

SOLAR ENERGY AS A NATIONAL ENERGY RESOURCE

NSF/NASA SOLAR ENERGY PANEL

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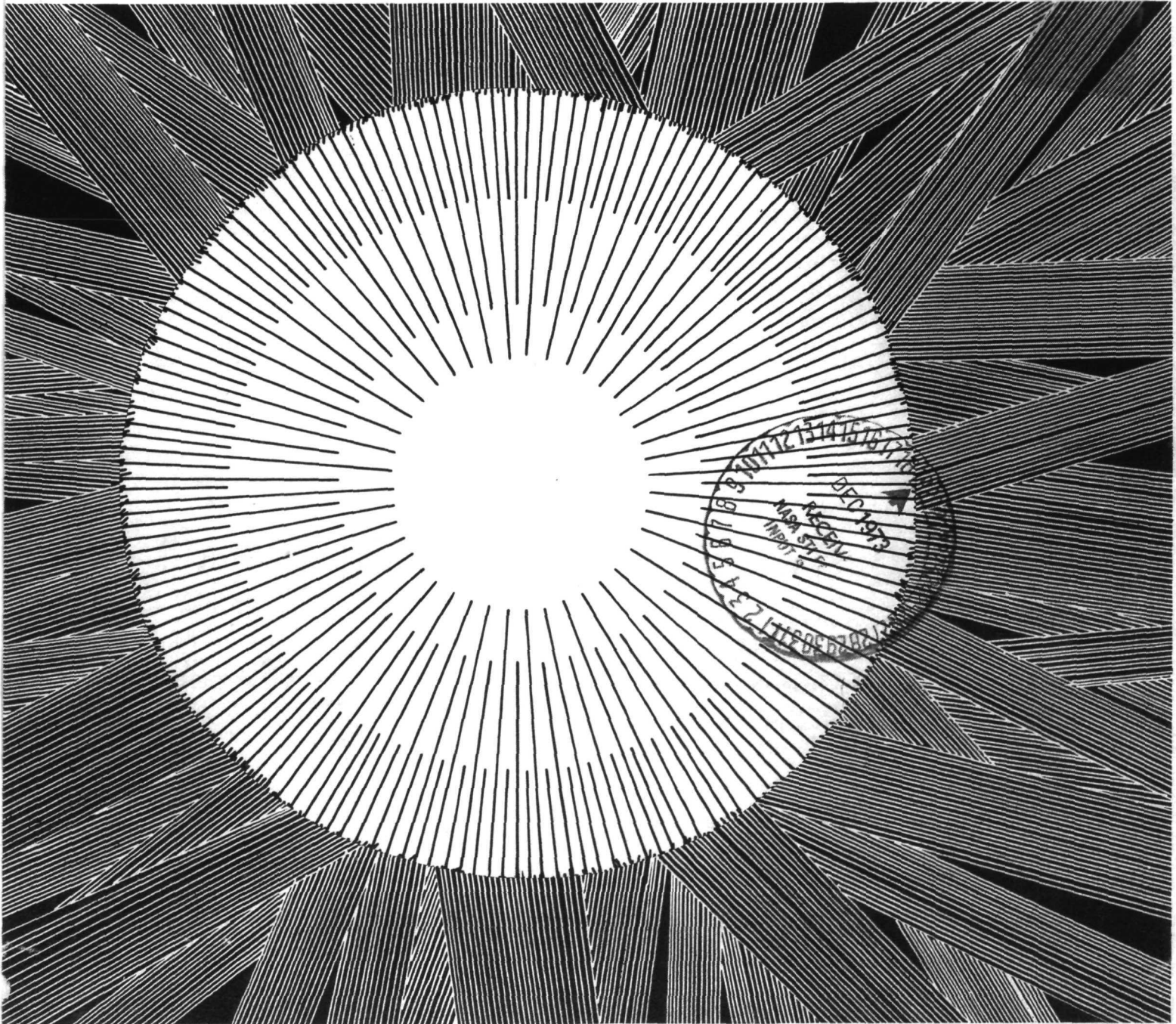
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**AN ASSESSMENT OF SOLAR ENERGY
AS A NATIONAL ENERGY RESOURCE**

PREPARED BY THE

NSF/NASA SOLAR ENERGY PANEL

Dr. Paul Donovan, Co-Chairman
Mr. William Woodward, Co-Chairman
Mr. William R. Cherry, Executive Secretary
Dr. Frederick H. Morse, Technical Coordinator
Dr. Lloyd O. Herwig, Executive Committee

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Any opinions, findings, conclusions or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the United States government or the agencies represented on this Panel.

NSF/NASA SOLAR ENERGY PANEL

CO-CHAIRMEN

Dr. Paul Donovan – NSF
Mr. William Woodward – NASA

EXECUTIVE COMMITTEE

Mr. William R. Cherry – NASA, Executive Secretary
Dr. Frederick H. Morse – University of Maryland, Technical Coordinator
Dr. Lloyd O. Herwig – NSF

SUBPANEL CHAIRMEN

Bioconversion – Prof. Martin D. Kamen, University of California
Thermal Space Conditioning – Dr. Jerome Weingart, California Institute of Technology
Photovoltaics – Prof. Martin Wolf, University of Pennsylvania
Unique Systems – Prof. Robert L. Bailey, University of Florida
Central Electric Power – Dr. Friedolf M. Smits, Bell Telephone Laboratories

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Environmentalist: Dr. James McKenzie – National Audubon Society, Massachusetts
Psychologist: Prof. Raymond Bauer – Harvard Business School
Sociologist: Prof. Samuel Klausner – University of Pennsylvania
Industrialist: Mr. Paul Rappaport – RCA Research Center

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INTRODUCTION

The Solar Energy Panel was organized jointly by the NSF and NASA in January 1972, and comprised of nearly 40 scientists and engineers possessing expertise in solid state physics, chemistry, microbiology, power engineering, architecture, photovoltaics, and the thermal sciences as well as several economists, environmentalists, and sociologists (see Appendix B). The Panel was charged with assessing the potential of solar energy as a national energy resource and the state of the technology in the various solar energy application areas, and with recommending necessary research and development programs to develop the potential in those areas considered important. The scope of the Panel's activities was defined to include all applications of direct solar energy, as well as power from wind, ocean thermal differences, and useful energy from replenishable organic materials. This report presents the findings of the Panel.

Current projections [1] of the total U.S. energy demand, see Figure 1, show a growth from approximately 64×10^{15} BTU in 1969 to nearly 300×10^{15} BTU in the year 2020. A significant portion of this increase is projected to be derived from nuclear energy, with the rest being supplied by fossil fuels some of which are being rapidly depleted. In view of the Nation's and the world's growing concern with environmental and health/safety factors as well as our anticipated increasing dependence on imported petroleum and gaseous fuels, it is important to evaluate the potential impact of solar energy utilization, since it is an inexhaustible source of enormous amounts of clean energy [2].

The average yearly incidence of solar energy in space and on the ground in the continental U.S. is:

In near-earth space	130 thermal watts/ft. ²
On the ground (average)	17 thermal watts/ft. ²

The 17 thermal watts/ft.² results in an average daily (24 hour) energy supply of 410 thermal watt-hours/ft.². This value is approximately twice the amount needed to heat and cool an average house. Converting the 17 thermal watts/ft.² into electricity at a 10% conversion efficiency would result in an average daily electric output of approximately 1,140,000 kilowatt-hours per square mile. In 1969, the Potomac Electric Power Company sold a daily average of 30,000,000 kilowatt-hours to 425,000 customers in an area encompassing 643 square miles. Within 27 square miles or about 4% of the above PEPCO serviced area devoted to a solar electric generation system, PEPCO could in principle provide the necessary electric power. Under the same assumption of a 10% conversion efficiency and U.S. average solar incidence, in 1969 the total electric energy consumed in the U.S. could have been supplied by the solar energy incident on 0.14% of the U.S. land area.

There has been little Federal support of solar energy utilization other than for powering artificial satellites. Commercial and philanthropic support of solar power generation has been almost negligible. Programs in Australia, the USSR, France, and Israel have all substantially exceeded U.S. effort. In principle, solar energy can be used for any energy need now being met by conventional fuels [3]. Three broad applications have been identified by the panel as most promising from technical, economic, and energy quantity standpoints. These are: (1) the heating and cooling of residential and commercial buildings, (2) the chemical and biological conversion of organic materials to liquid, solid, and gaseous fuels, and (3) the generation of electricity. The Applications chapter of the report is organized into three primary sections corresponding to these broad application areas. Within each section, one or more methods or processes for

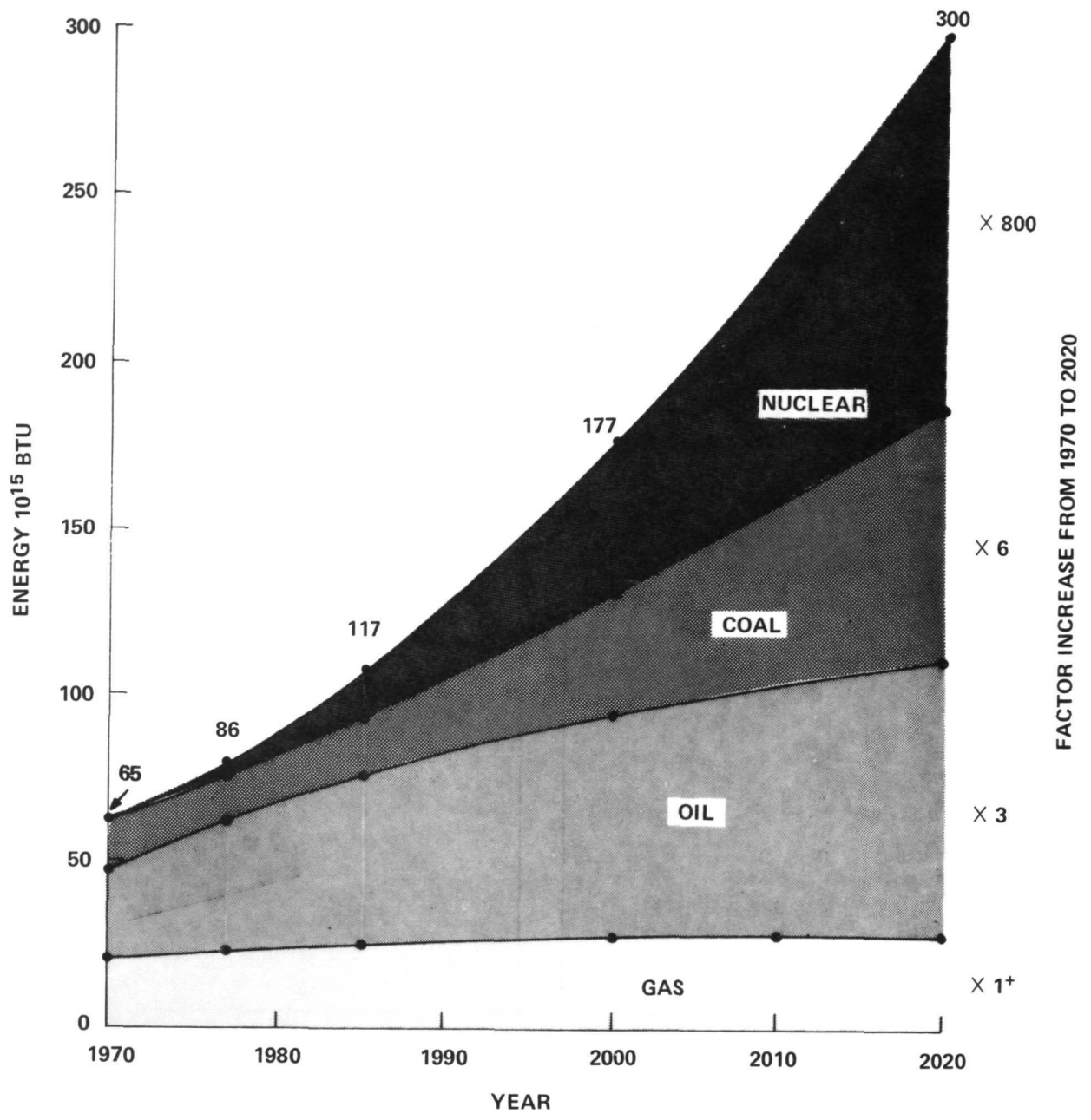


FIGURE 1. PROJECTED U.S. ENERGY DEMAND BY SOURCE [1]

converting solar energy to the desired form are presented in the following format:

- Description of Concepts
- Status
- Limiting Factors and Recommended Approaches
- Goals and Projected Impacts
- Short Range (3 year) R&D Program Recommendation
- Long Range (10-15 year) R&D Program Recommendation
- Phased Program Plan

The Panel is confident that solar energy can be developed to meet sizable portions of the Nation's future energy needs. This report is

intended to document this confidence. It must be recognized, however, that severe time limitations prevented a thorough and critical formulation and review of the technology, economics, relative prospects, and development tasks in each concept. Closer study is expected to eliminate certain areas from further attention, while some new and promising approaches may be added. A more detailed, in-depth examination of these and other methods for converting solar energy to useful forms is high on the agenda of our recommended research and development program. An introduction to the potential and uses of solar energy may be found in references [4] & [5].

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

- Solar energy is received in sufficient quantity to make a major contribution to the future U.S. heat and power requirements.

- There are numerous conversion methods by which solar energy can be utilized for heat and power, e.g., thermal, photosynthesis, bioconversion, photovoltaics, winds, and ocean temperature differences.

- There are no technical barriers to wide application of solar energy to meet U.S. needs.

- The technology of terrestrial solar energy conversion has been developed to its present limited extent through very modest government support and some private funding.

- For most applications, the cost of converting solar energy to useful forms of energy is now higher than conventional sources, but due to increasing prices of conventional fuels and increasing constraints on their use, it will become competitive in the near future.

- A substantial development program can achieve the necessary technical and economic objectives by the year 2020. Then solar energy could economically provide up to (1) 35% of the total building heating and cooling load; (2) 30% of the Nation's gaseous fuel; (3) 10% of the liquid fuel; and (4) 20% of the electric energy requirements.

- If solar development programs are successful, building heating could reach public use within 5 years, building cooling in 6 to 10 years, synthetic fuels from organic materials in 5 to 8 years, and electricity production in 10 to 15 years.

- The large scale use of solar energy as a national resource would have a minimal effect on the environment.

RECOMMENDATIONS

It is recommended that:

- The Federal government take a lead role in developing a research and development program for the practical application of solar energy to the heat and power needs of the U.S.

- The solar energy R&D program provide for simultaneous effort on three main objectives: (1) economical systems for heating and cooling of buildings, (2) economical systems for producing and converting organic materials to liquid, solid, and gaseous fuels or to energy directly, (3) economical systems for generating electricity.

- Research and development proceed on various methods for accomplishing the above objectives and that programs with phased decision points be established for concept appraisal and choice of options at the appropriate times.

- For those developments which show good technical and economic promise, the Federal government and industry continue development, pilot plant, and demonstration programs.

- Environmental, social, and political consequences of solar energy utilization be continually appraised and the results employed in development program planning.

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SUMMARY

The following information is tabulated to facilitate an overview of the Solar Energy Panel's findings:

- Table 1. Status of Solar Utilization Techniques.
- Table 2. Summary of Major Technical Problems.
- Table 3. Impact of Solar Energy Applications on the Reference Energy System.
- Table 4. Summary of Overall Program Funding.
- Comments From the Solar Energy Panel's Consultants

TABLE 1. PRESENT STATUS OF SOLAR UTILIZATION TECHNIQUES

The checkmarks in this table indicate the approximate state of development for the various utilization techniques. The extreme right hand check indicates the progress as of 1972 but some work may still be required in the other areas. For example, water heaters are commercially available but combined water heating, heating and cooling systems are still in a state of development.

TABLE 2. SUMMARY OF MAJOR TECHNICAL PROBLEMS

This table identifies the major technical problems to be overcome. As an example, before any of the photovoltaic systems can become applicable on a large scale, solar arrays costing about \$1.00 per square foot will have to be developed. Before the space power station can be feasible, major advances are required in the deployment of huge lightweight structures in space, and low cost synchronous orbit transportation. In all

applications substantial cost reductions are important problems.

TABLE 3. IMPACT OF SOLAR ENERGY APPLICATIONS ON THE REFERENCE ENERGY SYSTEM

This table shows the expected impact that solar energy could have if developed to commercial utilization. The impact is compared with the Reference Energy System's annual consumption figures for the particular application, an estimate in percent of the expected market, the annual savings in fossil fuels based on \$1 per million BTU and an estimate of the significance of the impact based on the specific application and the total U.S. energy needs. A minor impact is considered to range from 0 to 5%, a modest impact from 5 to 10%, and a major impact is equal to or greater than 10%. For example, if by 2020, 30% of the Nation's methane needs are met by the bioconversion of organic wastes, then this would represent a major impact on the gas consumption market and a minor impact on the total U.S. energy consumption (4.2%). At \$1.00 per million BTU, assumed for natural gas costs, the value of the product is \$12 billion per year.

