAL CASE

Value	Near Term (1985)	Intermediate Term (2000)	Long Term (2020)
Market	37	30	28
Environment	19	25	28
Insurance	13	20	14
Speculative	--	5	10
Conservation	19	10	10
Central/decentral	6	5	5
International	<u>6</u>	<u>5</u>	<u>5</u>
	100	100	100

and economic forecast (low solar price). The maximum benefits points for market penetration available to each of these cases is 12.3 points. (Since each of the three cases contributing to market penetration benefits in the near term is given 12.3 maximum benefits points, the total maximum benefits points for market penetration is 37 in this time frame. This is the value derived from Table 26.) The largest quad factor which any solar technology receives from these three is 0.19 for SHACOB market forecast (base case), 0.19 for SHACOB market forecast (high electrification), and 1.6 for SHACOB economic forecast (low solar price).^{*} Dividing the available points for each case, 12.3 for each in this illustration, by the associated maximum quad factor yields the normalizing factors for the near term. For the other time periods, the normalizing factors follow a similar approach:

	Maximum <u>Points</u>	Normalizing <u>Factor</u>
<u>Intermediate term (2000)</u>		
Economic forecast - base case	15.0	3.6
Technical limit - base case	15.0	0.52
<u>Long term (2020)</u>		
Economic forecast - base case	9.3	1.4
Technical limit - base case	18.6	0.7

^{*}These numbers are actually results which will be discussed in more detail in the following chapter. They are used here simply to illustrate the methodology.

For example, the biomass intermediate-term (1985) economic forecast (base case) is 2.4 quads and the technical limit (base case) is 13.0 quads. Benefits for biomass intermediate-term market potential are calculated as follows:

$$\begin{array}{rcl} 2.4 \times 3.6 & = & 8.6 \\ 13.0 \times 0.52 & = & \underline{6.7} \\ \text{Total} & & 15.3 \end{array}$$

Benefits are calculated in a similar manner for each solar technology and category.

- Environmental Value--This value is intended to reflect the environmental benefits associated with the market penetration of a solar technology compared with other solar technologies each compared with competitive technologies. It is the product of a market penetration factor and a relative environmental factor. In other words, a technology receives no environmental points unless it is utilized. The market penetration factor is the fraction of possible points received in the following categories:

Near term (1985)	Economic forecast: low solar cost
Intermediate term (2000)	Economic forecast: base case
Long term (2020)	Technical limit: base case

The relative environmental factors are as follows:

<u>Near term (1985)</u>	<u>Major Reduction</u>	<u>Minor Reduction</u>
• Residuals except CO ₂	12.5	0
• Resource requirements	6.3	0
<u>Intermediate term (2000)</u>		
• Residuals except CO ₂	10.0	0
• Resource requirements	5.0	0
• CO ₂ emissions	10.0	0
<u>Long term (2020)</u>		
• Residuals except CO ₂	9.5	0
• Resource requirements	4.8	0
• CO ₂ emissions	14.3	0

For each solar technology the environmental benefits were assessed and relative environmental factors assigned for each category and period. Values between the high and low were assigned where appropriate. For example, the intermediate-term (2000) biomass relative environmental normalizing factors are:

• Residuals, except CO ₂	5.0
• Resource requirements	4.0
• CO ₂ emissions	10.0

The fraction of possible points for biomass in the intermediate term (1985), economic forecast (base case) is 8.6 out of 15.0 or 0.57. Benefits are calculated as follows:

Residuals, except CO ₂	0.57 x 5.0 =	2.9
Resource requirements	0.57 x 4.0 =	2.3
CO ₂ emissions	0.57 x 10.0 =	<u>5.7</u>
Total		10.9

- Insurance Value--This value is intended to reflect the capability of solar technologies to contribute in scenarios in which alternative fuel costs are high and alternative fuels availability is low. Benefits are calculated in the same manner as market penetration value and are based on the economic forecast - high nonsolar prices scenario. The normalizing factors are as follows:

	<u>Factor</u>
Near term (1985)	3.4
Intermediate term (2000)	3.1
Long term (2020)	1.2

- Speculative Value--This value is intended to reflect the long-term potential for significant market penetration by solar technologies. It recognizes the uncertainty in current forecasts. Benefits are calculated in the same manner as market penetration value and are based on the technical limit-high demand scenario. (The derivation of technical limits is described in the next section.) The normalizing factors are as follows:

	<u>Factor</u>
Near term (1985)	--
Intermediate term (2000)	0.2
Long term (2020)	0.3

- Conservation Value--This value is intended to reflect solar technologies' capability to reduce gas and liquid fuels requirements. Benefits are calculated in the same manner as market penetration value and are based on the gas/liquid technical limit-high demand scenario. The normalizing factors are as follows:

	<u>Factor</u>
Near term (1985)	1.4
Intermediate term (2000)	0.7
Long term (2020)	0.7

- Central/Decentral Value--This value is intended to recognize the historical emphasis on centralized technologies and give a corresponding credit to decentralized technologies. It is a product of a market penetration factor and a relative central/decentral factor. The market penetration factor is the fraction of possible points received in the following subcategories:

Near term (1985)	Economic forecast: low solar cost
Intermediate term (2000)	Economic forecast: base case
Long term (2020)	Technical limit: base case

The relative central/decentral factors are:

	<u>Central</u>	<u>Decentral</u>
Near term (1985)	0	6.3
Intermediate term (2000)	0	5.0
Long term (2020)	0	4.8

Values between the high and low were assigned to reflect the fact that many solar technologies are suitable for both types of installation. This approach is similar to that applied to calculate environmental benefits.

- International Value--This value is intended to reflect the benefits of international cooperation and an improved balance of payments. Each solar technology was reviewed and the potential for export of products or licensing of technology (export of expertise) was evaluated. Points were assigned as follows:

<u>Product Export</u>	<u>Yes</u>	<u>No</u>
Near term (1985)	3.1	0
Intermediate term (2000)	2.5	0
Long term (2020)	2.4	0
<u>Technology Export</u>		
Near term (1985)	3.1	0
Intermediate term (2000)	2.5	0
Long term (2020)	2.4	0

Intermediate values were assigned where appropriate.

Technical Limit

The technical limit rather than market penetration in a given scenario has been used as a factor to evaluate the speculative and conservation benefits of the solar technologies. As discussed in Section II, this approach was taken to assess the benefits that can be ascribed to these two values independent of a market projection. We discuss how these two technical limits were derived for each of the solar technologies. The reference scenario for these limits is the base case. All technical limits are expressed in quads of energy, fossil fuel equivalent.

Values Assigned to Technical Limit

The largest technical limit is for wind, 29 quads. This limit represents the entire peak and intermediate electricity market and 25 percent of the baseload market in 2020. Wind is permitted this share of the baseload market because wind energy systems have a resource available during the night. Although there are significant technical difficulties that must be overcome for wind to contribute in this degree to base power, the technical limit is chosen to represent a maximal contribution under favorable circumstances.