TABLE 4. SUMMARY OF OVERALL PROGRAM FUNDING

The funding recommended by the Panel for the total 15 year program is shown in this Table. Since some systems will terminate at phased decision points in the R&D program, the items have not been totaled. Specific decisions justified by the progress made in a preceding phase are required before progressing to the next phase. In general, the transitions will progress

Table 1. Present Status of Solar Utilization Techniques

Application	Status					
	Research	Development	Systems test	Pilot plant demonstration	Prototype plant	Commercial readiness
Thermal energy for buildings						
Water heating	X	X	X	X	X	X
Building heating	X	X	X			
Building cooling	X	X				
Combined system	X	X				
Renewable clean fuel sources						
Combustion of organic matter	X	X	X	X		
Bioconversion of organic materials to methane	X	X	X	X		
Pyrolysis of organic materials to gas, liquid, and solid fuels	X	X	X	X	X	
Chemical reduction of organic materials to oil	X	X	X			
Electric power generation						
Thermal conversion	X					
Photovoltaic						
Residential/commercial	X					
Ground central station	X					
Space central station	X					
Wind energy conversion	X	X	X			
Ocean thermal difference	X	X	X			

X indicates effort is underway but not necessarily complete.

from feasibility studies, to component development, to prototype or pilot plant, to demonstration models or plants. It is assumed that some of the funds designated for demonstration plants will be cost shared by the industry and thus reduce the government investment.

COMMENTS FROM THE SOLAR ENERGY PANEL'S CONSULTANTS

To include the concerns from the various other disciplines which would interface with the

development of any new energy source, the Solar Energy Panel had representatives from the economic, environmental, psychological, sociological and industrial interests. A summary of their comments follows:

Economic

On close examination, the possibilities for the economic use of solar power, given reasonable R&D support, appear much better than generally realized. In regard to the level of R&D, if the nation is to obtain the maximum benefits

Table 2. Summary of Major Technical Problems

Application	Major technical problems to be solved
Thermal energy for buildings	Development of solar air-conditioning and integration of heating and cooling.
Renewable clean fuel sources Combustion of organic materials Bioconversion of organic materials to methane Pyrolysis of organic materials to gas, liquid and solid fuels Chemical reduction of organic materials to oil	Development of efficient growth, harvesting, chipping, drying and transportation systems. Development of efficient conversion processes and economical sources of organic materials. Optimization of fuel production for different feed materials. Optimization of organic feed system and oil separation process.
Electric power generation Thermal conversion Photovoltaic Systems on buildings Ground station Space station	Development of collector, heat transfer and storage subsystems. Development of low-cost long-life solar arrays. High temperature operation and energy storage. Energy storage. Development of light-weight, long-life, low-cost solar array; transportation, construction, operation and maintenance; development and deployment of extremely large and light-weight structures.
Wind energy conversion	Integration of large wind conversion system with suitable energy storage and delivery systems.
Ocean thermal difference	Large low pressure turbines, large heat exchangers, and long, deep-water intake pipe.

for its energy R&D expenditures, then R&D expenditures on various sources of energy and processes should be carried to the point of equal marginal productivity of the incremental research dollar for each source and process. On the basis of this, as well as other, criteria, it appears that an objective allocation of R&D funds would call for substantially increased R&D support for a number of solar energy opportunities. There are also international benefits in making a viable solar technology available to the world as well as balance of payments and national security benefits in limiting our almost inevitable dependence on foreign energy sources.

Environmental

Solar energy utilization on a large scale could

have a minimal impact on the environment if properly planned. It is important, therefore, that a policy of research and review for environmental effects be made an integral part of the R&D process. Continuous feedback into the development program is critically important to prevent the undue expenditure of funds for processes that could ultimately prove unacceptable from a public point of view. One of the major obstacles to public acceptance of new technologies is the fear that there are unknown side effects that have not been adequately investigated or disclosed.

The most environmentally benign solar energy systems might be those of small scale that would fit into space already occupied by buildings. When considering large land based systems, great

Table 3. Impact of Solar Energy Applications on the Reference Energy System⁽¹⁾

System	Year	Annual consumption ⁽²⁾ (10 ¹⁵ BTU)	Percent of total energy consumption in USA	Estimated percent of market captured	\$10 ⁶ Annual savings in fossil fuel @ \$1.00/10 ⁶ BTU	Significance ⁽⁶⁾ of impact on reference energy system by 2020
Thermal energy for buildings	1985	(3)17	15	<1		Major on building industry Minor on total energy consumption
	2000	(3)21	12	10	2,100	
	2020	(3)30	10	35	10,500	
Conversion of organic materials to fuels or energy						
Combustion of organic matter	1985	37	32			Major on electric utility Modest on total energy consumption
	2000	76	43	1	760	
	2020	160	53	10	16,000	
Bioconversion to methane	1985	(4)27	23	1	270	Major on gas consumption Minor on total energy consumption
	2000	(4)31	18	10	3,100	
	2020	(4)41	14	30	12,300	
Pyrolysis to liquid fuels	1985	(5)50	44			Major on oil consumption Minor on total energy consumption
	2000	(5)63	36	1	630	
	2020	(5)80	27	10	8,000	
Chemical reduction to liquid fuels	1985	(5)50	43			Major on oil consumption Minor on total energy consumption
	2000	(5)63	36	1	630	
	2020	(5)80	27	10	8,000	
Electric power generation						
Thermal conversion	1985	37	32			Modest on electric utility industry Modest on total energy consumption
	2000	76	43	1	760	
	2020	160	52	5	8,000	
Photovoltaic						
Systems on buildings	1985	(3)9	9			Major on building industry Minor on total energy consumption
	2000	(3)15	9	5	750	
	2020	(3)21	6	50	10,500	
Ground stations	1985	37	32			Major on electric utility industry Modest on total energy consumption
	2000	76	43	1		
	2020	160	52	10	16,000	
Space stations	1985	37	32			Major on electric utility industry Modest on total energy consumption
	2000	76	43	1	760	
	2020	160	52	10	16,000	
Wind energy conversion	1985	37	32			Major on electric utility industry Modest on total energy consumption
	2000	76	43	1	760	
	2020	160	52	10	16,000	
Ocean thermal difference	1985	37	32			Major on electric utility industry Modest on total energy consumption
	2000	76	43	1	760	
	2020	160	52	10	16,000	

Notes: (1) Each of the above impact estimates assumes the successful development of practical economically competitive systems. However in each case a judgement has been made resulting in estimates that are less than the maximum possible. The estimates are not necessarily additive since not all systems will be carried to commercial readiness.

(2) Nonrenewable fuel consumed to generate the electric power as projected in the energy reference systems and resource data report, AET-8, Associated Universities, Inc., April 1972 [1].

(3) Nonrenewable fuel consumed to generate the projected electric power requirements for buildings, AET-8 [1].

(4) Methane consumed to meet projected energy needs, AET-8 [1].

(5) Oil consumed to meet projected energy needs, AET-8 [1].

(6) Minor, 0-5%; Modest, 5-10%, Major, ≥10%.

Table 4. Summary of Overall Program Funding*

Applications	Long Range R&D Program (15 years) \$ M
Thermal energy for buildings	100
Renewable clean fuel sources	
Photosynthetic production of organic materials and hydrogen	60
Conversion of organic materials to fuels or energy	310
Electric power generation	
Solar thermal conversion	1130
Photovoltaic conversion	780
Wind energy conversion	610
Ocean thermal gradients	530

*See Appendix A for additional funding information.

care must be taken to find suitable areas that would not be of unique ecological or recreational importance or cause serious alterations in local climate or weather.

One can indeed imagine designing "optimum size" environmentally oriented communities which would meet most of its energy needs from direct solar energy and the solar derived fuels from the local waste treatment plant.

Industrial

Before solar energy becomes a major source of clean energy for our nation, it will require the involvement of industrial ingenuity and productive know-how to produce economic hardware and services. Some of the difficulties in achieving industry participation are: (1) most companies are looking for short term projects

for their new enterprises with return on their investments in 2 to 3 years; (2) long range projects present great risk, and investment capital is very scarce unless there is a high probability of return in a major line in their business; and (3) companies will undergo major change only under crisis (they will take chances but cannot take failure).

To overcome these problems several things are needed. (1) The item needed must be defined very carefully so that the direction is clear and feasibility shown. (2) The Government must make a long range commitment to assure that the interest will not wane in a couple of years. (3) The incentives must be substantial so that future profit is sufficiently assured over a period of time that makes industrial investment pay off. Further, industries must feel that the system is socially acceptable so that the public will look upon it favorably. Solar energy utilization fits into this pattern extremely well.

Sociological

Research on the social conditions which foster solar energy technology protects against the truncating of a technological policy by the social responses it engenders. Analysis of social problems accompanying solar energy technology development requires a shift of focus from the physical world to the world of social activity. There is a need for more social scientific work to define the social (including economic, political, and cultural) problems presented by solar energy utilization. The establishment of National priorities for the use of solar among other energy forms should recognize the social impacts of the utilization of each energy form.

APPLICATIONS

THERMAL ENERGY FOR BUILDINGS

INTRODUCTION

Buildings may be heated and cooled with solar energy by use of some type of solar receiver or collector in which a fluid, such as water or air is heated. The system includes an insulated storage tank or rock bin and an auxiliary heat supply unit of some type to supplement or substitute for the solar source when it is insufficient to meet the demand. A heat-operated air conditioner provides cooling when supplied with solar or auxiliary energy, and various pumps, controls, and facilities are needed for circulating air from the conditioned space to either the heating or cooling unit. Figure 2 is a schematic diagram of one system employing water as the heat collection fluid. As seen, hot water for household use may also be supplied by a system of this type. Numerous alternate designs are possible.

The solar collector is one of the most important, and most expensive, element in the system. A sketch of one type is shown in Figure 3. Solar radiation is transmitted by the glass covers and absorbed by the blackened metal sheet. This causes the temperature of the metal sheet to increase, so that water circulated through the tubes is heated. Water temperatures of 100 to 200°F are commonly obtained, depending on conditions. Heat losses are minimized by the rear insulation and overlying glass covers.

A practical location, and suitable area, for the solar collector is the house roof. The collector should be south-facing for maximum efficiency, and it may be supported on the roof, on a frame work above the roof in building walls particularly in the high Northern latitudes. Storage may be conveniently located in a house at

ground level or in a basement. In a temperate, sunny central U.S. location, a 1,500 square foot house could be provided about three-fourths of its heating and cooling needs with a 600 to 800 square foot collector and 2,000 gallons of hot water storage. Greater attention to energy conservation in house design can significantly reduce the heating and cooling requirements, by more effective insulation, roof and wall orientation, window arrangement, surface properties for radiation control, solar transmission and shading.

STATUS OF RESIDENTIAL SOLAR HEATING AND COOLING

The three residential solar applications, water heating, space heating, and space cooling differ substantially in status of development, so they are discussed individually below. It is evident, however, that combinations of the three functions in integrated heating, cooling, and water heating systems will have the best prospects for economical use. The status of the integrated system is outlined after the discussion of each component.

Water Heating

Solar water heaters are commercially manufactured in Australia, Israel, Japan, USSR, and on a small scale in the U.S. The aggregate business of these enterprises is probably several million dollars per year. Solar water heaters are standard items of equipment in households in particular areas (e.g., northern Australia); areas of use are growing slowly. Application in the

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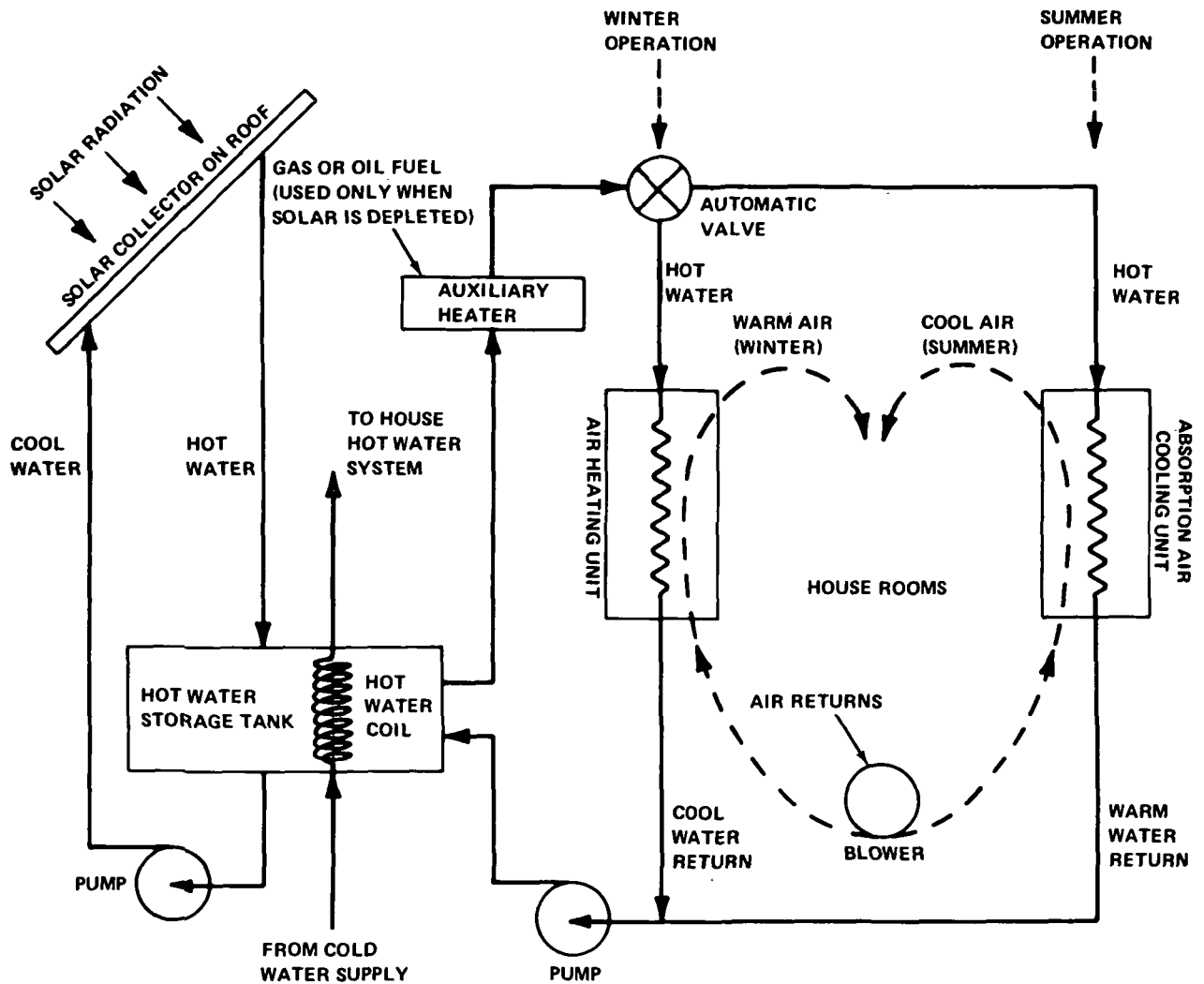


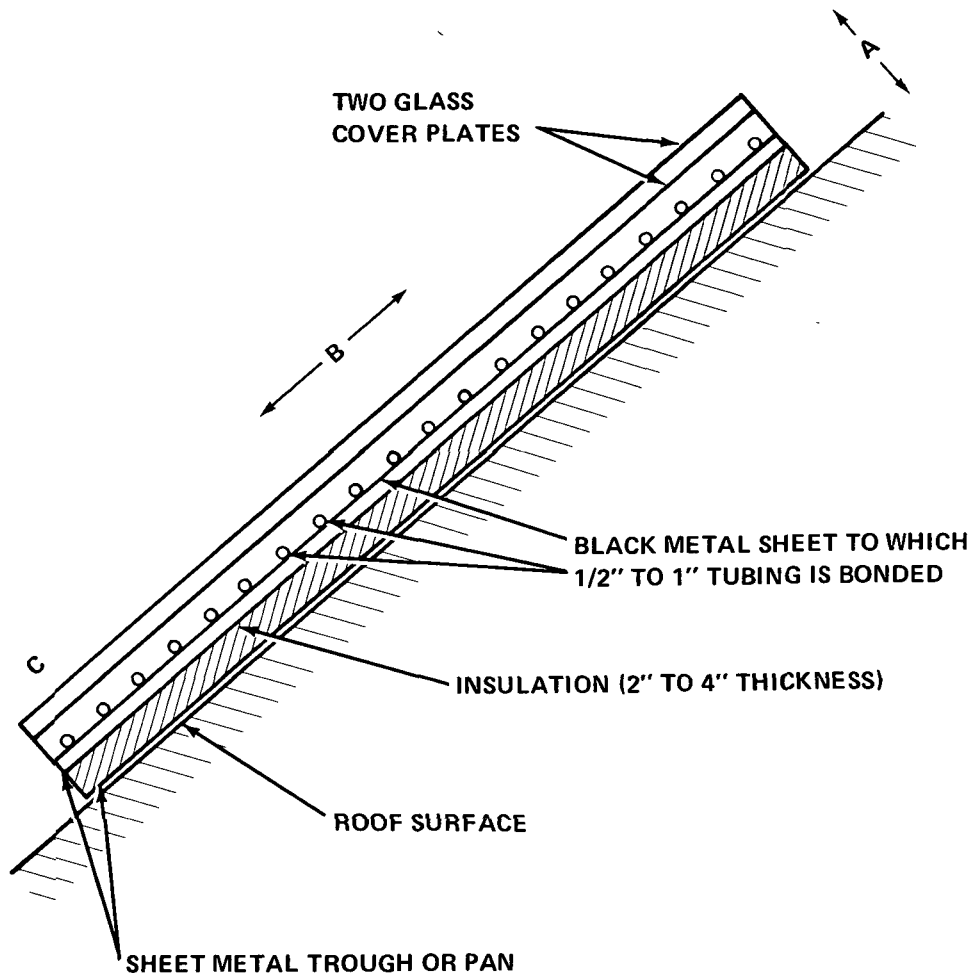
FIGURE 2. RESIDENTIAL HEATING AND COOLING WITH SOLAR ENERGY: SCHEMATIC DIAGRAM OF ONE ALTERNATIVE

U.S., once common in Florida but then diminished by the availability of natural gas, is now beginning to increase. In addition to household applications, institutional installations are beginning to appear in Australia, for schools, hospitals, etc. [6].