Solar heating receives 19 quads as its technical limit. This is 80 percent of the total heating load of buildings in the base case scenario in 2020. This is again an optimistic limit based on complete saturation of all buildings except an arbitrary 20 percent that is assumed to be unsuitable for solar heating.

Photovoltaic receives 17 quads as its technical limit. This is the total intermediate and peak electricity demand in 2020 for the base case. It is assumed that photovoltaic devices will not be able to penetrate the baseload market.

Thermal electric receives 10.3 quads as its technical limit. This is the total intermediate and peak electricity demand in all regions of the U.S. except the eastern seaboard and northern regions. The primary reason for the reduction in the size of the technical limit for thermal electric from that of photovoltaic is that thermal electric systems do not pick up diffuse light whereas photoelectric devices do. This significantly reduces the potential of thermal electric systems in regions of the nation for which solar insolation is less than the average. A secondary reason for reducing the technical limit of thermal electric relative to photovoltaic is that the former requires large, dedicated land areas that are not likely to be available in many parts of the nation. (Photovoltaic is assumed to be used on rooftops; wind energy systems are presumed to be sited on land that can also be devoted to other purposes, such as grazing.)

OTEC receives 14 quads as its technical limit. This is the total base load electricity in the South Atlantic, East South Central, and West South Central regions of the U.S. This assumes that OTEC plants would be located off the coast of Florida and could serve the eastern and southern portions of the U.S.

Biomass receives 13 quads as its technical limit. This is based on the analysis of the supply curve for biomass presented in Section VII of volume II. It represents the quantity of biomass that is thought to be available in 2020 at reasonably competitive prices with competing fuels.

Process heat receives 6.3 quads as its technical limit. This is 40 percent of the industrial demand for process heat in the base case

scenario in 2020. This factor was arrived at subjectively by allowing for the fact that most major industrial applications run at night and that solar systems are most likely to supply only low temperature heat for industrial application.

The technical limit is used in calculating the speculative value of the different solar systems. The maximum benefits points assigned to speculative are 5 in 2000 and 10 in 2020. As such, the benefits points given to wind are 10 in 2020. Photovoltaic receives 17/29 or about 0.6 times this number--a total of 6 benefits points in 2020.

Values Assigned to Gas/Oil Technical Limit

The gas/oil technical limit is needed to estimate the conservation value of the solar systems. This limit is expressed as a fraction of the overall technical limit discussed above. For photovoltaic and thermal electric, the fraction is 0.8 under the assumption that about 20 percent of the peak and intermediate market could be supplied by coal used in low Btu gas combined cycles. Approximately the same gas/oil technical limit was used for wind as for photovoltaic, under the assumption that the baseload electricity market is supplied by coal and nuclear fuel in 2020. For biomass, the fraction is 0.8 under the assumption that 20 percent of biomass is used to replace coal for direct heat applications in 2020. For solar heating, the fraction is 0.6, assuming that about 40 percent of the heating market is supplied by baseload electricity in 2020. For process heat, the fraction is 1.0. This is because the technical limit for process heat is only 40 percent of the market, leaving considerable flexibility to use solar to replace the highest priced sources of process heat--oil and gas. For OTEC, the fraction is 0.0 because all baseload electricity is presumed to be produced from coal and nuclear fuel in 2020.

Energy Supply/Demand/Price Scenarios

To ensure that the analysis adequately reflects the large number of uncertainties in future energy scenarios, four different future energy scenarios have been developed and used in the market penetration and technology ranking analysis. Each scenario presents a self-consistent framework of energy supply, demand, and prices, in which the various solar technologies are compared with one another. The four cases are the base case, or most likely scenario, a low solar price scenario, a high electrification-high demand scenario, and a high noncolar price scenario.

Base Case Scenario

The energy demands and alternative fuel prices contained in the base case scenario have been derived from data obtained from SRI's

National Energy Model calculations and from independent estimates of the U.S. energy outlook. (These estimates include information from Brookhaven National Laboratory, the FEA, the Ford Foundation, and others.)

The base case primary energy supply assumptions are summarized in Table 27 and Figure 15. The average annual growth in primary energy is 1.9 percent to the turn of the century, dropping to approximately 1.0 percent through the end of the study period, 2020. A complete description of the base case scenario is presented in the appendix to Volume II.

Table 27

BASE CASE PRIMARY ENERGY CONSUMPTION FOR THE TOTAL UNITED STATES
(Quadrillion Btu per Year)

	<u>1975</u>	<u>1985</u>	<u>2000</u>	<u>2020</u>
Coal	13.0	21	29-31.5	35-52
Domestic liquids	21.0	23	25	15
Imported liquids	13.0	15	15-15.5	15-21
Domestic gas	19.5	20	18	11
Imported gas	--	--	0-1	0-5.5
Nuclear fuel	1.5	6	17	34
Hydro and geothermal	3.0	4	5	6
Solar*	<u>0.5</u>	<u>1</u>	<u>4</u>	<u>9</u>
Total [†]	71.5	90	114.5-115.5	136.5-142

*These solar market penetration estimates are preliminary evaluations that do not reflect the results of the detailed market penetration analysis discussed in Section VII.

[†]The lower estimate for 2000 and 2020 corresponds to "moderate" growth of the synthetic fuels industry; the higher estimate corresponds to rapid growth of the synthetic fuels industry.

The solar market penetrations shown in Table 27 are only preliminary estimates that were used to calculate the dynamic effect of solar use on alternative fuel prices. They do not reflect the results of the market penetration analysis conducted in this study and described in Section VI.

Table 28 presents more detailed information on the base case end-use energy demand and the prices of end-use energy from energy sources competitive to solar energy. The quantities of energy shown here define

FIGURE 15. BASE CASE U. S. ENERGY CONSUMPTION
(1975, 1985, 2000, 2020)

Table 28

BASE CASE SCENARIO ENERGY DEMAND PRICES: END-USE MARKETS
IN WHICH SOLAR ENERGY TECHNOLOGIES COMPETE, 1985-2020

	Quads (End Use)			Nonsolar End-Use Prices* (in 1975 \$/MM Btu)		
	1985	2000	2020	1985	2000	2020
1. Industrial heat/high Btu gas	2.4	2.0	1.6	\$ 4.6	\$ 5.7	\$ 6.0
2. Industrial heat/coal	2.6	5.0	7.9	1.8	1.9	1.9
3. Industrial heat/liquids	1.8	1.6	1.6	4.3	4.9	5.4
4. R/C cooling/electricity [†]	3.2	5.7	7.7	4.0	4.7	5.2
5. R/C space heat/high Btu gas	2.6	3.2	3.4	4.0	5.2	5.5
6. R/C misc. heat/high Btu gas	2.0	2.5	2.7	5.6	7.2	7.7
7. R/C space heat/electricity	0.7	1.0	1.1	10.8	10.9	11.9
8. R/C misc. heat/electricity	0.3	0.4	0.5	10.8	10.9	11.9
9. R/C space heat/liquids	1.2	1.5	1.5	3.8	4.6	4.8
10. R/C misc. heat/liquids	0.4	0.5	0.5	5.2	6.4	6.7
11. R/C rural heat/LPG	0.6	0.8	0.8	4.5	5.1	5.5
12. R/C rural heat/distillate	0.6	0.5	0.5	3.8	4.6	4.8
13. R/C rural heat/electricity	0.4	0.3	0.3	10.8	10.9	11.9
14. Baseload electricity	6.8	10.3	14.4	9.0	9.7	9.8
15. Intermediate electricity	1.5	3.7	5.2	15.6	17.0	17.4

*Prices are those estimated for the mid-Atlantic region. Average prices are shown for the end use energy (e.g., for market number 1, the price is for heat, not high Btu gas), except for base load and intermediate electricity, where marginal prices at the bus bar (not including transmission and distribution costs) are quoted.

[†]Coefficient of performance of 3 taken for air conditioners.

the size of the end-use markets in which the various solar technologies compete, while the prices describe the competitive environment that solar energy faces in the market penetration calculations discussed earlier in this section. The demand quantities are listed as national totals. However, for the market penetration analysis, these demands are regionally disaggregated, and regional variations in the nonsolar end use prices are considered. More detail on the base case prices and quantities is found in the appendix to Volume II.

The base case solar energy prices were described in Section V in conjunction with each solar technology. These prices are further discussed and summarized in the market penetration section of Section VI.

Low Solar Price Scenario

The low solar price scenario makes the same assumptions about end use energy demand levels and alternative energy prices as does the base case scenario. The solar prices of this scenario, however, reflect a more optimistic outlook for cost reductions in the implementation of solar technologies. The estimated price reduction differs for each technology, reflecting the varying possibilities of price reduction. These optimistic solar prices are presented as a part of the sensitivity analysis of the next section.

High Electrification/High Demand Scenario

Growth rates of energy consumption depend on many complex and inter-related factors, many of which are difficult to predict accurately. Therefore, projections of future growth of energy demand are subject to a large measure of uncertainty. The high electrification/high demand scenario provides a means of considering this uncertainty. It investigates the effects of a situation in which energy consumption in general, and electric power demand in particular, rises at much more rapid rates than those of the base case scenario. Table 29 compares the difference in growth rates for several energy categories between these two scenarios.

To make this scenario self-consistent, the prices of alternative fuels are also assumed to rise more rapidly than in the base case. This change reflects the effect of an increased demand for energy commodities that are limited by resource or production capacity constraints.

High Nonsolar Price Scenario

The high nonsolar price scenario provides a means of considering the uncertainty in the price forecasts of the energy sources that compete against the various solar technologies. In this scenario, all the nonsolar prices are increased from those of the base case by a multiplier that varies with time. In the near term (1985), prices are raised by a

Table 29

COMPARISON OF AVERAGE ANNUAL GROWTH RATE ASSUMPTIONS
IN THE BASE CASE AND HIGH ELECTRIFICATION/HIGH DEMAND SCENARIOS

	<u>1975-2000</u>		<u>2000-2020</u>	
	<u>Base Case</u> <u>Scenario</u>	<u>High Elect./</u> <u>High Demand</u> <u>Scenario</u>	<u>Base Case</u> <u>Scenario</u>	<u>High Elect./</u> <u>High Demand</u> <u>Scenario</u>
Total energy demand	1.9 %	2.7 %	1.0 %	1.5 %
Electricity demand	3.3	4.4	1.7	2.2
R/C urban space heat	1.2	1.8	.9	1.8
R/C urban water heat	1.9	2.8	1.1	1.6
Industrial heat	1.8	3.0	1.3	1.8

factor of 1.25; in the intermediate term and the long term, 2000 and 2020, multipliers of 1.6 and 2.0 are used, respectively. These price increases are over and above those included in the base case. For this reason, this scenario represents an unexpectedly severe case as might accompany very serious failures to develop traditional energy supplies and/or unexpectedly serious environmental problems with traditional energy supplies.

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VI APPLICATION OF THE EVALUATION METHODOLOGY TO THE ASSESSMENT OF SOLAR ENERGY TECHNOLOGIES

Introduction

The objectives of this section are to:

- Apply the evaluation methodology (described in Section V) to integrate the vast amount of data pertinent to the assessment of the potential role of solar energy technologies in the context of alternative energy futures
- Summarize the most important results of this application
- Interpret these results as an aid to the Solar Working Group in its assessment of solar energy research priorities.

To achieve these objectives, the analysis was conducted in three distinct steps: (1) analysis of the potential solar energy market contribution, under the base case scenario conditions and under the other energy scenarios; (2) evaluation of the benefits of the solar energy technologies, under the assumptions of the benefits calculation methodology, the results of which are termed the "nominal benefits case;" and (3) the assessment of the sensitivity variables that could affect the relative contribution and benefits of the solar energy technologies.

The basic conclusions from the use of the evaluation methodology were derived through a careful study of these sensitivity analyses. Specifically, SRI attempted to provide a semiquantitative or qualitative assessment of the manner in which changes in these variables can affect the relative contribution and potential benefits of the solar energy technologies.

This evaluation methodology appropriately applied can provide useful insights into the solar energy RD&D priority process. At the same time, the limitations of the approach should be recognized. The evaluation methodology is meant to be a tool to guide one's judgment as to the relative benefits of different solar energy technology development options under a range of conditions. It is not a prediction. Because of the uncertainties in many of the data that are input into the evaluation methodology, its results should not be used without carefully selecting and analyzing applicable sensitivity cases and without exercising judgment in assessing the relative difficulties in achieving RD&D objectives for the different solar energy technologies.

Potential Market Contribution of Solar Energy Technologies

Market Description

The potential market contributions of the solar energy technologies have been obtained through the use of the market penetration model described in Section V. The input data to the model that dealt specifically with the different scenarios were also summarized, as well as the assumptions for distinguishing a market that responds rapidly to economic signals ("no behavioral lag" case) from a more realistic market that is expected to behave sluggishly to a new technology until its effectiveness, reliability, and other operating characteristics are proved ("behavioral lag" case). The input data summarizing the estimates of the price of energy in 1985, 2000, and 2020 from each solar technology are summarized in Table 30. To understand these numbers in the context of the total energy system, they are compared with the base case estimates of alternative energy prices in the same table. These estimates vary both by region of the country--they are shown for the mid-Atlantic region in Table 30--and by a specific market in which the technology is used.