The technology of solar water heaters is well developed; further product engineering (particularly of collectors) and larger scale manufacturing would result in cost reductions and increased utilization.

Space Heating

Approximately 20 experimental solar heated structures have been designed, built, and operated. Various combinations of collector types, heat storage techniques, heat transfer media, and auxiliary energy supplies have been used. Some of these buildings were laboratories, and some were also designed as residences; only one fully instrumented and evaluated system has been in continuous use, so long-term experience with solar heating systems is limited.



**NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING
ON CONDITIONS**

**DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON
WINTER-SUMMER LOAD COMPARISON**

**FIGURE 3. SOLAR COLLECTOR FOR RESIDENTIAL HEATING AND COOLING
DIAGRAMATIC SKETCH OF ONE ALTERNATIVE
(elevation-section)**

The performances of several of these heating systems were fully measured and evaluated, and the results were published [6]. The capabilities of the various designs have thus been well established. Subsequent economic studies have shown that in a wide variety of U.S. climates, solar heating is less expensive than electric heating, and in a few locations, it is nearly competitive with gas or oil heating [7]. Table 5 and Figure 4, based on one of these analyses, clearly demonstrates that solar heating, even without supplemental savings from cooling, can be a practical alternative to conventional heat sources.

Workable heating systems have evolved from these experiments. However, they are not fully

engineered, both from the point of view of selecting the best systems or optimizing the design of those systems. Also, solar collectors, energy storage units and heat transfer systems are in an early stage of component development and engineering. Though technical feasibility is assured, economic feasibility is being approached for major regions of the U.S. Further R&D is needed to reduce costs and develop better systems.

Air Conditioning

A few experiments have been conducted in the U.S., Australia, and the USSR to study the operation of absorption refrigeration systems

Table 5. Costs of Space Heating (1970 Prices) In Dollars Per Million BTU Useful Delivery [7].

Location	Optimized solar heating cost in 25,000 BTU/degree-day house, capital charges @ 6%, 20 years		Electric heating, usage 30,000 kwh/year	Fuel heating, fuel cost only	
	Collector @ \$2/ft. ²	Collector @ \$4/ft. ²		Gas	Oil
Santa Maria	1.10	1.59	4.28 ¹	1.52	1.91
Albuquerque	1.60	2.32	4.63	0.95	2.44
Phoenix	2.05	3.09	5.07	0.85	1.89
Omaha	2.45	2.98	3.25 ³	1.12	1.56
Boston	2.50	3.02	5.25	1.85	2.08
Charleston	2.55	3.56	4.22	1.03	1.83
Seattle-Tacoma	2.60	3.82	2.29 ^{2,3}	1.96	2.36
Miami	4.05	4.64	4.87	3.01	2.04

Notes: ¹Electric power costs are for Santa Barbara, Electric power data for Santa Maria were not available.

²Electric power costs are for Seattle.

³Publicly owned utility.

Solar heat costs are from optimal design systems yielding least cost heat.

Electric power heat costs are from U.S. Federal Power Commission, All Electric Homes, Table 2 (1970). Conventional heat fuel costs are derived from prices per million BTU reported in P. Balestra, The Demand for Natural Gas in the United States, Tables 1.2 and 1.3 (North Holland Publishing Co., 1967). The 1962 costs were updated to 1970 by use of national price indexes on gas (121.1 in 1970 versus 112.8 in 1962) and on fuel oil (119.22 in 1970 versus 101.2 in 1962) as adjustment factors on each fuel price in each state. Bureau of Labor Statistics fuel prices indexes obtained from Gas Facts. Fuel prices were converted to fuel costs by dividing by the following national average heat (combustion) efficiencies: gas, 75%; oil, 75%. Heat efficiencies are from American Society of Heating, Refrigerating and Air Conditioning Engineers, Guide and Data Book 692-694 (1963 ed.).

All solar heat costs based on amortizing entire solar system capital costs in 20 years at 6 percent interest. Capital investment based on current prices of solar water heaters at \$4 per sq. ft. plus current costs of other components, and on anticipated near-term solar collector price of \$2 per sq. ft.

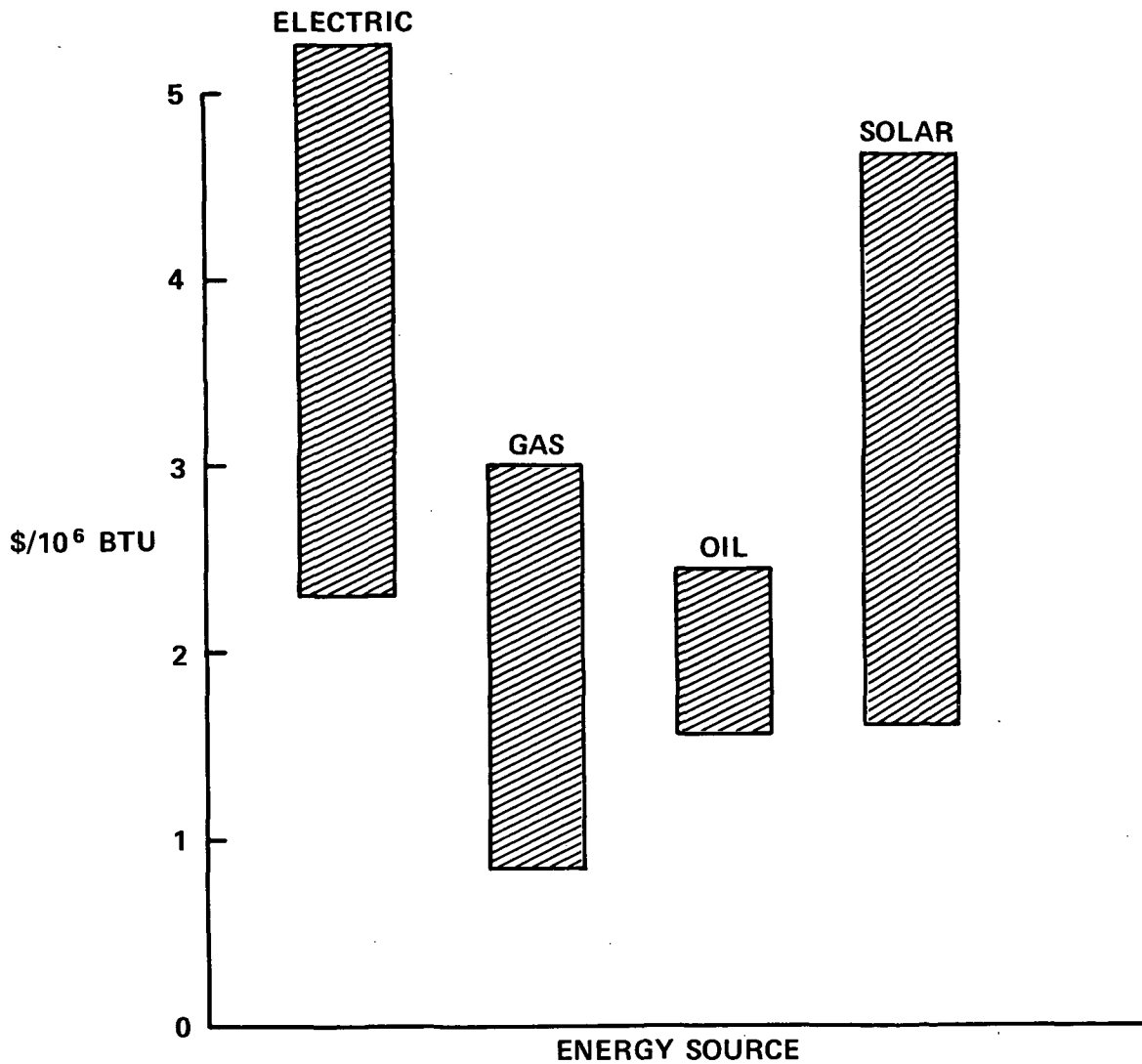


FIGURE 4. COSTS OF SPACE HEATING

using heat from solar collectors [6, 8]. These experiments show that the concept is promising, and no major technical barriers to successful development are seen. Other cooling methods, by use of dehumidifying agents with solar regeneration, jet compression with solar input, are also possibilities on which a very few experiments have been performed. It is evident that there are numerous technological options to be explored; these include many types of cooling equipment [9] and cycles, alternative methods of providing energy storage and auxiliary energy input, and combinations of these components in systems. Economic projections based

on the preliminary experiments done to date and not reflecting major developments in components or systems are promising.

Combined Systems

Although no experiments have yet been performed, the same major components, solar collectors and energy storage units, can be used to supply hot water, space heating, and air conditioning. Most of the solar heated experimental houses have included means for heating water; only one has included air conditioning other than by nocturnal radiation or by use of

heat pumps. The economics of combined systems, with their higher use factor on capital intensive equipment, can be expected to be much better than that of either heating or cooling alone.

There remain, however, numerous design and operating problems which require solution before practical systems can be marketed and used.

LIMITING FACTORS AND RECOMMENDED APPROACHES

The principal factor limiting the adoption of solar heating in favorable sections of the U.S. is the lack of well-engineered and economically manufactured and distributed solar heat collectors. The key problem is the development, optimization, production design, and manufacture of such units. The difference in the cost of heat supplied by solar collectors relative to conventional sources is disappearing and no longer appears to be a major problem. Marketing may however, require innovative concepts for general acceptance by builders and home owners.

The key problems impeding wide utilization of solar cooling and combined systems, in addition to questions analogous to those for heating, are economical cooling subsystems, evaluation of alternatives, designs and product engineering, construction and operating experiences. These are technical development problems whose solutions can be assured by reasonable effort. As with heating alone, high capital investment may impede initial adoption, but full appraisal of costs shows that fuel savings will more than offset first-cost disadvantage when systems become commercially available.

The approaches to wide utilization of combined systems are indicated by the character of the problems. Support is needed for engineering development and design studies, testing and improving well conceived systems, optimization studies, and production engineering design, followed finally by full demonstrations and trial public use.

There is no doubt that among all the possible uses for solar energy, residential heating and cooling has the highest probability of success.

There are the least uncertainties both in the technology and the economics of these domestic applications. There is, moreover, a very high benefit/cost ratio in that the total funds needed for the development of a viable enterprise will be only a small fraction of the annual value of fuel savings, or of equipment sales, or of some other measure of benefits to the economy.

GOALS AND PROJECT IMPACTS

The goal of research on solar heating and cooling is fully developed and engineered systems suitable for wide public use. Research toward this end must have the following aims:

- Efficient and economical solar collector designs.
- Heat storage materials and containers, low in cost and dependable in performance.
- An air cooling unit efficiently operable by heat from the solar collector-storage system.
- Economical system designs for house heating, cooling, and water heating, supplied with optimum combinations of solar and auxiliary energy.

Achievement of the broad objectives listed above, through various specific projects involving research, engineering development, system design, economic analysis, production engineering, component and system testing, and full scale demonstration, will place this application in trial public use well within a decade. A suitable and achievable practical goal is a 10 percent penetration of the market for new building heating and cooling installations by 1985.

The impact of successful solar heating and cooling development may be forecasted in several ways as indicated in Table 6. The maximum potential use of solar heating and cooling would involve virtually all new houses and commercial buildings. Assuming solar energy could supply an average of 80 percent of the heating and cooling requirements in 90 percent of all new houses and single-story commercial buildings, 4.5 percent or 8.4×10^{15} BTU per year of the Nation's year-2000 energy requirements may be

Table 6. Impact of Heating and Cooling of Building by Solar Energy

	Water heating		Solar heating		Solar cooling		Combined thermal systems	
	1975	1980	1980	1985	1980	1985	1980	1985
Time scale								
New buildings (1%) (10%)		1980	1980	1985	1980	1985	1980	1985
Total buildings (1%) (10%)		1985	1985	1990	1990	2000	1990	2000
Resource effect								
Fuels	Ultimately (1) 30-80 percent of fuels and electricity normally used for space heating/cooling can be saved.							
Materials	Use of average additional 1,000 ft. ² glass/house + other materials. No shortage of materials.							
Environment	3D zoning; sun rights. 3D zoning 3D zoning							
Land	None No increase over present systems.							
Noise	Minimal Significant element in total design.							
Visual	None (2) None (2)							
All others	None (2) None (2)							
Economics								
Capital	\$200-\$400 (3)		\$1,500-\$2,500 (4)		\$3,000-\$4,000 (4)		\$3,000-\$4,000 (5)	
\$/MBTU heat	\$3-\$6 (6)		\$2-\$3.		\$2-\$3.		\$1.50-\$2.50 (5)	
Solar	\$2-\$4 present		\$1.50-\$2.50 present		\$1.50-\$2.50 present		\$1.50-\$2.50 (7) present	
Conventional	\$3-\$5 1990 estimated		\$2.50-\$4.50 1990 estimated		\$2.50-\$4.50 1990 estimated		\$2.50-\$4.50 1990 estimated	
¢/Ton-hr. solar cooling					8¢-20¢			
¢/Ton-hr. conventional cooling					5¢-15¢ (8)			

Notes: (1) Percent of energy used for space heating and cooling (2) Percent of total U.S. energy

1990 7 1
2000 50-80 10

- (2) Except for indirect positive benefits due to decreased use of other resources.
- (3) 50 ft² collector; 100-200 gallon hot water tank; thermal transfer, controls.
- (4) 500 ft² collector, \$2-\$4/ft², plus controls and storage cost.
- (5) Including \$1,500 cost of cooling unit.
- (6) \$200-\$400 unit cost. 15% year discount—\$60/year; 1,200 BTU/ft² day incident; E = 50%—3,000 kWh² delivered/year.
- (7) Including cost of heat supply to cooling unit.
- (8) Electrically operated compression systems and heat-operated systems using natural gas.

saved. The corresponding figures for 2020 would be 8 percent and 23×10^{15} BTU per year.

A more probable impact, considering the time required for a new development to achieve wide use and the greater suitability and economy of the system when used in new rather than old buildings, is 10 percent of new buildings constructed in 1985, 50 percent in 2000, and 85 percent in 2020. As percentages of *total* buildings, these figures become approximately 1 percent, 12 percent, and 31 percent, respectively. Corresponding energy savings are 0.12, 2.1, and 10.5×10^{15} BTU/year.

Equivalent annual values of probable fuel savings at these three intervals are \$180 million, \$3,600 million, and \$16,300 million. Gas and oil costs are estimated at a present average price of \$1.50 per million BTU delivered to residential customers.

The probable sales of solar heating and cooling equipment should reach an annual gross value of \$0.75 billion by 1985, \$4.5 billion by 2000, and \$9 billion by 2020. This new billion dollar industry will involve heating and cooling equipment manufacturers, their material suppliers, and their customers. Heating and cooling contractors, their employees, and other services will participate.

Some of the intangible benefits of this development will be the alleviation of problems related to inadequate gas supplies in some areas of the country, the reduction of excessive and expensive electricity peak loads and associated power system failures during very hot weather, and the extension of oil and natural gas supplies further into the future.

RECOMMENDATION FOR SHORT RANGE RESEARCH AND DEVELOPMENT (YEARS 1-3)

The short range goal of R&D effort in residential solar heating and cooling should be a fully workable prototype system suitable for test operation in favorably situated residences. This can be achieved within three years of the start of a program so oriented. It cannot be expected that the system will be the most economical or most efficient or most convenient

that is possible, because more time and development will be required for such advantages to be realized.

Component design and system design studies, optimization studies, cost analyses, and prototype construction and testing of components and the integrated system are the main requirements of the three-year R&D program. The studies must involve solar collectors, heat storage units, heat exchangers, absorption refrigeration equipment, auxiliary heat supply facilities, control instruments, and various sub-assemblies and full assemblies of these components.

RECOMMENDATIONS FOR DEVELOPMENT IN 4TH TO 10TH YEARS

After initial performance testing of a functional unit, the residential solar heating and cooling system should be subjected to a rigorous program of improvement and optimization. Three interrelated objectives are increased: efficiency, reduced cost, and greater simplicity and practicability of application to general use. Most of the effort should be placed on concepts previously investigated, but there should be some work on promising alternatives, especially those involving cooling methods.

The types of projects requiring support in this phase of development are the same as those listed for the initial program, plus engineering design and testing to increase effectiveness of components and complete systems, production design and engineering study (ideally in cooperation with manufacturers) to reduce equipment cost, and architectural and construction analyses to achieve practical applicability to residential use. Prototype testing and demonstration operation of complete systems will be a substantial portion of the total effort during this period. A public information and education program should be included in the demonstration phase of development. Commercial production and sale of residential and commercial solar heating and cooling systems should commence before the end of this ten-year period.

PROGRAM PLAN FOR THERMAL ENERGY FOR BUILDINGS

Table 7 contains a recommended program of development to achieve practical use of solar energy in the heating and cooling of buildings. Tasks previously discussed are indicated here in abbreviated form. Sub-division of tasks to the extent herein is necessarily subject to modifications as work proceeds and results are obtained. Some tasks may require more effort than indicated, others less. The program must therefore have sufficient flexibility for modification as needed.