Potential Market Contribution in the Base Case

Table 31 presents the potential solar energy contribution of the seven solar technologies evaluated for the base case scenario. The upper portion of the table contains the contributions with a behavioral lag parameter retarding the market response to the solar technologies in the years after initial commercial appearance of the technology. The lower portion of the table shows the potential contribution of the solar technologies in the base case without behavioral lag (i.e., under the hypothetical assumption of rapid market response to the changing economics of a new technology). The difference between the "behavioral lag" and "no behavioral lag" case, which is significant only for the near-term results, suggests the degree to which measures that the government or other parties might take to reduce market and institutional obstacles (e.g., to reduce the risk associated with purchasing an unproved technology) could increase the contribution of solar energy technologies. The "no behavioral lag" case for the near term is undoubtedly an overestimate of the near-term potential of the solar technologies, unless extraordinary measures are taken to promote solar energy.

The potential solar energy market contributions shown in Table 31 are not predictions. They indicate the degree to which the different solar energy technologies could contribute to U.S. energy supply under the base case scenario assumptions with best estimates of future solar energy costs and prices. The high degree of uncertainty surrounding the estimates of future solar energy technology costs should be recognized in the use of these results. Notwithstanding this uncertainty, several general conclusions can be drawn from the information contained in Table 31 (and the analysis that supported the data used in the model

Table 30

SOLAR AND ALTERNATIVE FUELS PRICE INPUT INTO MARKET PENETRATION MODEL
(1975 \$/MM Btu)*

Solar Technology (Central)	Base Case Solar Prices in Year			Competing Fuel Prices		
	1985	2000	2020	1985	2000	2020
				Electricity (intermediate at the bus bar):		
Photovoltaic (dispersed)	50	29	16	15.65	17.00	17.40
Photovoltaic (central)	55	31	19	15.65	17.00	17.40
Thermal electric (dispersed)	52	46	42	15.65	17.00	17.40
Thermal electric (central)	52	34	25	15.65	17.00	17.40
				Electricity (avg. base + intermediate fuel costs):		
Wind	9.00	8.40	8.20	7.30	7.80	7.60
				End-use cooling (electricity): [†]		
R/C air conditioning	25.00	16.00	16.00	4.30	4.90	5.40
				Oil:		
R/C water heating	6.50	5.25	5.20	5.20	6.40	6.70
				Gas:		
				5.60	7.20	7.70
				Electricity (delivered):		
				10.00	10.90	11.90
				Oil:		
R/C space heating	5.95	4.30	4.25	3.80	4.60	4.80
				Gas:		
				4.00	5.20	5.50
				Electricity (delivered):		
				10.80	10.90	11.90
				Coal:		
Industrial heat	13.20	10.80	9.60	1.80	1.90	1.90
				(Other sources not shown)		
				Coal:		
Biomass resource	Calculates biomass resource availability at competing coal prices			1.40	1.50	1.50
				Electricity (base at the bus bar):		
OTEC	23.00	18.40	16.40	8.95	9.70	9.80

*Prices quoted for mid-Atlantic region, except for OTEC, which is for the Southeast coastal regions.

[†]Coefficient of performance of 3 taken for air conditioning.

Table 31

POTENTIAL SOLAR ENERGY MARKET
CONTRIBUTION FOR THE BASE CASE SCENARIO

Base Case

Solar Penetration in Quads of Primary Energy Equivalent--
Behavioral Lag

	<u>Near Term (1985)</u>	<u>Intermed Term (2000)</u>	<u>Long Term (2020)</u>
Photovoltaic	.0	.0	3.4
Thermal elec	.0	.0	.0
Wind	.0	2.0	3.8
SHACOB	.2	4.0	6.7
Process heat	.0	.0	.1
Biomass	.2	2.1	5.1
OTEC	.0	.0	.0

Solar Penetration in Quads of Primary Energy Equivalent--
No Behavioral Lag

	<u>Near Term (1985)</u>	<u>Intermed Term (2000)</u>	<u>Long Term (2020)</u>
Photovoltaic	.0	.0	3.6
Thermal elec	.0	.0	.0
Wind	.1	2.3	3.9
SHACOB	1.3	4.1	6.7
Process heat	.0	.0	.1
Biomass	1.1	2.4	5.2
OTEC	.0	.0	.0

calculation). If conditions similar to those of the base case scenario prevail over time, then:

- In the near term (1985), SHACOB and biomass have the greatest potential of contributing to U.S. energy supply.
- Wind energy conversion systems also have the potential for energy supply in the near term.
- These three energy systems--SHACOB, biomass, and wind--have the greatest market potential in the intermediate-term (2000); SHACOB is estimated to have a greater market potential in the intermediate term than wind or biomass, if the base case cost estimates of SHACOB are realized.
- SHACOB, biomass, wind, and photovoltaic appear to have the greatest potential for the longer term (2020); however, the uncertainty in the cost data for the long term suggests that only limited confidence be placed on these results. In particular, the emergence of photovoltaic depends on the base case assumption that numerous technical and economic barriers to a commercial photovoltaic energy system will be overcome in time to permit the initial penetration of this technology shortly after the turn of the century.

These observations are summarized in Figure 16.

Potential Market Contribution: Sensitivity Cases

The base case can be described as the "most likely" scenario. However, as described in the previous sections, it is not the only scenario on which the benefits analysis is based. In fact, of the 15 different locations in the ranking process in which results of a scenario are utilized, the base case is used seven times, the high electrification case is used once, the low solar cost case is used four times, and the high alternative fuels cost case is used three times. The impact of a scenario is not directly proportional to the number of times it is used because of the weighting factors applied to the seven benefits values. Nevertheless, it is important to recognize the role of these other scenarios. The market penetrations for the three sensitivity scenarios are presented in Tables 32a, 32b, and 32c.

The major results from these cases are:

- In the low solar price case, the solar technology which changes the most from the base case is photovoltaics. This is due to the fact that more than any other solar technology, major breakthroughs are possible in photovoltaics. Wind, SHACOB, biomass, and process heat increase slightly (modest price reductions from base case are possible), whereas OTEC and thermal power show no change (i.e., even with price reductions, the technologies are still too expensive).

FIGURE *6. POTENTIAL SOLAR MARKET CONTRIBUTION: BASE CASE

Table 32

SOLAR MARKET POTENTIAL
IN SENSITIVITY CASE SCENARIOS

(a) Low Solar Price Case

	<u>Solar Penetration (In Quads of Primary Energy Equivalent)</u>		
	<u>Near Term (1985)</u>	<u>Intermed Term (2000)</u>	<u>Long Term (2020)</u>
Photovoltaic	.0	.5	10.9
Thermal elec	.0	.0	.0
Wind	.0	3.9	5.4
SHACOB	.2	4.4	7.0
Process heat	.0	.0	.2
Biomass	.3	2.3	5.4
OTEC	.0	.0	.0

(b) High Electrification, High Demand Case

	<u>Solar Penetration (In Quads of Primary Energy Equivalent)</u>		
	<u>Near Term (1985)</u>	<u>Intermed Term (2000)</u>	<u>Long Term (2020)</u>
Photovoltaic	.0	.0	9.9
Thermal elec	.0	.0	.0
Wind	.0	4.9	9.0
SHACOB	.2	4.7	9.3
Process heat	.0	.0	.4
Biomass	.2	2.2	6.6
OTEC	.0	.0	.0

(c) High Nonsolar Price Case

	<u>Solar Penetration (In Quads of Primary Energy Equivalent)</u>		
	<u>Near Term (1985)</u>	<u>Intermed Term (2000)</u>	<u>Long Term (2020)</u>
Photovoltaic	.0	1.6	8.1
Thermal elec	.0	.2	5.2
Wind	.4	6.5	8.7
SHACOB	.3	5.8	10.5
Process heat	.0	.2	.8
Biomass	.3	3.0	6.3
OTEC	.0	1.3	10.6

- The high electrification/high demand case has results qualitatively similar to the low solar cost case.
- The high nonsolar price case shows the greatest change from the base case. In this case, all the solar options come on strongly, even by the year 2000. Although this scenario might not be too likely, since it represents an extreme increase in the costs of alternative fuels, it shows that all the solar options could be important under conditions of very high alternative prices. In this scenario, many of these solar technologies (e.g., OTEC) have captured a majority of their reasonable market (i.e., they are approaching their technical limit).