There should be continuous objective evaluation of the results of the program in order that planning of subsequent work or program termination can be timely and effective. In addition to this continuous decision process, there should be certain planned milestones or decision points. The first of these is set at 3 years from program commencement. At that

time, technical and economic data, some of which will be provided by prototype system operation, will provide a firm basis for planning the next development steps or for discontinuing the development. Abandonment is not anticipated, but many factors, some not even related to solar energy, may alter the present favorable prospects of this application.

Another decision point is indicated at the end of the fifth year, prior to starting a substantial demonstration program. Information available at that time will permit confident appraisal of the market for solar heating and cooling, the impact of this application, and the requirements and orientation of a demonstration program.

The funding level estimated for the entire 10 year program is \$100 million. If the total program is carried through approximately as outlined, it is fully expected that at its conclusion, residential heating and cooling with solar energy will be in general public use.

Table 7. R&D Summary and Milestones for Solar Heating and Cooling of Buildings

Task	Year									
	1	2	3	4	5	6	7	8	9	10
Collector	[]			[]						
Storage	[]			[]						
Cooling	[]			[]						
System design	[]			[]						
System construction and testing	[]			[]						
Production engineering				[]						
Architectural			[]	[]						
Demonstration ⁽¹⁾ (including public information)						[]				

- Notes: (1) In cooperation with commercial builders and developers.
 ▲ Technical and economic viability decision.
 △ Demonstration decision.

RENEWABLE CLEAN FUEL SOURCES

The natural conversion of solar energy into plant materials by photosynthesis and the further conversion of this stored energy into more concentrated forms such as natural gas, petroleum and coal is the basis of the world's fossil fuel supply.

Because these fossil fuel reserves are being depleted rapidly, it is essential that consideration be given to means for providing large additional supplies of high quality, concentrated fuels by using forces similar to those which produced our fossil fuels. The managed production of plant tissue (e.g., trees, grasses, water plants, fresh water and marine algae) with more efficient use of solar energy and required nutrients carried out on suitable land and water areas could provide starting organic materials.

The plant materials which constitute the product of photosynthesis have a comparatively low heat content per unit weight. The conversion of this plant material into higher heat content fuels (gases, oils, solids) similar to those making up the fossil fuel reserves is therefore essential for effective storage and efficient use as clean, contemporary fuels.

This section considers methods for production of various forms of stored energy via photosynthesis and also considers a number of promising methods for conversion of organic materials produced by photosynthesis into commonly used fuels. Figure 5 presents a summary of typical processes and products.

PHOTOSYNTHETIC PRODUCTION OF ORGANIC MATERIALS AND HYDROGEN

Introduction

As indicated in Figure 6, the successful utilization of a moderate portion of the area (land and water) under the control of the United States for conversion of solar energy into stored chemical energy via photosynthesis could provide the entire electrical energy needs of the country.

The large scale photosynthetic production of

plant material at solar energy conversion efficiencies, e.g., 3-5%, greater than usually observed in ordinary agricultural operations, 0.1%, would supply materials that could serve directly as fuels for production of part of man's energy needs or that could be subsequently converted into other forms of higher quality fuels. Concepts to be considered here are directed toward production of large amounts of land-grown products, e.g., trees or grasses, and also large amounts of water-grown products, e.g., algae or water plants. Because the ultimate purpose of growing the plant material is to provide a source of material that can be converted to heat energy by combustion or to enriched fuels by application of appropriate conversion processes, other available organic materials that can be converted in the above ways will also be examined. These latter materials comprise the large amounts of solid wastes—agricultural, animal, industrial, and urban—which are presently creating grave environmental problems and which actually represent a rich energy resource.

LAND PLANTS

In natural ecosystems, land plants such as trees and grasses show a net productivity ranging from about 4 to 26 tons of dry plant material per acre per year. Under intense cultivation the yields of certain crops have been reported to be about 40 tons of dry material per acre per year. Assuming an average yearly insolation of about 2.4×10^{10} BTU per acre per year and an average heat of combustion of the dried plant materials of 16×10^6 BTU/ton, the efficiency of solar energy conversion ranges between about 0.3% and 3.0%.

If, through advanced management practices including exploitation of modern developments in plant genetics, plantations were operated to produce continuous crops at greater than 3% solar energy conversion, less than 3% of the land area of the U.S. would produce stored solar energy equivalent to the anticipated U.S. electric energy requirements for 1985.

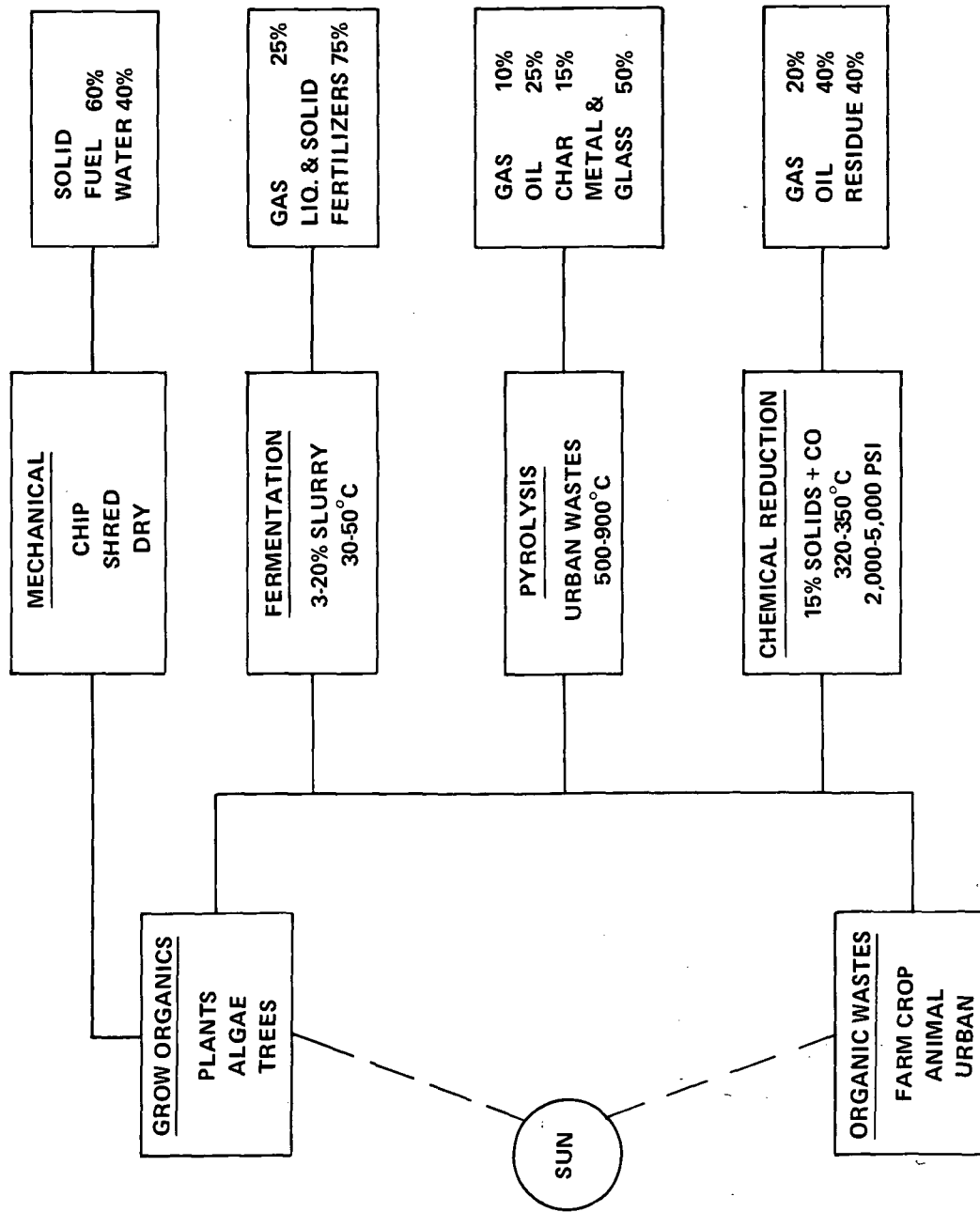


FIGURE 5. PRODUCTION OF FUELS FROM SOLAR ENERGY

PROJECTED ENERGY REQUIRED TO PRODUCE U.S. ELECTRICAL POWER

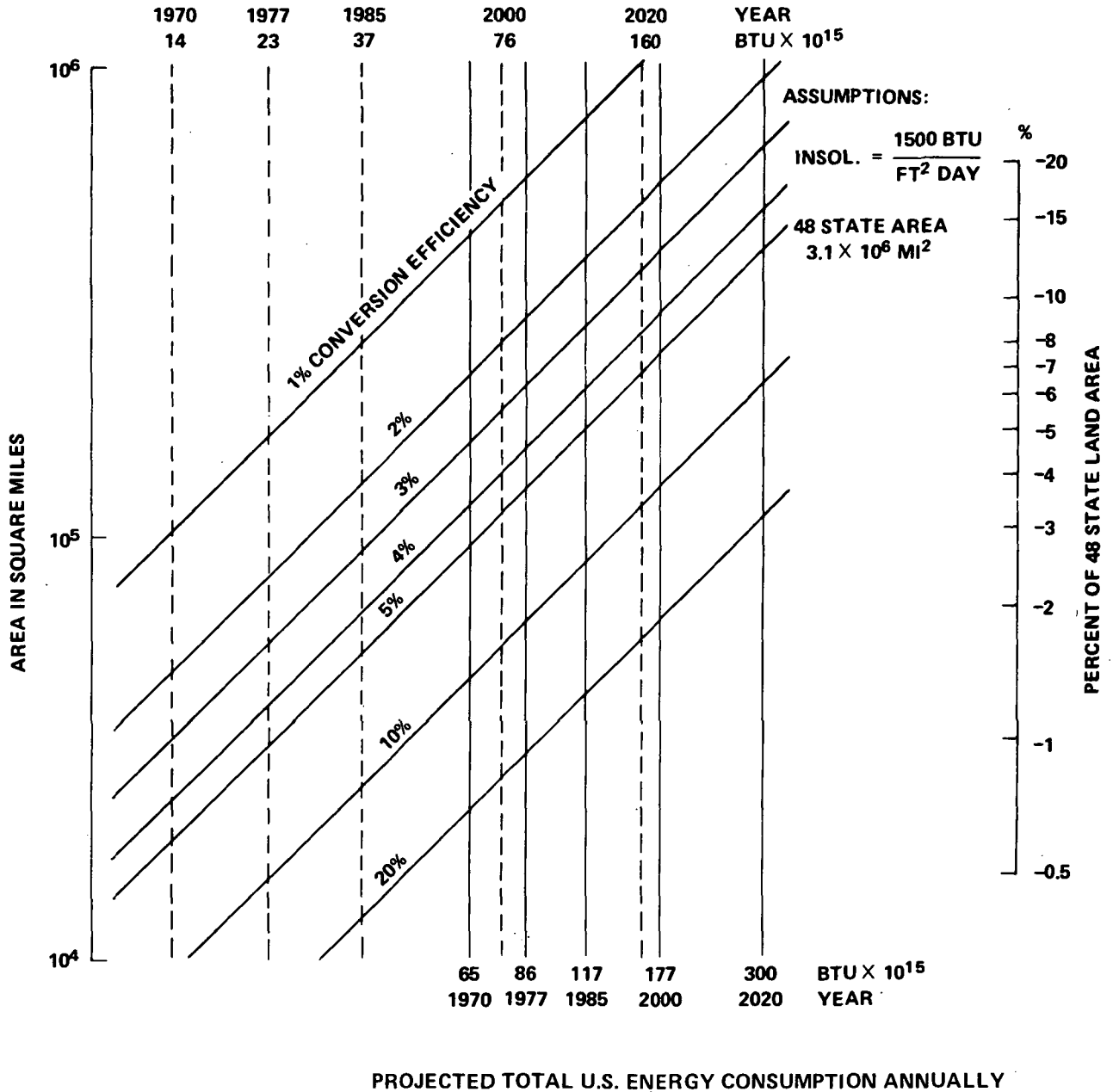


FIGURE 6. AVAILABILITY OF SOLAR ENERGY VS. LAND AREA

WATER PLANTS

The fixation of solar energy in the form of plant tissue grown in, or on the surface of, bodies of water can supply large amounts of organic material. Algae may be grown in shallow ponds and with management and some addition of nutrients to the water can produce large quantities of organic materials. Floating plants can be cultivated in a similar fashion.

If high levels of nutrients in the form of animal wastes are added to ponds containing appropriate bacterial populations, algae and floating water plants can produce heavy yields of plant tissue. In the process of growth, the plants remove soluble nutrients from the water. Removal of the plants by harvesting therefore requires continued addition of waste materials to the ponds.

Status

PRODUCTS OF PHOTOSYNTHESIS

Tree Farming

All aspects of tree farming in the sense of planting, cultivating, and harvesting trees on a large scale and as a continuing crop, are presently practiced for such industries as lumber and paper. Therefore, no new technology is needed to demonstrate the technical feasibility of that part of the concept. Tree farming for energy may be somewhat different because it will be total plant farming. The objectives will be to maximize the total pounds per acre produced, including trunk, limbs, and roots [10].

Grasses

The intensive farming of grasses, which have been reported to produce in the range of 13-15 tons per acre per year, would be expected to be similar in all respects to the cultivation and harvesting of hay.

Algae Culture

Extensive studies have been carried out over many years relating to the culture of specific algae strains as a potential high protein food source. The growth of algae for the purpose of removing nutrients in sewage oxidation ponds is

a common procedure. Recent reports [11,12] have indicated continuing yields of 20-30 tons of dry material per acre per year with peak production at the rate of about 50 tons per acre per year.

The harvesting of this material is commonly carried out using flocculation and centrifugation procedures. Using these processes of harvesting, the reported costs of a dried product are about \$.05/pound [13]. A small scale pilot plant system has been operated at the University of California, Berkeley, since 1959. Larger systems are operating in Asia.

Water Plants

Floating water plants, such as water hyacinth, presently are pest plants in many rivers and lakes in tropical and semitropical areas. The rate of growth is rapid and in nutrient-rich ponds net productivity of up to 85 tons of dry product per acre per year has been reported [14]. Present methods of harvesting these plants do not appear to be sophisticated but interest in the plants as a cattle feed is developing and improvements may be forthcoming.

ORGANIC WASTES

Agricultural Plant Wastes

The principal wastes in this category are the crop residues left in the field at the time of harvest. The main problem relating to utilization of most crop residues is that of material collection and transportation. Although it has been estimated that the annual amount of wasted straw is sufficient to satisfy all of the annual U.S. cellulose demand, it is not utilized for economic reasons.

Animal Wastes

On the basis of 118×10^6 head of cattle in the U.S. [15,16], the expected dry organic waste would amount to about 13×10^7 tons per year. Much of this waste is found on open range and is not recoverable. If it is assumed that 10-20% of the cattle are maintained in restricted area feed lots, the total waste from which energy recovery can be considered amounts to 13×10^6 to 26×10^6 tons of dry organic

material per year. Lesser amounts of wastes are also available from other types of animals raised in confined areas. It is therefore estimated that about 2×10^7 tons of dry waste per year would be available for use. Since local concentrations of these wastes may be very large, the cost as a raw material could be the cost of transportation to a processing site less some credit for accepting the waste.

Urban Solid Wastes

Urban waste generation may be assumed to approximate 5 pounds per person per day [17]. Of this approximately one-half is dry organic material obtained from waste paper, kitchen wastes, and garden or lawn wastes. Although this amounts to about 10^8 tons of dry organics per year over the entire population, the portion generated in cities where severe disposal problems exist approximates 2 to 4×10^7 tons per year. As with the animal wastes the cost of this material as an energy source could be the transportation charges to the conversion site less a credit for accepting the waste.

Summary

It is considered that the total animal and urban solid wastes available under conditions not involving potentially prohibitive collection costs may amount to 4 to 6×10^7 tons of dry organic material per year. The average heat content of this material may be 16×10^6 BTU per ton. Therefore, an annual energy supply amounting to 0.6 to 1.0×10^{15} BTU is available. This represents approximately 6% of present energy requirements for electrical generating plants.

Limiting Factors and Recommended Approaches

PRODUCTS OF PHOTOSYNTHESIS

Tree Farming

Considering a tree crop as a source of raw material for conversion to energy or to an upgraded fuel, the technical problems fall primarily in the area of cost reduction. At the present time, the cost of wood chips produced from lumbering wastes is reported to be about \$20 a ton at a production site. Assuming a

similar cost at the "forest plantation" site, an additional cost for transportation of the chips to the point of use must be considered.

If utilization of the tree crop is envisioned as fuel for a 1,000 MW power plant, the required fuel supply is assumed to be obtained from an area of 400-500 square miles and would require transportation over distances of 10 to 15 miles. Handling of the fuel during drying operations incurs additional costs. These processing charges suggest fuel costs at the power plant in the range of \$1.50 to \$2.00/ 10^6 BTU.

There appear to be no significant social problems associated with this concept. Environmental problems would involve particulate emissions and low-level sulphur dioxide emissions. These would be handled by adequate controls on the combustion unit.