Nominal Case Benefits Analysis^{*}

For the near and intermediate term, the nominal case benefits, derived from the application of the evaluation methodology presented in Section V are determined by the potential market contributions of the solar energy technologies as modified by the subjective factors that describe their potential benefits attributed to values of environmental, conservation, insurance, speculative, central/decentral, and international benefits. Many of these latter values are weighted in proportion to the market potential of solar technologies, because the benefits in many cases (e.g., environmental) do not accrue unless the technology has the potential of penetrating the market in the specified time frame. As such, the benefits values obtained for the solar technologies in the nominal case--for both near and intermediate term--are roughly proportional to their base case scenario potential market contribution. This proportionality does not obtain uniformly among the technologies for two reasons: (1) the technology benefits values depend on the market potential in scenarios other than the base case and (2) the market potential results are subjectively modified in determining benefits due to the values weighting. Thus, the benefits values contain more information than the potential market contribution results; but they are also more subjective in their meaning.

Table 33 shows the solar technologies ranked in each period for the nominal case. Tables 34 through 40 show the detailed benefits results by value for each technology group.

In the near and intermediate term, SHACOB, biomass, and wind clearly offer the highest potential benefits, primarily as a result of their current status of development and economics. Forecast improvements in

^{*}The term "base case" refers to a market penetration scenario. The term "nominal case" refers to an analysis of benefits that uses four market penetration scenarios to derive the benefits (weighting the base case scenario results most heavily).

the economics of photovoltaics make that technology an important potential source of benefits in the intermediate and long term. OTEC and thermal electric applications having the potential of some benefits in the long term, primarily because of the size of their possible markets and their value as insurance against very high future costs.

In the ensuing discussion, the effect of variations in assumptions concerning solar technologies and alternatives as well as alternative RD&D programs is presented.

Table 33

SOLAR TECHNOLOGIES RANKED BY BENEFITS
FOR THE NOMINAL CASE

Rank	Near Term (1985)		Intermediate Term (2000)		Long Term (2020)	
1	SHACOB	79.4	SHACOB	86.3	Wind	89.6
2	Biomass	67.6	Wind	78.1	SHACOB	73.1
3	Wind	67.0	Biomass	49.3	Photovoltaic	64.9
4	Photovoltaic	21.3	Photovoltaic	36.1	Biomass	47.5
5	Thermal elec	12.2	OTEC	17.0	OTEC	39.9
6	Process heat	9.7	Thermal elec	16.2	Thermal elec	34.5
7	OTEC	1.3	Process heat	10.7	Process heat	20.9

Changes in Solar Technology Benefits at Reduced Solar Costs

Analyzing Changes in Technology Benefits under Different Assumptions

The potential market contribution and the calculated benefits values of the solar technologies indicate the contributions and benefits anticipated if current solar energy RD&D activities are continued. The SWG is primarily interested in how these contributions and benefits might change with altered RD&D efforts. As such, this analysis evaluates how changes in solar technology benefits values can result from changes in emphasis and outcomes of the different solar RD&D programs. Insight into this issue is obtained through a consideration of the sensitivity of technology benefits values to potential cost reductions in the solar technologies that could be achieved through increased RD&D efforts.

Two sets of sensitivity cases are evaluated: one in which the cost reductions achieved for all solar technologies are an equal percentage to illustrate which technologies would yield the greatest benefits if equal relative RD&D successes were achieved for all technologies; one in which a presumed lower solar cost limit, different for each solar technology, is achieved, under relatively optimistic assumptions about RD&D successes in the solar programs. These two cases may bound the likely outcome of solar energy RD&D efforts.

Table 41 summarizes the approach to evaluating changes in solar technology benefits values. The changes in benefits resulting from

Table 34

RANKING VALUES FOR PHOTOVOLTAIC DEVICES

	NEAR TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.0	10.0	.0	.0	-0.0	0.0	3.4	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.0	10.0	.0	.0	-0.0	0.0	9.9	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	.0	10.0	.0	1.0	-0.0	0.0	11.7	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	.0	-0.0	0.0	.0	15.0	.1	3.6	10.0	5.4
TECHNICAL LIMIT (BASE CASE)	17.0	-0.0	0.0	17.0	15.0	8.8	17.0	20.0	11.7
CATEGORY TOTAL			.0			8.9			17.1
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	.0	10.0	.0	.1	10.0	.0	11.7	10.0	5.9
RESOURCE REQUIREMENTS	.0	5.0	.0	.1	5.0	.0	11.7	5.0	2.9
CO2 EMISSIONS				.1	10.0	.0	11.7	15.0	8.8
CATEGORY TOTAL			.0			.1			17.6
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	.0	10.0	.0	3.3	20.0	10.2	8.5	15.0	11.3
4. SPECULATIVE									
TECHNICAL LIMIT	17.0	-0.0	0.0	17.0	5.0	2.9	17.0	10.0	5.9
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	14.0	15.0	15.0	14.0	10.0	10.0	14.0	10.0	10.0
6. CENTRAL/DECENTRAL									
DECENTRAL	.0	4.0	.0	.1	4.0	.0	11.7	4.0	2.3
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		2.0	2.0		2.0	2.0
EXPERTISE EXPORT		2.0	2.0		2.0	2.0		2.0	2.0
CATEGORY TOTAL			2.0			4.0			4.0
TECHNOLOGY TOTAL			17.0			30.1			68.2
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			21.3			35.1			64.9

Table 35

RANKING VALUES FOR THERMAL ELECTRICITY

	NEAR TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	.0	-0.0	0.0	.0	15.0	.0	.0	10.0	.0
TECHNICAL LIMIT (BASE CASE)	10.3	-0.0	0.0	10.3	15.0	5.3	10.3	20.0	7.1
CATEGORY TOTAL			.0			5.3			7.1
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	.0	10.0	.0	.0	10.0	.0	7.1	10.0	3.6
RESOURCE REQUIREMENTS	.0	3.0	.0	.0	3.0	.0	7.1	3.0	1.1
CO2 EMISSIONS				.0	10.0	.0	7.1	15.0	5.3
CATEGORY TOTAL			.0			.0			9.9
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	.0	10.0	.0	.4	20.0	1.2	5.0	15.0	6.7
4. SPECULATIVE									
TECHNICAL LIMIT	10.3	-0.0	0.0	10.3	5.0	1.8	10.3	10.0	3.6
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	8.2	15.0	8.8	8.2	10.0	5.9	8.2	10.0	5.9
6. CENTRAL/DECENTRAL									
DECENTRAL	.0	3.0	.0	.0	3.0	.0	7.1	3.0	1.1
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		1.0	1.0		1.0	1.0
EXPERTISE EXPORT		1.0	1.0		1.0	1.0		1.0	1.0
CATEGORY TOTAL			1.0			2.0			2.0
TECHNOLOGY TOTAL			9.8			16.2			36.2
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			12.2			16.2			34.5

Table 36

RANKING VALUES FOR WIND

	NEAR TERM (1995)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.6	10.0	.1	2.0	-0.0	0.0	3.8	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.6	10.0	.2	4.9	-0.0	0.0	9.0	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	1.6	10.0	9.6	4.1	-0.0	0.0	5.6	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	.1	-0.0	0.0	2.3	15.0	8.5	3.9	10.0	5.9
TECHNICAL LIMIT (BASE CASE)	29.0	-0.0	0.0	29.0	15.0	15.0	29.0	20.0	20.0
CATEGORY TOTAL			9.9			23.5			25.9
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	9.6	10.0	9.6	3.5	10.0	5.7	20.0	10.0	10.0
RESOURCE REQUIREMENTS	9.6	4.0	3.8	8.5	4.0	2.3	20.0	4.0	4.0
CO2 EMISSIONS				8.5	10.0	5.7	20.0	15.0	15.0
CATEGORY TOTAL			13.4			13.7			29.0
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	3.7	10.0	10.0	6.5	20.0	20.0	6.7	15.0	11.6
4. SPECULATIVE									
TECHNICAL LIMIT	29.0	-0.0	0.0	29.0	5.0	5.0	29.0	10.0	10.0
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	13.5	15.0	14.5	13.5	10.0	9.6	13.5	10.0	9.6
6. CENTRAL/DECENTRAL									
DECENTRAL	9.6	4.0	3.8	8.5	4.0	2.3	20.0	4.0	4.0
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		2.0	2.0		2.0	2.0
EXPERTISE EXPORT		2.0	2.0		2.0	2.0		2.0	2.0
CATEGORY TOTAL			2.0			4.0			4.0
TECHNOLOGY TOTAL			53.6			78.1			94.1
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			67.0			78.1			89.6

Table 37
RANKING VALUES FOR SHACOB

	NEAR TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	1.2	10.0	7.3	4.0	-0.0	0.0	6.7	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	1.2	10.0	8.0	4.7	-0.0	0.0	9.3	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	1.6	10.0	10.0	4.5	-0.0	0.0	7.0	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	1.3	-0.0	0.0	4.1	15.0	15.0	6.7	10.0	10.0
TECHNICAL LIMIT (BASE CASE)	19.0	-0.0	0.0	19.0	15.0	9.8	19.0	20.0	13.1
			----			----			----
CATEGORY TOTAL			25.2			24.8			23.1
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	10.0	10.0	10.0	15.0	10.0	10.0	13.1	10.0	6.6
RESOURCE REQUIREMENTS	10.0	5.0	5.0	15.0	5.0	5.0	13.1	5.0	3.3
CO2 EMISSIONS			----	15.0	10.0	10.0	13.1	15.0	9.8
			----			----			----
CATEGORY TOTAL			15.0			25.0			19.7
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	1.9	10.0	5.1	5.9	20.0	18.0	10.6	15.0	14.0
4. SPECULATIVE									
TECHNICAL LIMIT	19.0	-0.0	0.0	19.0	5.0	3.3	19.0	10.0	6.6
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	11.4	15.0	12.2	11.4	10.0	8.1	11.4	10.0	8.1
6. CENTRAL/DECENTRAL									
DECENTRAL	10.0	5.0	5.0	15.0	5.0	5.0	13.1	5.0	3.3
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		1.0	1.0		1.0	1.0
EXPERTISE EXPORT		1.0	1.0		1.0	1.0		1.0	1.0
			----			----			----
CATEGORY TOTAL			1.0			2.0			2.0
			----			----			----
TECHNOLOGY TOTAL			53.5			86.3			76.8
			----			----			----
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			79.4			86.3			73.1

Table 38

RANKING VALUES FOR AGRICULTURAL AND INDUSTRIAL PROCESS HEAT

	NEAR TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.0	10.0	.0	.0	-0.0	0.0	.1	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.0	10.0	.0	.0	-0.0	0.0	.4	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	.0	10.0	.0	.0	-0.0	0.0	.2	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	.0	-0.0	0.0	.0	15.0	.0	.1	10.0	.2
TECHNICAL LIMIT (BASE CASE)	6.3	-0.0	0.0	6.3	15.0	3.3	6.3	20.0	4.3
CATEGORY TOTAL			0.0			3.3			4.5
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	.0	10.0	.0	.0	10.0	.0	4.3	10.0	2.2
RESOURCE REQUIREMENTS	.0	5.0	.0	.0	5.0	.0	4.3	5.0	1.1
CO2 EMISSIONS				.0	10.0	.0	4.3	15.0	3.3
CATEGORY TOTAL			0.0			0.0			6.5
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	.0	10.0	.0	.3	20.0	.8	.8	15.0	1.1
4. SPECULATIVE									
TECHNICAL LIMIT	6.3	-0.0	0.0	6.3	5.0	1.1	6.3	10.0	2.2
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	6.3	15.0	6.7	6.3	10.0	4.5	6.3	10.0	4.5
6. CENTRAL/DECENTRAL									
DECENTRAL	.0	5.0	.0	.0	5.0	.0	4.3	5.0	1.1
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		0.0	0.0		1.0	1.0
EXPERTISE EXPORT		1.0	1.0		1.0	1.0		1.0	1.0
CATEGORY TOTAL			1.0			1.0			2.0
TECHNOLOGY TOTAL			7.8			10.7			21.9
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			5.7			10.7			20.9