In this concept, the main problems are to find cheap land, increase the solar conversion efficiency, and develop low cost methods of harvesting, processing, and transporting the material. Specifically the cost of dried wood fuel delivered to the power plant site must be competitive with alternate fuels at the time the plant goes on line. To accomplish this goal innovative procedures for harvesting, size reduction, drying, and transporting of the fuel may be required to develop commercial feasibility.

Similar costs of the wood chips would be associated with their conversion to fuels with higher energy content. The resulting fuel would obviously have a still higher cost.

Grasses

Reduction of costs attached to cultivation, harvesting and transportation appear to be the primary problem areas. There may also be significant problems connected with plant pests. No estimates of costs for this crop are immediately available but costs for hay should provide a guide.

Algae Culture

Some technical problems which have been recognized include development of unwanted algae predators and pathogens in algae cultures, accumulation of non-algae turbidity, and algae separation. Some problems of an economic

nature are large land use and associated costs, cost of pond construction and maintenance, and harvesting costs. Estimates using present technologies indicate costs of \$0.05 a pound for dry algae mass. New harvesting techniques are needed to bring about large decreases in costs.

Water Plants

Technical problems associated with growth and harvesting of floating water plants include those of predation by animals; elimination of nuisance insects; and development of innovative harvesting procedures to minimize expenditure of energy for harvesting and transporting them.

Studies are required which will lead to improvements in the efficiency of conversion of solar energy to stored chemical energy in plant tissue for each of the several classes of plants considered suitable for use as fuels or as sources of new supplies of high quality fuels.

System studies are required to establish firmly the step or steps in the plant growth and harvesting which make the largest contributions to the total cost. Harvesting presently appears to be the highest cost item and primary effort should be directed towards innovative developments in this area.

Studies of optimum transportation methods for candidate plant materials should be carried out.

ORGANIC WASTES

Technical problems related to use of organic waste materials as energy sources are largely due to the variable composition and tendency towards degradation of the wastes. These properties make themselves apparent during storage and transport.

Goals and Projected Impacts

The goals and R&D requirements for processes involving the production of organic materials by photosynthesis to serve as energy sources or as raw materials for enriched fuels production are described in Table 8. The potential impact of these materials on the energy supply system is presented in Table 9.

Recommendations for R&D

Continued improvements are needed in solar energy conversion to plant material and in harvesting and transportation processes. A phased program plan for new fuel and energy sources is shown in Table 10.

Emphasis should be directed toward possible large scale utilization of marine areas for photosynthesis of new plant material and for conversion of plant material to high quality fuels. The funding level estimated for the entire 10 year program is \$30 million.

ADVANCED CONCEPT-BIOPHOTOLYSIS OF WATER TO PRODUCE HYDROGEN GAS

Concept Description

The direct formation of hydrogen gas using the photosynthetic apparatus of green plants or blue-green algae has been proposed. Under the stimulation of light, the photosynthetic apparatus in chlorophyll and other accessory pigments can raise the oxidation-reduction potential of the electrons released from water to a level as much as 0.3 volt more negative than the hydrogen electrode. Thus it is thermodynamically possible to couple the reducing potential of these electrons with an enzyme (hydrogenase) to bring about the reduction of hydrogen ions to form hydrogen gas. The hydrogenases may exist either endogenously in algae or exogenously in bacterial sources. A particular problem is the need to accomplish the reduction to hydrogen gas in the normal presence of oxygen. Several possibilities can be investigated for accomplishing the required coupling of photosynthetically reduced substances and appropriate hydrogenase activity. In effect, the normal processes of photosynthesizing cells in fixing carbon are interrupted and diverted to provide hydrogen gas as the reduced product. This process represents essentially a photolysis of water.

The requirements for such an aqueous system would be (1) light, (2) a stabilized photosynthetic apparatus capable of generating reductants from water, (3) a suitable electron

Table 8. R&D Requirements for Development of New Fuel and Energy Sources

Steps to economic feasibility	Major technical problems	Time scale
1. Improve solar energy conversion in fresh water algae, marine algae, and floating plants by maintaining required nutrients in ample supply.	1. Improvement in crop yield.	Steps 1-6 Research 1973-1976
2. Develop new harvesting procedures for algae.	2. Cost of harvesting.	Steps 7-9 Development 1977-1988
3. Optimize algae-bacteria symbiosis.	3. Cost of transportation.	Step 10 Commercial after 1988
4. Develop new harvesting procedures for floating water plants.		
5. Attempt improvement in solar energy conversion in land plants.		
6. Decrease cost of harvesting of land plants.		
7. System selection and system components development.		
8. Pilot plant, 500 lb./day.		
9. Demonstration plant, 25 ton/day.		
10. Commercial plant, 1,000 ton/day.		

carrier such as ferredoxin, and (4) a ferredoxin-coupled hydrogenase under conditions to convert hydrogen ions to molecular hydrogen.

This concept is being pointed out in spite of its relatively speculative nature because of recent developments that suggest its accomplishment and the extremely important ramifications of producing hydrogen directly. The use of hydrogen obtained in this process to produce electric power via the H₂-O₂ fuel cell offers the possibility of providing very clean and very efficient power sources dependent largely on solar energy.

Status

The thermodynamic feasibility of this process for producing hydrogen gas has been established. An efficiency as high as 10% has been observed for the photosynthetic portion of the process. The combination of the process components to

produce a working system has not been demonstrated.

Limiting Factors and Recommended Approaches

TECHNICAL

Besides the large amount of multidisciplinary basic research and development work necessary to demonstrate the ability to actually produce hydrogen by biophotolysis of water using solar energy, engineering studies will need to be conducted to determine the technical feasibility of capturing the solar energy in the photosynthetic apparatus in a closed system in a manner permitting recovery of the hydrogen formed.

ECONOMIC

If the economics of the technical process for hydrogen production referred to above are favorable, other costs, such as raw materials, will

Table 9. Impact of New Energy and Fuel Sources.

Time Scale	Plant growing	Solid wastes
1% 10%	2000 2020	1985-2000 2000-2020
Resource Effect		
Fuels	Conserves fossil fuels.	Conserves fossil fuels.
Environmental Effects		
Land use	Large areas required for land plant growth.	Some storage area required.
Air	Beneficial—O ₂ added, CO ₂ removed.	
Water	Large areas required for water plant growth.	Some storage required.
Waste		Beneficial, eliminates waste disposal problem.
Thermal	None.	None.
Economics (Projected)		
Primary or Secondary Energy Source	\$1.50-\$2.00/10 ⁶ BTU (Assumes development of successful harvesting process).	1.00/10 ⁶ BTU.

be negligible. Hydrogen as a fuel can be transported economically and its use in H₂-O₂ fuel cells provides an efficient means for electric power generation.

SOCIOLOGIC

The cycle of converting water to hydrogen fuel and of using this fuel in H₂-O₂ fuel cells resulting in water as the combustion residue has great attraction for preserving the environment and for recycling of materials.

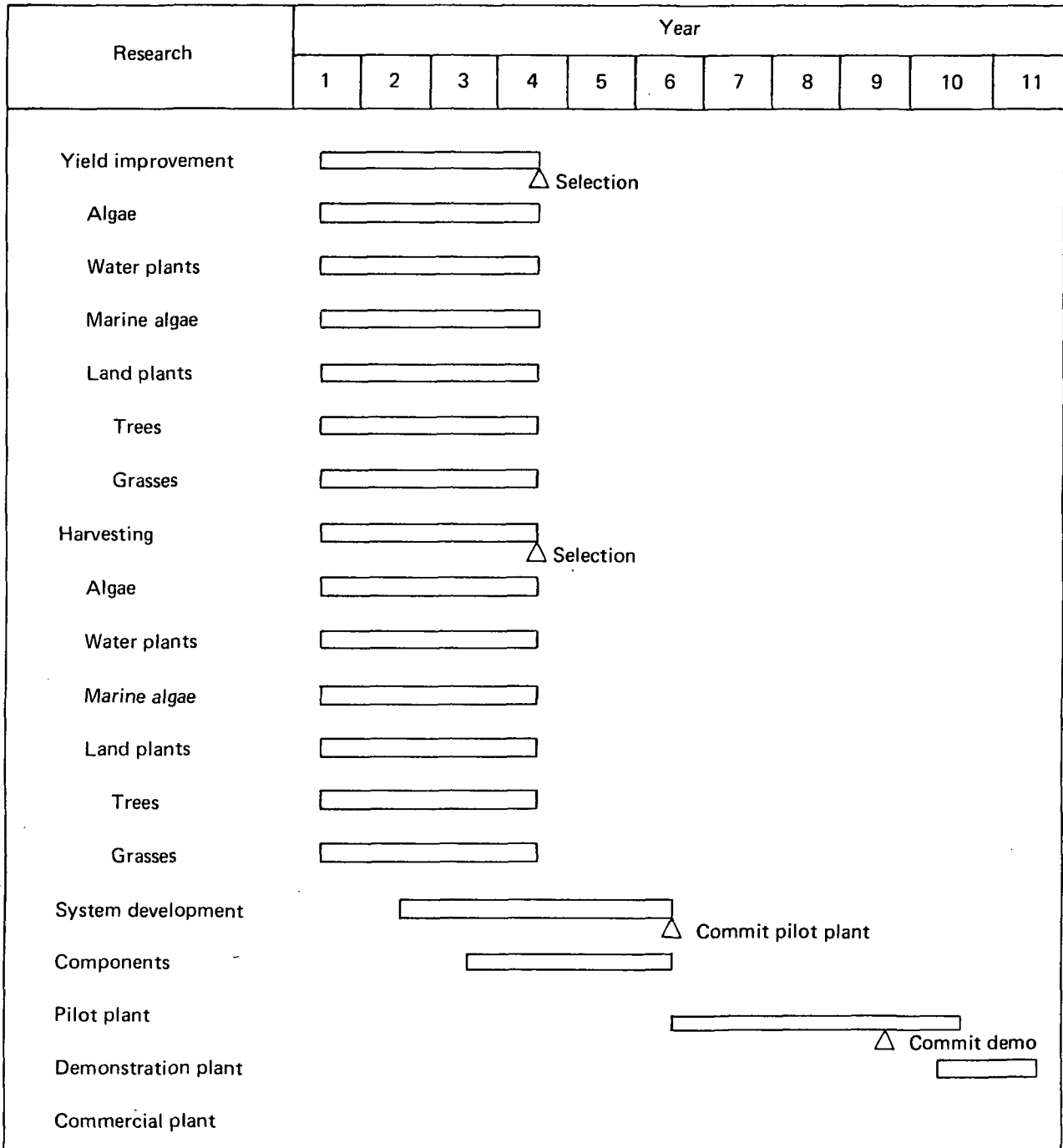
Although this is a speculative area of technology, the benefits to be gained from development of an economic process for producing large quantities of hydrogen are very large. A modest level of support should be provided for these types of concepts that can lead to important

breakthroughs. The estimated funding for a 15 year program is \$30 million.

CONVERSION OF ORGANIC MATERIALS TO FUELS OR TO HEAT ENERGY

Each of the organic materials described in the preceding section can be converted directly into thermal energy by combustion or can be converted to more concentrated fuels by a number of biological or chemical processes. The choice of conversion method is frequently dictated by the physical nature of the material. For example, certain freshly harvested plants having a very high water content would be most profitably converted to a concentrated storable fuel by a biological process that operates in an

Table 10. Phased Program Plan for New Fuel and Energy Sources.



aqueous medium. In other cases where the material is relatively dry or is resistant to biodegradation, direct combustion to heat energy or conversion to concentrated fuels by pyrolysis would be indicated.

This chapter will consider the advantages and disadvantages of direct combustion of the various organic materials or their conversion to other fuels by fermentation, pyrolysis, or chemical reduction. These methods are compared in Table 11.

Combustion of Organic Materials

CONCEPT DESCRIPTION

The photosynthetically produced organic matter described earlier can be burned to produce steam in equipment similar to that used with coal. Since the plant material has a high percentage of constituents other than carbon and hydrogen, the heat of combustion per unit

weight is significantly smaller than coal. Also the plant material, if freshly harvested, would contain water to the extent of about 47% in the case of most trees and of about 95% for some water-grown plants. In order to provide enough heat for the combustion to be self-sustaining, the fuels are normally dried to about 10-15% water.

The organic solid wastes which constitute an important additional source of stored energy may also be burned directly. They have water contents ranging from about 85% for freshly collected agricultural plant and animal wastes to about 20% for many urban solid wastes, so again a drying step is usually required. The heats of combustion of these materials are in the same range as those of the plants mentioned above.

Because of the varied form and size of organic materials, size reduction or briquetting may be practiced. Particulates in the stack gases may require additional pollution control equipment,

Table 11. Comparison of Methods for Conversion of Solid Wastes to Clean Fuel

Process requirements	Chemical reduction	Pyrolysis	Fermentation
Form of feed	Aqueous slurry (15% solids)	Dried waste	Aqueous slurry (3-20% solids)
Temperature	320°-350°C	500°-900°C	20°-50°C
Pressure	2,000-5,000 psi	Atmospheric	Atmospheric
Agitation	Vigorous agitation	None	Slight
Other	Uses CO	None	None
Form of product	Oil	Oil and Char	Gas
Yield (percent of original material)	23%	40% oil; 20% char	20%-26% (maximum)
Heating value	15,000 BTU/lb.	12,000 BTU/lb. oil* 9,000 BTU/lb. char*	23,800 BTU/lb.
Percent of original heat content recovered in product (assume 8,000 BTU/lb. dry waste)	37% (corrected for CO use) 65% anticipated	82% (60% if char not included)	60% (77% maximum)

*All of gas and 1/3 of char used to supply heat.

and certain of the materials contain significant levels of sulfur.

STATUS

Power production by combustion of urban solid wastes is already practiced on a commercial scale [18], principally in Europe, and most technical problems have been solved. There have been reports of corrosion problems and of uneven boiler operation due to variable composition but they are not considered serious.

Although not used for large scale power production, wood in the form of chips or sawdust is used extensively for power production in lumbering and related industries.

Animal wastes are used regularly in India to provide at least a part of the relatively small heat requirements.

The technical feasibility of power production from varied organic materials has been established, but the economic feasibility is uncertain. The efficiency with which power can be generated and the costs associated with pollution control, corrosion, fuel collection, processing and transportation must be examined.

LIMITING FACTORS AND RECOMMENDED APPROACHES

Economic

The actual cost of the fuel at the power plant is probably the key factor in establishing the viability of this concept. In the cases of use of urban solid wastes and concentrated animal wastes produced at large feed-lots there could be a credit paid for removal of the wastes.

Technical

The non-uniformity of the fuel and the relatively low heat content due to presence of water and inerts can lead to uneven operation of steam producing plants. The nature of the fuels may also result in problems involving pollutants and particulates which must be removed from stack gases [19].

GOALS AND PROJECTED IMPACTS

Although quite large quantities of urban, animal, and agricultural wastes are produced in the U.S. every year, the amounts available in

restricted areas and in sufficiently high concentrations to suggest probable economic utilization is thought to be between 4 and 6×10^7 tons of dry organic material. The average heat content of this material is assumed to be about 15×10^6 BTU per ton.

If all this material were burned to produce steam and subsequently electric power, the power generating capability would be in the range of 5,000-10,000 Mw(e). This is a relatively small percentage of the electrical power consumption in the U.S. in recent years, however a potential supply of this magnitude should not be neglected.

For the above reasons it becomes important to consider the impact of the combustion of plant materials grown specifically for the purpose of providing a continuing large volume supply of stored chemical energy.

For example, selected tree crops can be grown on a large farm and harvested on a continuing basis. The product can be reduced in size, dried, and transported to an electric power plant site (1,000 Mw) and used for fuel. The ash resulting from the combustion can be returned as a fertilizer component to the farm. The tree-fired electric plant would be centered in a forested area where the land could not be used profitably for other crops. This land would be harvested and replanted to provide a continual regenerating fuel supply. Because this process would result in the mining of a lesser amount of coal, benefits which can be foreseen include a reduction in strip mining and of the acid waste problems accompanying such mining, and a reduction in the emissions of sulfur dioxide resulting from the combustion of high sulfur coals.

The R&D requirements for further development of the process of direct combustion of organic material is described in Table 12. The potential impact of the process on the energy supply system is described in Table 13.

RECOMMENDATIONS FOR R&D

Studies of solid waste collection, drying, and transportation should be carried out to develop lower cost, more effective procedures for obtaining benefit from large amounts of potential

Table 12. R&D Requirements for Combustion of Organic Matter.

Steps to economic feasibility	Major technical problems	Time scale
<p>Plants/trees</p> <ol style="list-style-type: none"> 1. Feasibility study. 2. Develop new harvesting methods. 3. Develop new techniques for size reduction, drying and storage of the prepared fuel. 4. Improve total crop yields. 5. Develop sulphur removal techniques. 6. Component development. 7. Pilot plant—1 MW. 8. Demonstration plant—50 MW. 9. Commercial plant—500-1,000 MW. 	<ol style="list-style-type: none"> 1. Large energy expenditure in chipping operation. 2. Efficient drying. 3. Transportation of fuel to plant site. 4. Efficient removal of sulphur oxides and particulates from stack gases. 	<p>Steps 1-5 Research 1973-1976</p> <p>Steps 5-8 Development 1977-1988</p> <p>Step 9 Commercial After 1988</p>
<p>Organic solid wastes</p> <ol style="list-style-type: none"> 1. Feasibility study. 2. Develop combustors for agricultural waste. 3. Develop collection, drying, and transportation techniques. 4. Laboratory experiments. 5. Pilot plant—1 MW. 6. Demonstration plant—50 MW. 7. Commercial plant—500-1,000 MW. 	<ol style="list-style-type: none"> 1. Combustion of wastes of variable composition and energy content. 2. Reduction of moisture content of wastes. 3. Efficient removal of sulphur oxides and particulates from stack gases. 	<p>Steps 1-3 Research 1973-1976</p> <p>Steps 4-6 Development 1977-1988</p> <p>Step 7 Commercial After 1988</p>

energy. Studies of whole plant farming to increase the solar conversion efficiency are required. Detailed systems analysis and economic and optimization studies should be undertaken to evaluate system concepts for growing and preparing organic materials for direct combustion for electric power generation. These studies should be primarily oriented to identifying process steps making the largest contributions to the total cost, and to suggest procedures for improving the economics. The expected funding for the 15 year program is \$140 million.