Table 39

RANKING VALUES FOR BIOMASS

	NEAR TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.2	10.0	10.0	2.1	-0.0	0.0	5.1	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.2	10.0	10.0	2.2	-0.0	0.0	6.6	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	1.3	10.0	7.8	2.6	-0.0	0.0	5.4	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	1.1	-0.0	0.0	2.4	15.0	8.6	5.2	10.0	7.7
TECHNICAL LIMIT (BASE CASE)	13.0	-0.0	0.0	13.0	15.0	6.7	13.0	20.0	9.0
CATEGORY TOTAL			27.8			15.3			16.7
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	7.8	5.0	3.9	8.6	5.0	2.9	9.0	5.0	2.2
RESOURCE REQUIREMENTS	7.8	5.0	3.9	8.6	4.0	2.3	9.0	3.0	1.3
CO2 EMISSIONS				8.6	10.0	5.7	9.0	15.0	6.7
CATEGORY TOTAL			7.8			10.9			10.3
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON SOLAR)	1.5	10.0	3.9	3.3	20.0	10.1	6.4	15.0	8.5
4. SPECULATIVE									
TECHNICAL LIMIT	10.4	-0.0	0.0	10.4	5.0	1.8	10.4	10.0	3.6
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	10.4	15.0	11.1	10.4	10.0	7.4	10.4	10.0	7.4
6. CENTRAL/DECENTRAL									
DECENTRAL	7.8	3.0	2.4	8.6	3.0	1.7	9.0	3.0	1.3
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		1.0	1.0		1.0	1.0
EXPERTISE EXPORT		1.0	1.0		1.0	1.0		1.0	1.0
CATEGORY TOTAL			1.0			2.0			2.0
TECHNOLOGY TOTAL			54.1			49.3			49.8
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			67.6			49.3			47.5

Table 40

RANKING VALUES FOR OTEC

	SHORT TERM (1985)			INTERMED TERM (2000)			LONG TERM (2020)		
	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS	QUAD FACTOR	MAX POINTS	BENEFITS
1. MKT PENETRATION									
MKT FORECAST (BASE CASE)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
MKT FORECAST (HIGH ELECTRIFICATION)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
ECONOMIC FORECAST (LOW SOLAR PRICE)	.0	10.0	.0	.0	-0.0	0.0	.0	-0.0	0.0
ECONOMIC FORECAST (BASE CASE)	.0	-0.0	0.0	.0	15.0	.0	.0	10.0	.0
TECHNICAL LIMIT (BASE CASE)	14.0	-0.0	0.0	14.0	15.0	7.2	14.0	20.0	9.7
CATEGORY TOTAL			.0			7.2			9.7
2. ENVIRONMENTAL									
RESIDUALS EXCEPT CO2	.0	10.0	.0	.0	10.0	.0	9.7	10.0	4.8
RESOURCE REQUIREMENTS	.0	1.0	.0	.0	1.0	.0	9.7	2.0	1.0
CO2 EMISSIONS				.0	5.0	.0	9.7	7.5	3.6
CATEGORY TOTAL			.0			.0			9.4
3. INSURANCE									
ECONOMIC FORECAST (HIGH NON-SOLAR)	.0	10.0	.0	1.7	20.0	5.3	11.3	15.0	15.0
4. SPECULATIVE									
TECHNICAL LIMIT	14.0	-0.0	0.0	14.0	5.0	2.4	14.0	10.0	4.8
5. CONSERVATION									
GAS/LIQUID-TECHNICAL LIMIT	0.0	15.0	0.0	0.0	10.0	0.0	0.0	10.0	0.0
6. CENTRAL/DECENTRAL									
DECENTRAL	.0	2.0	.0	.0	2.0	.0	9.7	2.0	1.0
7. INTERNATIONAL									
PRODUCT EXPORT		-0.0	-0.0		1.0	1.0		1.0	1.0
EXPERTISE EXPORT		1.0	1.0		1.0	1.0		1.0	1.0
CATEGORY TOTAL			1.0			2.0			2.0
TECHNOLOGY TOTAL			1.0			17.0			41.9
NORMALIZED TECHNOLOGY TOTAL TO A MAXIMUM OF 100 POINTS			1.3			17.0			39.9

solar cost reductions depend on market penetration, environmental, insurance, and central/decentral benefits values in the nominal and reduced solar cost cases. The changes do not depend on speculative, international, or conservation benefits values, because these latter terms are evaluated from the technical limits for the solar technologies and the technical limits are unaltered by reduced solar energy prices.

Table 41

METHOD OF ESTIMATING CHANGE IN SOLAR TECHNOLOGY
BENEFIT VALUES WITH CHANGES IN SOLAR COSTS

Definition

$$\Delta \text{ Benefits (Y)} = \text{Benefits (Y Percent Solar Cost Reduction)} \\ - \text{Benefits (Nominal Solar Costs)}$$

Therefore,

Δ Benefits Measures the Change In

- Market Penetration
- Environmental
- Insurance
- Central/Decentral

Values for Each Solar Technology Resulting from Specified
Solar Cost Reductions

Changes in Benefits Values at Uniform Percentage Solar Cost Reduction

The evaluation of changes in technology benefits values for a uniform reduction in nominal solar costs is done in a straightforward manner: nominal case benefits values are calculated; then the costs and prices of each of the solar technologies are reduced by the same percentage and the benefits values of the technologies are recalculated; finally, the differences in benefits between the two cases is obtained by subtracting the results.

Results of the evaluation of a decrease in solar costs of 5, 10, and 20 percent for each solar energy technology are shown in Tables 42 through 44. Table 42 contains the changes in benefits values for the near term; Table 43, for the intermediate term; and Table 44, for the long term. The conclusions from these results are that:

- In the near term, a 5 to 20 percent reduction in nominal solar costs could significantly increase the potential benefits of biomass, SHACOB, and wind.

- In the intermediate term, this reduction in nominal solar costs could result in the largest increase in potential benefits of wind.
- In the long term, little differentiation in potential benefits of solar technologies is apparent if the same cost reduction is achieved for all solar technologies.

Table 42

CHANGES IN SOLAR TECHNOLOGY BENEFITS POINTS
FROM NOMINAL CASE WITH 5, 10, AND 20 PERCENT
COST REDUCTIONS - NEAR TERM, 1985

<u>Technology</u>	Δ Benefit Points At		
	<u>5% Solar Cost Reduction</u>	<u>10% Solar Cost Reduction</u>	<u>20% Solar Cost Reduction</u>
Photovoltaic	0	0	0
Thermal electric	0	0	0
Wind	1.2	3.1	10.8
SHACOB	1.9	3.9	8.4
Process heat	0	0	0
Biomass	2.7	5.5	10.6
OTEC	0	0	0

Table 43

CHANGES IN SOLAR TECHNOLOGY BENEFITS POINTS
FROM NOMINAL CASE WITH 5, 10, AND 20 PERCENT
COST REDUCTIONS - INTERMEDIATE TERM, 2000

<u>Technology</u>	Δ Benefit Points At		
	<u>5% Solar Cost Reduction</u>	<u>10% Solar Cost Reduction</u>	<u>20% Solar Cost Reduction</u>
Photovoltaic	1.4	2.8	5.7
Thermal electric	0.7	1.7	4.7
Wind	7.2	13.5	21.1
SHACOB	1.8	3.7	7.8
Process heat	0.2	0.5	1.3
Biomass	1.3	2.4	5.2
OTEC	1.5	3.1	6.6

Table 44

CHANGES IN SOLAR TECHNOLOGY BENEFITS
FROM NOMINAL CASE WITH 5, 10, AND 20 PERCENT
COST REDUCTIONS - LONG TERM, 2020

Technology	Δ Benefit Points At		
	5% Solar Cost Reduction	10% Solar Cost Reduction	20% Solar Cost Reduction
Photovoltaic	0.7	1.5	3.6
Thermal electric	0.4	0.8	1.4
Wind	0.7	1.5	3.0
SHACOB	0.6	1.3	2.8
Process heat	0.1	0.2	0.4
Biomass	0.3	0.6	1.2
OTEC	0.6	1.2	2.0

Changes in Benefit Values with "Optimistic" Solar Cost Reductions
from Nominal Solar Cost Projection Levels

In this calculation, the solar technology cost projections from the nominal case are reduced by a variable percentage to reflect the potential for differing cost reductions of the solar technologies under "optimistic" RD&D outcomes for solar energy. No precise rationale can be formulated for these estimated solar energy cost reductions, shown for each of the seven generic technologies in Table 45--other than that they represent educated guesses about solar systems whose design reflects relatively advanced ideas and concepts (see Section IV). A basic feature of the "optimistic" case of Table 45 is that photovoltaic is judged to have the greatest potential for cost reductions below the nominal case cost projections around the year 2000 and thereafter. This is a reasonable possibility, because advances in electronics research could yield large cost reductions in photovoltaics; research advances resulting in similar solar cost reductions for the other solar technologies are much harder to imagine.

The issue then is the effect of an "optimistic" outcome of solar research and development on the change in the benefits values of the solar technologies from those of the nominal case. The results of the calculations of the "optimistic" solar cost reduction case are shown in Table 46. To the extent that this case is a reasonable projection of "optimistic" RD&D outcomes--the assessment of the state of the art in Section IV provides some support for this case--these results suggest that:

- In the near term, additional RD&D to reduce solar costs and market resistance to new technologies has the greatest potential for increasing the potential benefits of SHACOB, wind and biomass.

- In the intermediate term (2000), additional RD&D to reduce solar costs could yield the greatest increases in the potential benefits of photovoltaic and wind and could yield moderate increases in potential benefits of SHACOB.
- In the long term (2020), additional RD&D could yield the greatest increases in the potential benefits of photovoltaic.

Table 45

"OPTIMISTIC" SOLAR COST REDUCTIONS
FROM NOMINAL SOLAR COSTS BASED ON ASSUMPTIONS
DERIVED FROM CURRENT STATE OF THE ART

	Percent Cost Reduction from Nominal Solar Costs for the Same Year		
	(1985)	(2000)	(2020)
Photovoltaic	10%	42%	39%
Thermal electric	10	10	10
Wind	12	12	12
SHACOB	13	8	7
Process heat	8	11	0
Biomass	10	10	10
OTEC	0	7	7

Table 46

CHANGES IN SOLAR TECHNOLOGY BENEFITS POINTS
FROM NOMINAL CASE WITH "OPTIMISTIC"
SOLAR COST REDUCTIONS

	Δ Benefits Points		
	Near Term (1985)	Intermediate Term (2000)	Long Term (2020)
Photovoltaic	0	18.4	11.1
Thermal electric	0	1.4	0.5
Wind	7.1	15.9	2.3
SHACOB	8.4	4.8	1.3
Process heat	0	0.6	0.1
Biomass	5.5	1.9	0.6
OTEC	0	1.5	0.7

Sensitivity Cases

Sensitivity cases provide a means to assess the degree to which the conclusions stated in this section depend on key variables and assumptions of the evaluation methodology. Four key parameters that could significantly affect the results are:

- The ranking weights
- Behavioral lag parameters
- Capital recovery factor
- Solar cost projections.

Numerous sensitivity calculations have been performed to test the effects of variations in these parameters. The most important of the sensitivity results are summarized here.

Ranking Weights

The choice of ranking weights has little effect on the conclusions in this section, within a broad range of weight selection. For example, the sensitivity run on ranking weights suggested by a member of the SWG in which market weights decrease over time, conservation weights are high in the near term, and central/decentral and speculative weights increase over time resulted in no change in the grouping of technologies by benefits values and an insignificant change in Δ benefits points (indicative of the effect of lower solar prices in the nominal and sensitivity cases). Other sensitivity runs have verified this result.

Behavioral Lag Parameters

Altering behavioral lag parameters produced changes in the potential market contributions for SHACOB and biomass in the near term. Sensitivity calculations on behavioral lag parameters resulted in no significant changes in any conclusions related to the technology benefits evaluations.

Capital Recovery Factor

Changes in assumptions about the value of the capital recovery factor for the three economic sectors relevant to the assessment (R/C, utility, and industrial) have a significant effect on the results of the analysis. Specifically, the results of a sensitivity case in which a uniform capital recovery factor was used in all three sectors were compared with a nominal case (in which the magnitude of the capital recovery factor declines from industrial to utility to R/C sector). This comparison permits the conclusions that:

- The potential market contribution and benefits results for the solar energy technologies are strongly influenced by the differences of capital costs among sectors.
- If the nominal case assumptions about capital recovery factor (CRF) differences among sectors is correct, then equalizing CRFs for all sectors would in the intermediate term:
 - Increase the potential market contribution and benefits of solar systems competing in markets whose capital recovery factor is now estimated to be relatively high (i.e., industrial process heat).
 - Decrease the potential market contribution and benefits of systems competing in the residential/commercial markets, where the capital recovery factor is estimated to be relatively low (i.e., SHACOB).
 - Increase (or decrease) the benefits solar electric options, depending on whether the uniform CRF is lower (or higher) than the CRF assumed for the utility sector. The solar electric option most greatly affected is wind, because the economic estimator put it so close to the competitive range.

Solar Cost Projections

The potential market contribution results are highly sensitive to solar cost projections. In the intermediate term, wind appears to be most sensitive, because the nominal-case wind prices put wind just within the competitive range in this time frame.

The changes in technology benefits values for a reduction in nominal solar costs depend on solar cost projections in two basic ways:

- If the "nominal" cost of energy from a solar technology is estimated to be near or in the competitive range (as it is for wind, SHACOB, and biomass in the intermediate term; for these three and photovoltaic in the long term), then increasing the cost projections to levels significantly above this range reduces calculated benefits points.
- If the "optimistic" solar cost projection is estimated to be near or in the competitive range and is increased to be outside this range, then the change in benefits values between the nominal and "optimistic" cases is reduced. Under reasonable assumptions, this condition might occur for photovoltaic.

Conclusion

Based on the sensitivity runs that have been performed, most of or all results of the evaluation methodology appear to be relatively resilient in terms of the effect that reasonable sensitivity cases exert on them. However, the large uncertainty in solar cost projections means that even the most complete analysis of solar RD&D priorities can at best yield insights that need to be frequently reassessed as more information about solar energy technologies is gained and evaluated and as advances in solar energy technology through research, development, and demonstration are made.