Bioconversion of Organic Materials to Methane

CONCEPT DESCRIPTION

Most organic materials in the presence of some moisture and in the absence of oxygen are subject to natural fermentation in which a large percentage of the carbon content of the material is converted into a mixture of methane and carbon dioxide. Figure 7 is a schematic of a unit for converting solid waste to methane by anaerobic fermentation. The conversion occurs

Table 13. Impact of Combustion of Organic Matter on Energy System

Time scale	Plants/trees	Solid organic wastes
Initial (1%)	2000	2000 (possibly 1985)
Significant (10%)	2020	2020 (possibly 2000)
Resource effect		
Fuels	Conserve fossil fuels.	Conserve fossil fuels.
Materials		Reduce waste disposal problems.
Environment		
Land use	Large areas required for drying wood chips.	Some land areas required for drying and waste storage.
Air	Some sulfur oxide and unburned hydrocarbon emissions.	Combustion produces air pollutants.
Water	Same as for fossil fuel combustion.	Same as for fossil fuel combustion.
Visual		
Waste	Ash returned to soil.	Ash returned to soil.
Thermal	Same as for fossil fuel combustion.	Same as for fossil fuel combustion.
Other	Possible negative popular reaction to growing forests for burning.	Decreases supply of soil conditioning organics.
Economics		
Fuel cost (\$/MBTU)	\$1.25-\$2.00 (estimated).	\$1.00-\$2.00 (estimated). ¹

¹Based on reasonable truck and rail haul distances and costs. No charge for wastes. No subsidy for agricultural wastes.

at or around normal atmospheric pressures and at temperatures ranging from about 15°C up to about 50°C. The process operates with organic solid concentrations as low as a few percent and as high as 60-70%.

The volatile products of the fermentation are methane, carbon dioxide, trace amounts of hydrogen sulfide, and nitrogen gas. The volatile products as produced contain from 50 to 70% methane with carbon dioxide representing almost all of the residual. The heat of combustion of this crude product therefore ranges between 500 to 700 BTU/cu. ft. of gas and the gas can be burned directly for electric energy production. The gases can also be treated readily to remove carbon dioxide and hydrogen sulfide; and, the pure methane remaining can be pressurized for introduction into existing natural gas pipelines.

The heating value of this methane is about 1,000 BTU/cu. ft.

In general between 4.5 to 6.5 cu. ft. (STP) of methane can be obtained from the conversion of 1 pound of dry organic materials or from $9-13 \times 10^3$ cu.ft./ton. This corresponds to a heating value of $9-13 \times 10^6$ BTU/ton and represents 60-80% of the heating value of the original organic materials.

If the entire amount of solid wastes believed to be economically recoverable were subjected to anaerobic fermentation to methane, a total of between 3.6 and 7.8×10^{11} cu. ft. of methane would be expected. This would represent a recovery of 3.6 to 7.8×10^{14} BTU/year or approximately 2-3% of the yearly consumption of methane in the United States.

Under conditions where the starting organic

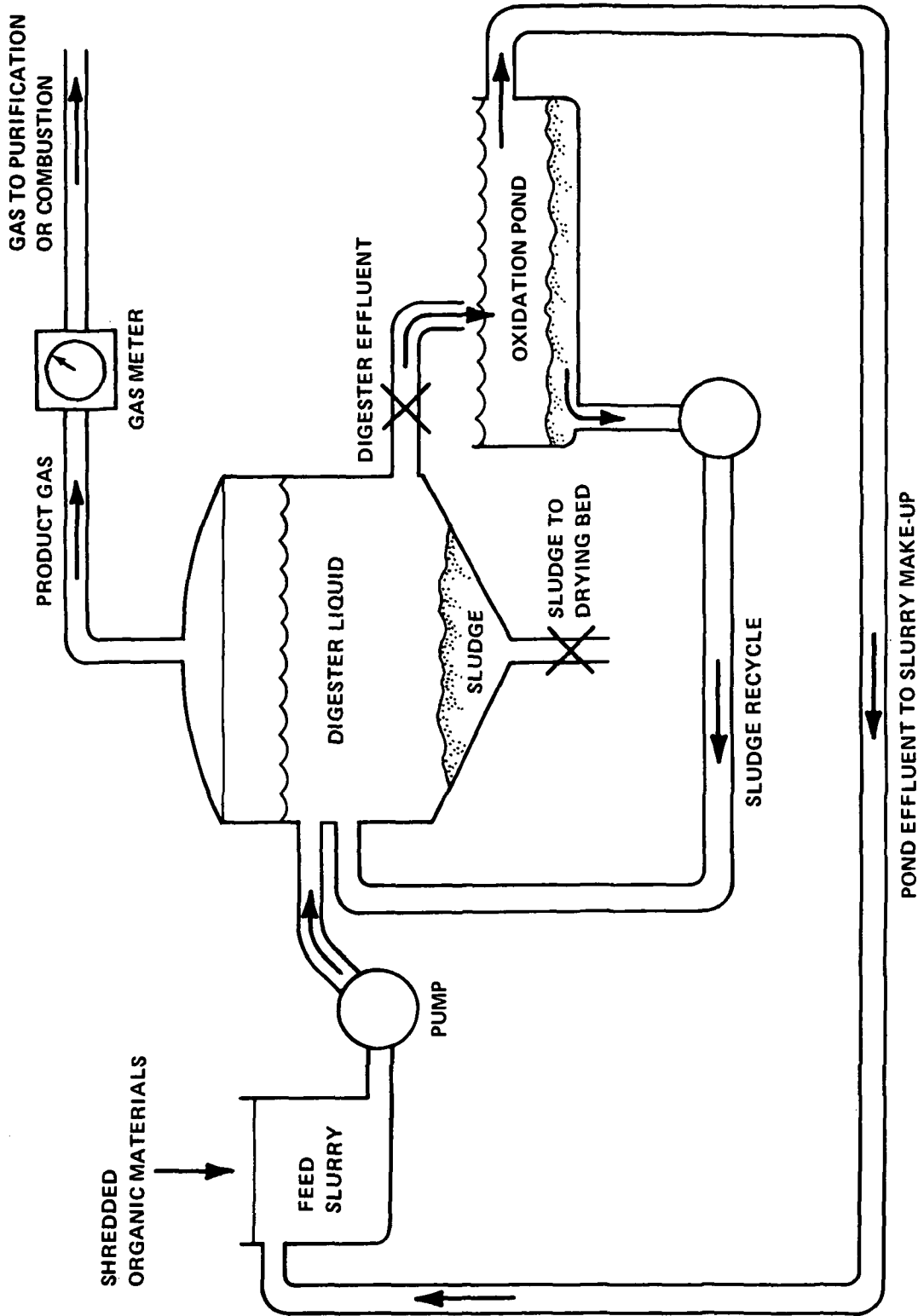


FIGURE 7. CONTINUOUS UNIT FOR CONVERTING ORGANIC MATERIAL TO METHANE BY ANAEROBIC FERMENTATION

material has a high water content the energy required for drying prior to combustion may equal or exceed the heat content of the organic material so a process such as fermentation, where drying is not required, becomes an efficient means for recovering the heat energy.

STATUS

The anaerobic fermentation process has been in use for many years for reducing the volume and weight of domestic sewage solids through conversion to liquid and gaseous products. In general the amount or composition of gas produced is of secondary interest since solids reduction is of principal concern. Many of the larger installations, processing up to 100 tons of sewage sludge per day, have used the generated gases for supplying their power requirements.

The use of anaerobic fermentation for the primary purpose of fuel production through conversion of organic materials such as urban organic wastes, agricultural wastes, animal wastes, and plant crops (including algae or floating plants) specifically grown for the purpose of such conversion is in its infancy.

Laboratory scale studies have been carried out at a number of locations using domestic solid wastes and animal wastes [20,21]. The studies have progressed to the point where most of the ground work leading to small pilot installations have been completed. The small pilot installations would accommodate solids up to 200 lb/day with expected gas production up to 1,000 cu. ft. methane per day.

Studies have also been carried out in which algae grown in sewage ponds and floating water plants (water hyacinth) grown on many tropical and semitropical bodies of water have been converted to methane by the fermentation process [13,22]. Bacterial populations have been developed which permit the fermentation process to be conducted in a marine environment.

Economic evaluations of the fermentation of solid wastes to methane have been made. Because a credit can be allowed for receiving the solid wastes from municipalities, the methane production costs using this raw material appear

to be competitive with imported liquified natural gas. Preliminary estimates of methane costs produced by fermentation of algae grown on sewage ponds suggest costs between \$1.50 and \$2.00/10⁶ BTU.

Similar estimates of costs of produced methane from all materials which are grown and harvested are to be expected and point up, in particular, the need for substantial improvements in harvesting techniques.

In addition to the obvious mitigation of the sewage disposal difficulties, advantages of the use of conversion of organics to methane by fermentation include the low energy requirements of the system, i.e., atmospheric pressure and temperatures from 20°C to about 50°C; the production of a single hydrocarbon gas which is easily purified; and, the relatively high recovery of the heat content of the feed in the form of methane. Disadvantages include the large size of installations and relatively slow rate of reaction, resulting from the necessary very mild operating conditions.

The process equipment, although of large size, is not complicated and is not excessively costly.

LIMITING FACTORS AND RECOMMENDED APPROACH

The technical feasibility of the process has been demonstrated. Full scale development can be undertaken after pilot scale operations have demonstrated optimum operating conditions for maximum conversion of organic material to methane; and, after established viable methods for ensuring operation of a living biological system exposed to numerous challenges have been developed.

GOALS AND PROJECTED IMPACT

The technical feasibility of bioconversion of organic material to methane has been established for many years. The immediate goal should be to establish the economics of the process using organic materials resulting from photosynthesis and organic wastes. This requires fermentation process optimization and construction and operation of pilot plants. The potential impact of this process is described in Table 14. The process has the potential to supply all our gas needs.

Table 14. Impact on Energy System of Fuel Production by Bioconversion of Organic Materials to Methane

Time scale	Methane production by fermentation of solid wastes	Methane production by fermentation of algae/floating plants
1% impact 10% impact	1985 1995	1985 1995
Resource effect		
Fuels	Could ultimately supply 2-3% of US gas needs.	If methane is produced from algae/F.P. 100% of US gas needs in 2020 could be supplied using 5% of the area of the U.S. (2% Solar Energy Conversion Efficiency).
Materials	Insignificant—only construction materials required.	
Environment		
Land use	Approximately same as present waste disposal land use.	5% of U.S. land area to produce 100% of year 2020 U.S. gas needs.
Air	Minimized air pollution from waste depositories and fossil fuel combustion.	
Water	Locally possible significant; nationally small.	Significant: surface areas of ponds and lakes may be covered with algae or floating plants.
Thermal	No thermal discharges involved.	No thermal discharges involved; for protein production from algae thermal pollution which would have accompanied farm energy production would be eliminated.
Visual	Significant improvement over garbage dump/burning facilities.	Low profile aesthetic appearance beautifies landscapes with artificial lakes; lake surfaces will be covered with vegetation.
Waste	There is approximately 60+% weight reduction in solid wastes; Solids equivalent to about 40% of the initial waste weight appear as sludge. Presently discarded.	Utilizes solid or liquid wastes on large scale instead of continuing present disposal problems.
Other		
Economic	A new multi-billion dollar protein food and methane fuel industry would be created if high protein cells in digester sludge are recovered and excess fresh water or marine algae are grown.	
Fuel cost	About same as imported LNG; could be less.	Higher than for solid wastes. Must reflect cost of producing algae or floating plants.

However, the amount of gas that will be supplied by this process will depend on the gas cost and the availability of land and/or water area for growing the organic feed.

A first estimate of the cost [23] of using waste as the organic feed is shown in Table 15. The costs are based on a 1,000 ton organic per day plant and are cited for each system component in terms of cost per 10^3 cu. ft. methane produced.

One configuration of system components, as indicated by asterisks on the table, indicates a cost of pure methane at pipeline pressure of $\$0.45/10^3$ ft.³ CH₄, or $\$0.45/10^6$ BTU assuming 10^3 BTU/ft.³ methane. The costs were developed using 1967-1969 dollars. The credit for receiving the waste from the municipalities was taken as representative of the East Coast of the U.S. and amounted to $\$5.25/\text{ton}$. There are numerous arrangements of components which could lead to even lower methane production costs but their utilization depends on specific geographic and other factors.

Table 15. Cost Estimate for Bioconversion of Organic Waste to Methane (Based on a 1,000 ton/day plant).

	Cost per 10^3 ft. ³ methane	Credit per 10^3 ft. ³ methane
* Acceptance of solid waste from municipality		\$0.880
* Transfer station	\$0.184	
* Size reduction	\$0.317	
* Salvage transportation (alternatives)		\$0.125
Rail haul 50 miles	\$0.166	
" 100 miles	\$0.213	
* Truck haul 50 miles	\$0.897	
" 100 miles	\$1.460	
Barge 50 miles	\$0.133	
" 100 miles	\$0.146	
Pipeline (10% slurry) 50 miles	\$0.352	
" 100 miles	\$0.600	
* Transfer station digestion (10^7 ft. ³)	\$0.146	
* Conventional	\$0.274	
Low cost	\$0.156	
* Sludge disposal	\$0.250	
* Gas purification	\$0.025	
* Gas pressurization to pipeline pressure	\$0.025	

No firm estimates of costs have been obtained for the conversion of other organic materials to methane. The use of animal manures and of plant wastes as biodegradable materials has been successful but process costs will depend strongly on transportation and gathering costs. The same uncertainties apply to the conversion of plants grown specifically for the purpose. The costs of harvesting, drying, transportation, and other processes using present techniques are too high to permit an economic process. Innovative low cost cultivation and harvesting procedures are essential.

RECOMMENDATIONS FOR R&D

The R&D recommendation for conversion of organic wastes is presented in Table 16. The R&D for the conversion of grown organic materials is much the same as that for organic wastes. Additional studies are required to establish which grown organic matter is best and to develop economic techniques for growing, harvesting, and processing organic materials for bioconversion. The expected funding for a 15 year program is \$60 million.

Pyrolysis of Organic Materials to Gas, Liquid, and Solid Fuels

CONCEPT DESCRIPTION

Pyrolysis is a process of destructive distillation, carried out in a closed vessel in an atmosphere devoid of oxygen. This process has long been applied commercially to wood for the recovery of organic by-products such as methanol, acetic acid and turpentine in addition to the residual charcoal. Any organic material may be subjected to this treatment with the expectation that there would be obtained gas, liquid and solid products all of which could serve as fuels. In addition, materials which are difficult to dispose of, for example, plastic and tires, can be converted to fuel or other useful products by this process. The gases are usually a mixture of hydrogen, methane, carbon monoxide, carbon dioxide, and the lower hydrocarbons. The liquids are oil-like materials, and the solids are similar to charcoal. Operating

Table 16. R&D Requirements for Bioconversion of Organic Wastes to Methane

Steps to economic feasibility	Major technical problems	Time scale
1. Minimize cost of waste transport.	1. Find better waste transport means.	Steps 1-3 Research 1977
2. Maximize efficiency of conversion to gas.		
3. Laboratory scale—1 lb. organic waste/day yielding 5-10 ft. ³ methane/day.	2. Minimize cost of methane fuel generated.	Steps 4-6 Development 1983
4. Pilot plant—10 tons organic waste/day yielding 100,000-200,000 ft. ³ methane/day.		
5. Demonstration plant—100 tons organic waste/day yielding 1-2M ft. ³ methane/day.		Step 7 Commercial After 1983
6. Commercial unit—1,000-10,000 tons organic waste/day yielding 10-100M ft. ³ methane/day.		

temperatures range from about 500°C to as high as 900°C or more.

STATUS

Extensive batch studies of pyrolysis of organic wastes have been carried out in the United States, Europe, and Japan [24,25, 26,27]. It has been established that pyrolysis is technically feasible as a method of processing solid municipal wastes. The efficiencies in the past have been low and the net fuel production was small. Significant increases in efficiency have apparently been made, and it is now reported that the combustible gases are sufficient to operate the plant and that about two barrels of oil are obtained per ton of dry organic material. A pilot plant handling four tons of urban waste per day has been operated. Figure 8 shows a schematic of the process. Laboratory tests show that at higher temperatures the process can also be used to make gas instead of oil. The heating value of the gas was about 770 BTU/ft.³, 80% of the dry organic matter being converted.

LIMITING FACTORS AND RECOMMENDED APPROACHES

There do not appear to be any factors limiting progress to the demonstration phase which

would be in the 50 ton per day size. Current designs are for processing urban wastes which are a non-uniform complicated mixture of materials. If a grown organic of relatively uniform properties were used, the efficiency might be improved and the operating costs reduced. The major uncertainty in the near term utilization of this process is the cost of the fuel.

GOALS AND PROJECTED IMPACTS

The immediate goal should be a 50 ton per day demonstration plant. The next step should be a 500 ton per day operation. The first use for such a plant would be for urban waste disposal. The 500 ton plant could handle the urban wastes for a city of about 300,000 people. The experience gained in operating the plant on waste organics would be directly applicable to one operating on grown organics.

If the total amount of solid wastes previously assumed ($4-6 \times 10^7$ ton/year) were converted to oil, 130,000 to 230,000 barrels per day would be produced which is about 1% of our daily requirement. When larger amounts of material are available economically the impact will increase.

A first estimate of the cost of producing fuel from organic wastes is presented below for a 2,000 ton/day pyrolysis plant.

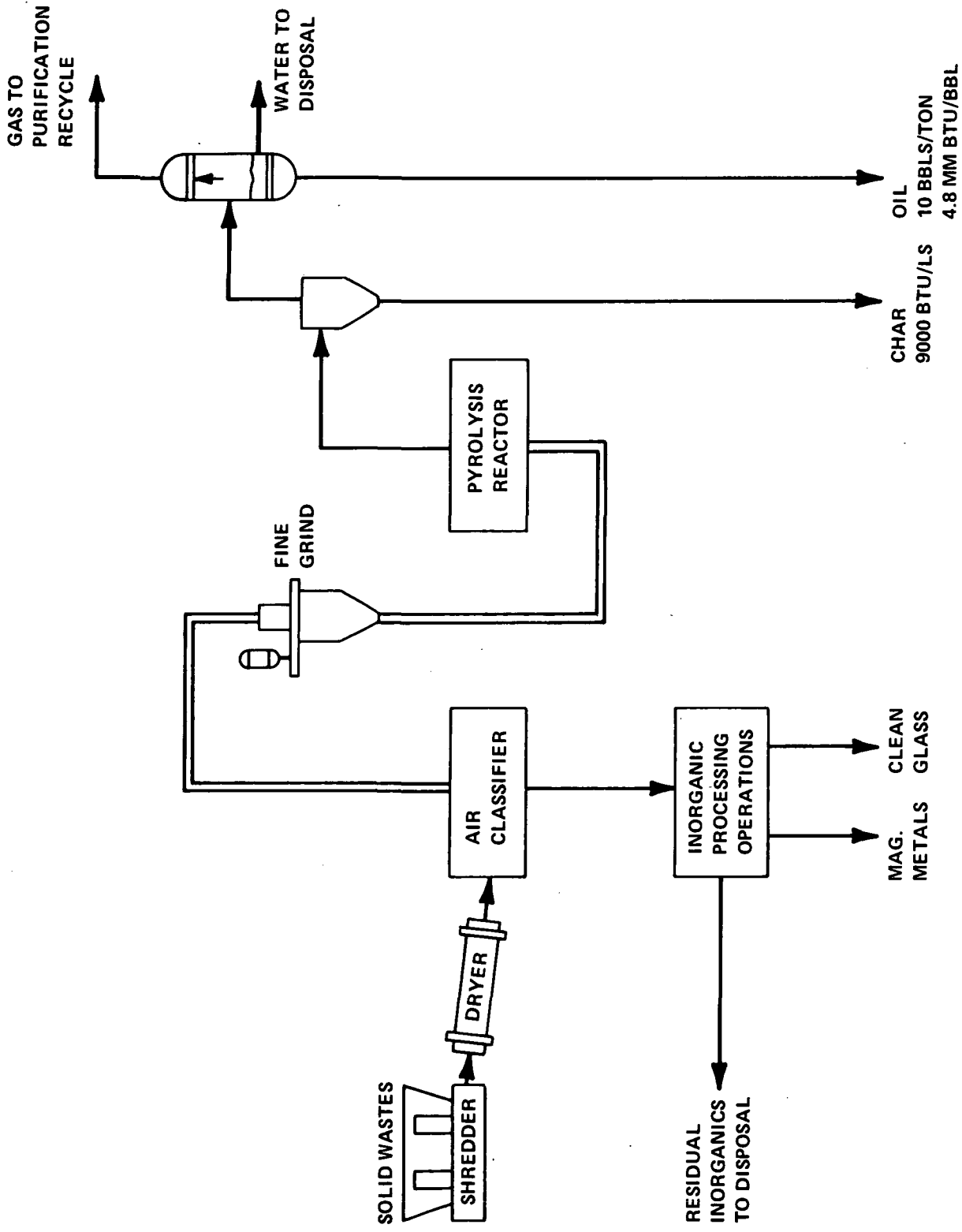


FIGURE 8. SCHEMATIC OF SOLID WASTE PYROLYSIS PROCESS

2,000 ton/day Solid Waste Pyrolysis Plant

Total Plant Capital (excludes land)	\$11.5 × 10 ⁶
Working Capital	\$0.4 × 10 ⁶
Annual Operating Costs (amortization, 25 years @ 6%	\$3.313 × 10 ⁶
Annual Net Profit From Sales	\$3.647 × 10 ⁶

This indicates a total operating cost of about \$.450/ton of as-received wastes. The net projected revenue from sale of products, after allowing for the disposal of unrecovered inorganics, is about \$5.00/ton (when based on 350 operating day/year). These economics suggest that a 2,000 ton/day processing plant could be operated at no net cost to a municipality.

RECOMMENDATIONS FOR R&D

Research is not required for the pyrolysis process. Although temperatures between 500°C and 900°C are used, the pressures are low and conventional structural materials can be used. The chemistry has been studied and demonstrated in both laboratory and pilot plant experiments. Work can begin immediately on a 50 ton per day production facility. Table 17 lists some major development projects. The expected funding for a 15 year program is \$50 million.

Chemical Reduction of Organic Materials to Oil

CONCEPT DEFINITION

Organic materials, when subjected to elevated temperatures and pressures in the presence of water, carbon monoxide and catalyst, are partially converted into oil having a heating value of about 15,000 BTU/lb. The continuous process is carried out at temperatures between 300°C and 350°C. Pressures between 2,000 psi and 4,000 psi are used with product yield increasing somewhat with increasing pressure. The residence time of organic material under reaction conditions is from 1 to 2 hours. During the reaction, oxygen is removed from the solids and appears as carbon dioxide in the product gas. Not all of the organic material is converted to oil and some residue is left for disposal. Figure 9 schematically illustrates the process.

STATUS

Laboratory batch experiments have converted organic refuse into oil by treatment with CO and water at elevated temperatures and pressures [28]. Simpler materials, such as sucrose and cellulose that typify the carbohydrate structure of organic wastes, were also studied. A small continuous unit, capable of handling one pound of feed per hour has been operated in tests of 5 to 20 hours duration. The product is a

Table 17. R&D Requirements for Pyrolysis of Organic Materials to Gas, Liquid, and Solid Fuels

Steps to economic feasibility	Major technical problems	Time scale
1. Full scale conceptual design studies.	1. Optimize operating parameters to maximize fuel production for different feed materials.	Steps 1-3 Research 1976
2. Economic, environmental and systems analysis pilot plant studies.		Step 4 Development 1980
3. Demonstration plant—50 b/bl. oil output/day.		Step 5 Commercial after 1985
4. Demonstration plant—500 b/bl. oil output/day.		
5. Commercial units—10,000 b/bl. oil output/day		

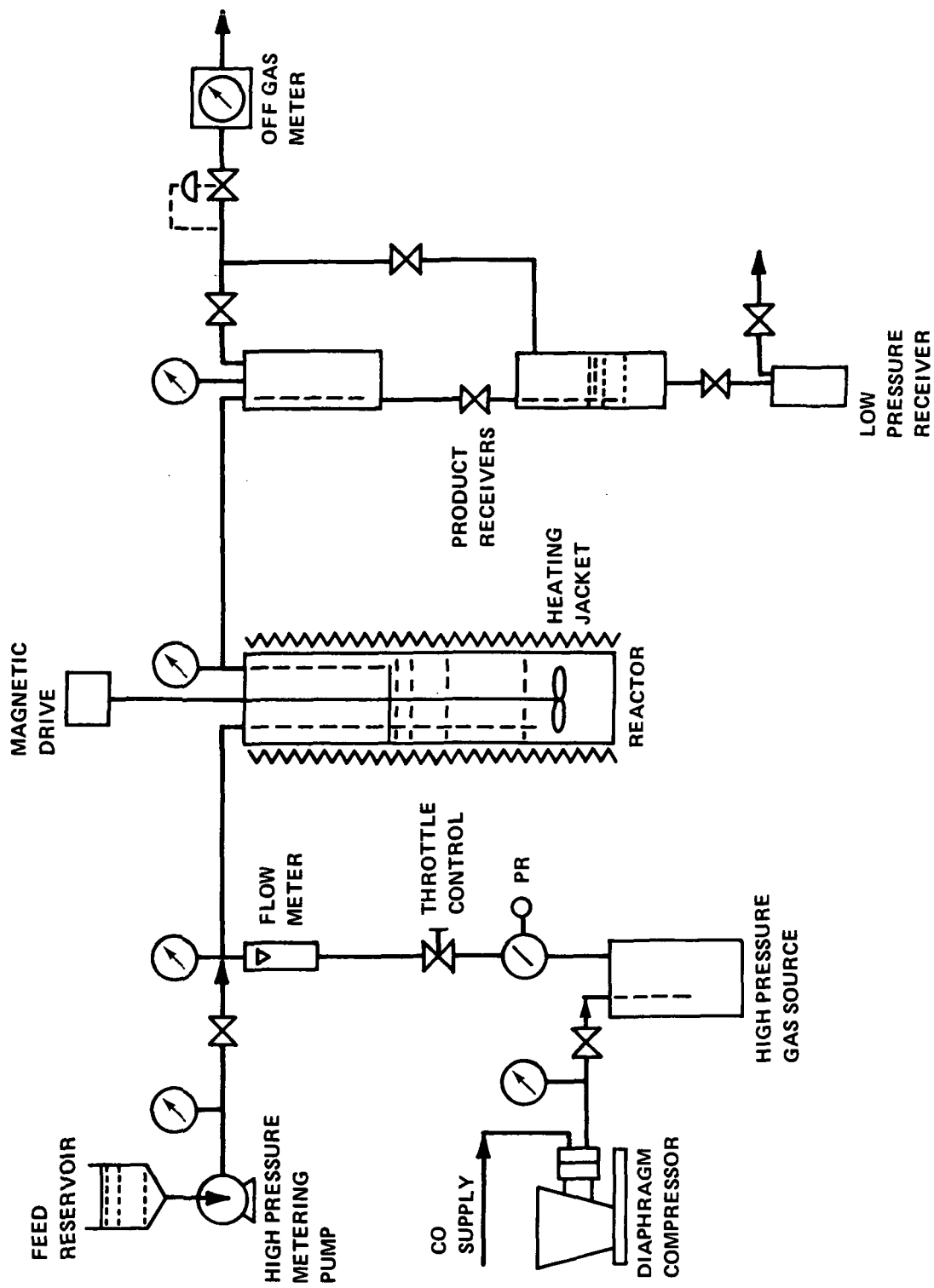


FIGURE 9. CONTINUOUS UNIT FOR THE CHEMICAL REDUCTION OF ORGANIC WASTES TO OIL WITH CO AND H₂O

liquid consisting of oil, water and unconverted refuse. The oil must then be separated from this liquid. Oil yields amounting to 40 percent by weight of the dry feed have been obtained in batch laboratory experiments.

LIMITING FACTORS AND RECOMMENDED APPROACHES

The process has been demonstrated in a laboratory size plant. No technical problems have been identified that would preclude full scale operations. The recommended approach is to proceed to a one to ten ton per day pilot plant to establish technical and preliminary economic feasibility. Successful performance would indicate economic information. This operation could lead to a commercial plant of 1,000 ton per day capacity. A one to ten ton per day plant would provide sufficient information to permit this process to be compared with other fuel making processes.

GOALS AND PROJECTED IMPACTS

The immediate goal is a pilot plant experiment of at least one ton per day. The organic feed systems and the oil separation system are sensitive to size. Consequently, the pilot plant size should be selected so that the important characteristics of these components are tested. The pilot plant would be used to qualify the process for the small scale demonstration plant phase (100 ton/day) leading to a 1,000 ton/day commercial operation. Information reported for this process suggests 100% recovery of the heat content of the feed in the form of an oil and carbon.

Using the solid waste quantity considered to be readily accessible, namely $4-6 \times 10^7$ tons dry organic material/year and assuming a 40% yield of a product having the stated heat of combustion of 30.4×10^6 BTU/ton, between 4.8 and 7.2×10^{14} BTU/year becomes available for use. This represents 67% of the heat value of the solid waste.

A first cost estimate for a 900 and a 10,000 ton/day oil production facility indicates:

Preliminary Cost Estimates:

Part A: Key Economic Factors

1. Process gas is CO, costing \$.01/lb.
2. CO consumption is 0.5 lb./lb. refuse.
3. System pressure is 4,000 psig.
4. Process yield is 2 b'bl. oil/ton of dry refuse (anticipated).
5. Income of \$4/b'bl. oil.
6. Income of \$5/ton of dry refuse, disposal charge.

Part B: Cost Figures

Plant size	900 ton/day	10,000 ton/day
Plant cost	$\$20 \times 10^6$	$\$200 \times 10^6$
Direct operating cost	$\$2.1 \times 10^6/\text{year}$	$\$15 \times 10^6/\text{year}$
Net operating profit	0	$\$11 \times 10^6/\text{year}$

The smaller plant was considered to have more than enough capacity to handle the solid wastes from a population of 300,000 people or from a cattle feedlot serving 200,000 head.

The larger plant was considered to handle the solid wastes from a population of 3.33×10^6 people or from a cattle feedlot serving 2.2×10^6 head.

RECOMMENDATIONS FOR R&D

Construct and operate a one ton per day pilot plant to pinpoint unforeseen technical problems and to establish the economics of the process. At least two years would be required to complete this task. At this time decision could be made relative to design, construction and operation of a 100 ton/day demonstration plant.

A total of seven years (2 years design and construction and 5 years operation) should allow development of good process cost information and, if economic, permit a commercial size plant to be built and operated. The estimated cost of this 15 year overall program is \$60 million.

Comparative costs of various fuels from different sources is shown in Figure 10.

Enzymatic Reduction of Organic Substances

CONCEPT DESCRIPTION

Closely related to the conversion of organic materials to gaseous fuel by means of a fermentation process is the conversion of suitable

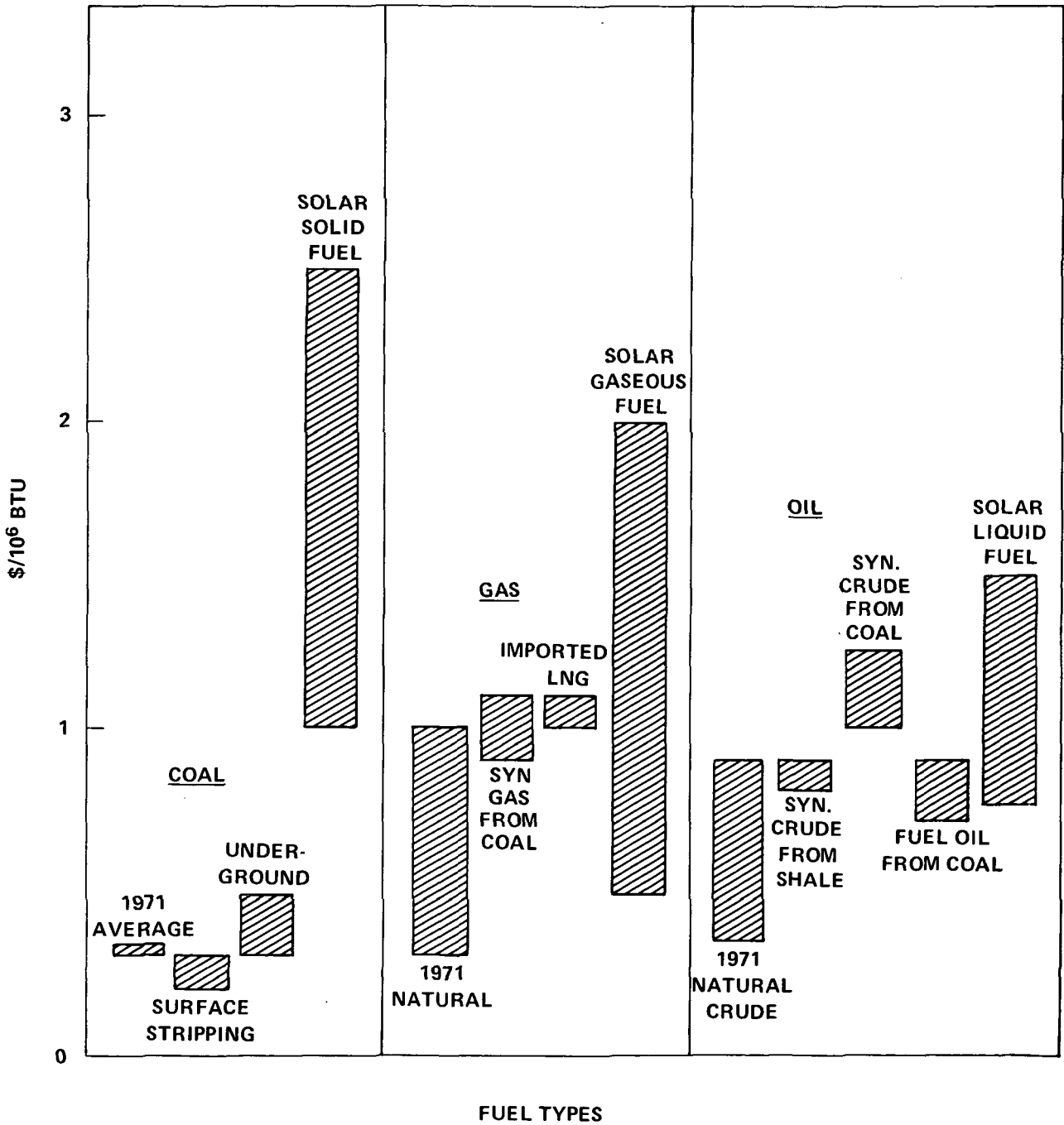


FIGURE 10. COSTS OF FOSSIL & SOLAR RENEWABLE FUELS

organic materials to valuable pure products, chemical raw materials or clean fuels by specific enzyme attack.

Enzymes are organic substances, produced by living cells, that are capable of catalyzing relatively specific synthesis or degradation reactions.

It is anticipated that the action of selected enzymes on components of organic solid wastes could lead to the production of salable products. For example, cellulases are able to convert cellulose (waste paper) to simple sugars; other enzymes are capable of converting these sugars to alcohol. In a similar sense proteases and

peptidases are able to hydrolyze the $-CO-NH-$ links in proteins and peptides to amino acids and other potentially useful foods.

STATUS, GOALS, AND IMPACTS

The recent developments which have resulted in the immobilization and stabilization of enzymes by physical or chemical coupling with various solid substrates promises the eventual low cost industrial scale conversion of organic substances to provide high yields of new compounds desirable as feed concentrates for man or animal, raw materials for further chemical synthesis or as clean fuels.

ELECTRIC POWER GENERATION

Solar generation of electricity for use on earth holds the promise of an abundant clean source of power. Solar energy systems can be designed so that they have a minimal effect on the local heat balance.

Even though most of the present power generation plants cause a very significant amount of pollution, it is technologically possible, but costly, to reduce air and water pollution to acceptable levels. The question of utilizing solar radiation for central power generation thus becomes primarily a question of establishing its economy in comparison with conventional power systems considering future trends in fuel cost, energy conversion and the cost of environmental protection.

A variety of approaches have been suggested for the use of solar radiation in central power generation. Each approach involves clearly identifiable steps in a chain leading from solar radiation to power delivered to the consumer as shown in Figure 11. Certain steps in different concepts correspond to the same generic function even though the specific implementations may be different.

At the start, a distinction is made between "natural" collection and "technological" collection of solar energy. Natural collection occurs in the atmosphere, giving rise to wind and rain, and on the earth's surface, resulting in the growing of plants, and the creation of temperature differences in the ocean.

In technological energy collection man-made structures collect the incoming solar radiation. The solar radiation may then be converted through the photovoltaic effect directly into electricity, or the heat generated by solar radiation, as one possibility, might be used directly to "fuel" a conventional power plant. In both cases there is power only while the sun shines.

In an alternate approach, an energy storage facility may be used from which heat is withdrawn at a constant rate, or on demand, for the operation of a power plant or from which electrical energy can be directly withdrawn. In a third possibility, the energy might be used to

generate a chemical fuel such as hydrogen and oxygen.

Electric power which is only available while the sun shines could be used to generate chemical fuel, for example, hydrogen, by the electrolysis of water. Chemical fuel could be shipped as such and could be converted to electrical power deliverable to a consumer either through a conventional power plant or through a fuel cell.

If one provides energy storage then electric power can be available on demand from a power source which delivers power only while the sun shines. After transmission, this power is deliverable to the consumer.

Solar power plants are capital intensive, while the "fuel" is free. This implies that all electricity that the power plant can generate should be used. Particularly if the power has to be transmitted over a considerable distance, the electrical output should be constant throughout a 24-hour cycle to minimize transmission cost. In order to equalize the diurnal variation in solar energy input, energy storage systems will be required in most cases.

In terms of today's cost, a large central solar powered plant with energy storage that is capable of delivering electricity at a constant rate, or on demand, must compete with other sources of electricity costing about 9 mills per kWh. Smaller plants, located close to an end user may compete with power worth up to three times the value indicated, due to savings in distribution cost and the higher fuel cost of conventional "intermediate load" plants.

In special cases, solar power generation without storage might be used for "peaking" applications. In general, however, such power if delivered directly into a network requires conventional standby capacity of equal magnitude. Energy provided in this manner would be worth the cost of fuel saved in the conventional plant.

Typically its value would be a factor of two or three lower than energy produced in a plant with energy storage. Other possible uses of such interruptible power include delivery to other

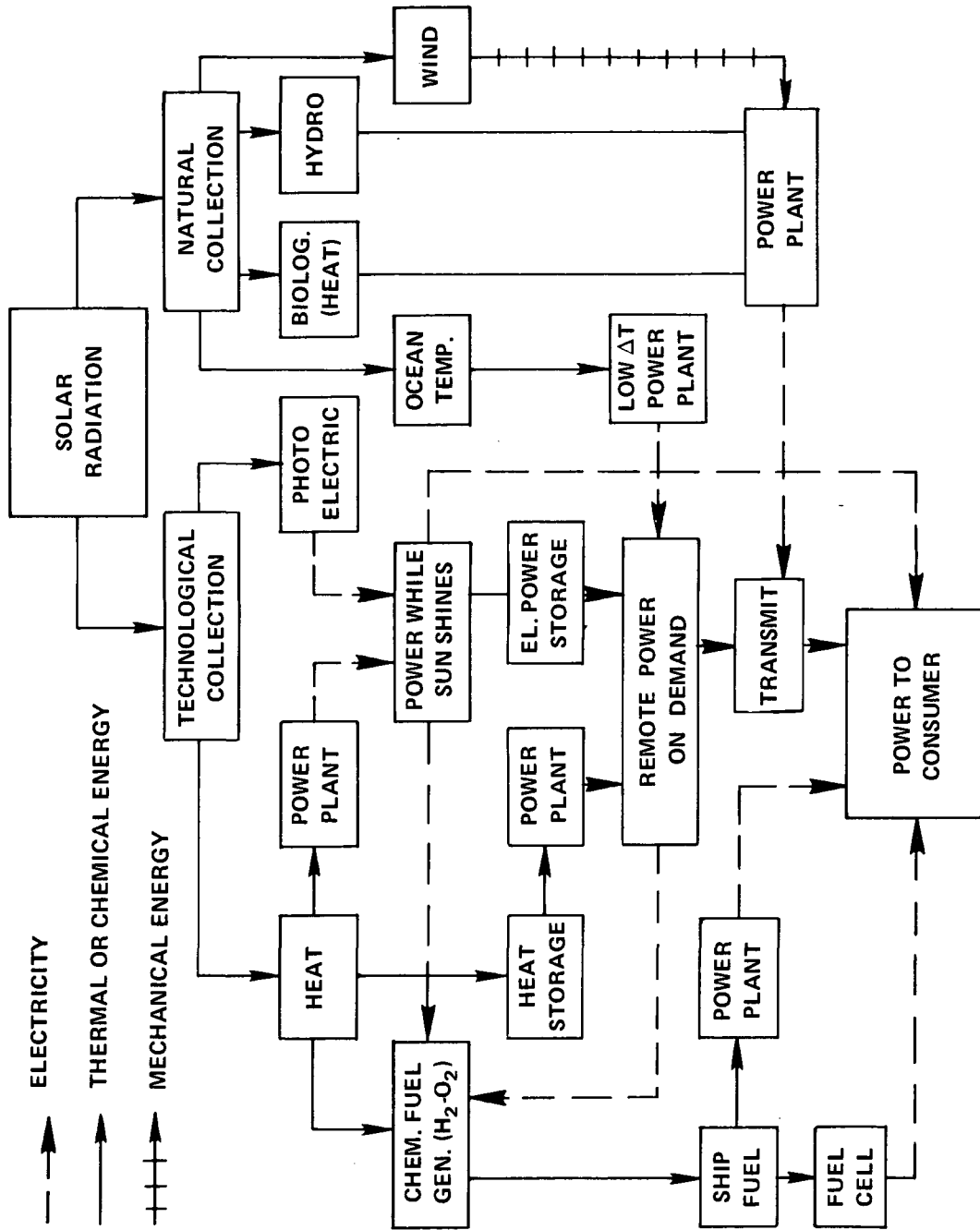


FIGURE 11. CONVERSION OF SOLAR ENERGY TO ELECTRICITY

energy storage facilities, the production of chemical fuel (another method of energy storage), or the use in certain manufacturing facilities such as aluminum plants. In all cases solar power without storage must compete with "dump" power such as excess energy from a plant which normally is not fully utilized around the clock.

Clearly if low cost methods of storing electricity become available, the power generated by all types of power systems can be made available on demand and will have the same nominal value. A potentially important energy storage and transmission system involves the use of hydrogen which can be generated by electrolysis and can be converted back to electricity at the demand point by use of fuel cell technology [29]. This system can not only provide storage but also permits very low energy transmission costs over long distances.

SOLAR THERMAL CONVERSION

Concept Description

Thermal conversion systems consist of solar collectors and thermal storage devices delivering thermal energy to a turbine power plant. Through the use of high temperature selective solar absorber coatings recently developed for the space program, temperature in the range of standard steam turbogenerators can be achieved with relatively low solar concentration—on the order of 10. This makes possible the use of relatively low precision optics for concentrating the solar radiation.

One of the current concepts [30] consists of five major elements, as shown in Figure 12: (1) a solar concentrator to concentrate the sun's energy; (2) a receiver to absorb the concentrated energy; (3) means to transfer the heat to the thermal storage facility or to the turbo-generator; (4) a thermal storage element to store thermal energy for use at night and on cloudy days; and (5) a turbo-generator to produce electrical energy.

Several variations of this basic approach have been proposed, and some are under active study. The most promising systems employ "linear"

heat absorbers, e.g., absorbers extending primarily in one dimension thus permitting heat transfer through a pipe and concentrators with cylindrical symmetry. Estimates of conversion efficiencies (direct solar insolation to electrical power) in the range of 20 to 30% have been made. In the southwestern part of the U.S. approximately 10 square miles are needed for a 1,000 megawatt power plant capable of operating on the average at 70% of capacity.

Status

There are no technical limitations that would prevent a solar thermal power station from being built today. The question is whether it would be economically competitive with other methods of power generation. It is this question which has to be answered to make the approach a practical reality.

Early systems, remarkably similar to the linear absorber system, were considered long ago. The most notable was a steam driven water pump built in Meadi, Egypt, in 1913-1914. With a parabolic trough reflector with cylindrical symmetry and a pipe receiver in its focal line sufficient steam was generated to operate a 50 hp steam engine.

Major new developments in civilian and military aerospace and in nuclear technologies, when applied to the basic thermal conversion approach, make the systems look far more attractive. For example, long life and low cost parabolic trough reflectors may result from recently developed durable reflective nickel coatings on plastic substrates. A variety of reflector coatings [31,32] were developed for the space program as well as high precision parabolic antennas made of fiberglass and reinforced plastic. Fresnel lenses represent today viable alternatives to reflectors.

The receiver located at the focus of the Fresnel lens or parabolic reflector is to be coated with selective solar absorber coatings which efficiently absorb solar energy and have low emissivity at longer wavelengths. Such coatings have been developed under government funding. With these coatings the design of efficient linear

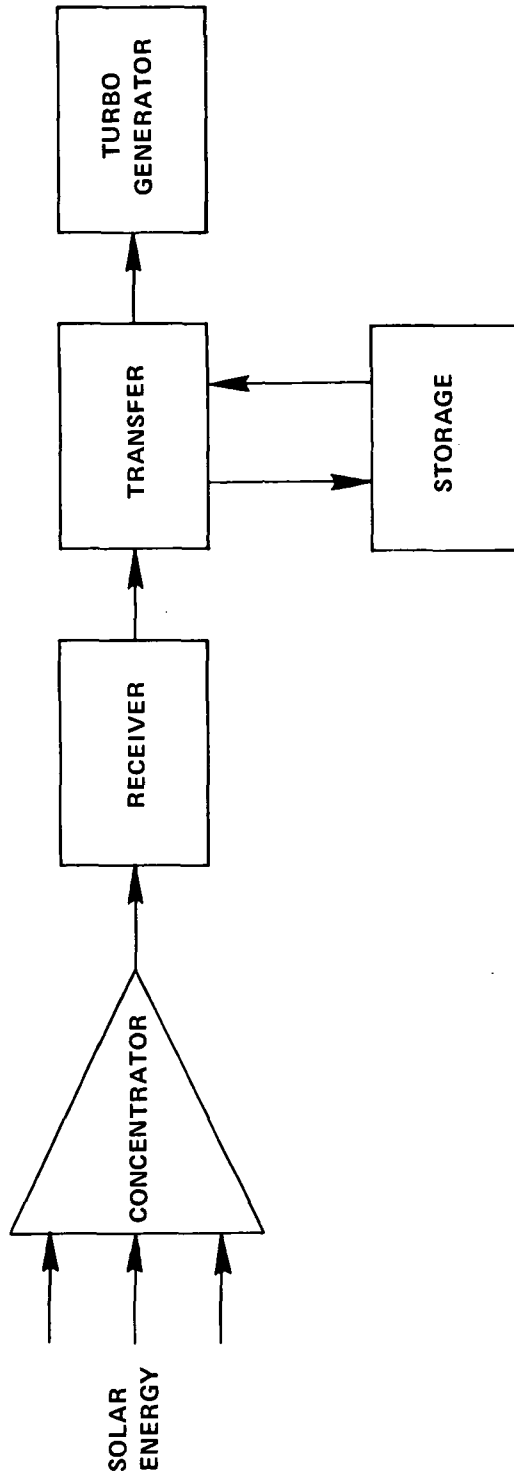


FIGURE 12. THERMAL CONVERSION CONCEPT

solar collectors with low precision optics operating at temperatures up to 1,000°F can be contemplated.

Considerable heat transfer technology has evolved as part of the reactor development and the space effort. Vast data exist on liquid metal heat transfer. Heat pipes* which can operate efficiently at steam turbo-generator temperatures have been developed and some of these heat pipes have been operated for over ten years.

Satisfactory schemes for storing thermal energy have been proposed, ranging from heat storage in large volumes of solids or liquids to heat of fusion of salts and salt mixtures. Liquid metal and molten salts containment techniques have been developed and heat storage using fused salts have been used in satellites. There is however a question of the applicability of the specific techniques from an economic point of view.

The present funding level of R&D directed specifically at solar thermal systems is approximately \$500,000 per year.

Limiting Factors and Recommended Approach

The key problem in central electric power generation via solar thermal conversion is to find an engineering solution that is economically viable and that assures long-life operation with a minimum of maintenance. Specifically, the optical components, e.g., concentrator and absorber surfaces, have to maintain their performance for many years while exposed to the elements.

It is recommended that all promising alternatives of component elements be studied under various environmental and simulated operating conditions. Subassemblies should be prepared and tested for feasibility demonstrations.

All available data on direct (nondiffuse) solar insolation for various parts of the country should be compiled. Measurements should be made to supplement any missing data needed for system trade offs. Continued systems analysis should be carried out in parallel with the component studies to evaluate the potential performance and cost competitiveness of the

subsystems under investigation. In addition, methods for best interfacing the solar-generated power with the existing electrical power grid should be studied.

When economic viability is indicated, a pilot plant of 10 to 25 megawatts should be constructed and operated. Based on the data from the pilot plant a size optimization study should be made and a full-scale demonstration plant should be considered. The size of the demonstration plant might be 100 to 1,000 MW as indicated by the optimization study.

A first attempt at estimating the cost of such a facility has been made, based on mass produced components. This pre-supposes a considerable amount of engineering and a successful solution to several unresolved problems. For the solar collection part including energy storage, a cost of \$600/kw has been obtained. The turbine generator unit and other power plant peripherals add about \$150/kw. Due to the summer-winter variation in average solar insolation such a plant can be expected to operate at a capacity factor of 70 percent. This gives an estimate of energy cost of about 20 mills/kWh assuming 15.5% cost of capital and 1 mill/kWh for operation and maintenance.

Although this number has a considerable amount of uncertainty it is sufficiently close to today's costs that a detailed evaluation leading to commercial readiness is warranted, since it is quite probable that this approach will be a viable alternative to electric power generation as fuel costs rise and environmental controls increase the capital cost of power plants.

Goals and Projected Impact

GOALS

The first major goal of the solar thermal conversion program is to establish technical feasibility for a low cost design. This should be achieved *within* about five years. If the cost or cost trends indicate that the system may be cost competitive in the future, a pilot plant followed by a full-scale demonstration plant should be built and operated. The program should be designed to permit commercial availability by 1990.

*A high efficiency, isothermal heat transfer device.

IMPACT

If at the date of commercial availability the approach proves economical, maximum impact on our nation's electrical needs is expected to be limited to about 1/4 of the new power plant starts after the year 2000 since the siting of such plants is restricted to areas with high direct (nondiffuse) solar radiation. Therefore, at best, about 15-20% of the total U.S. generating capacity in the year 2020 can be solar thermal. A more realistic estimate might be that 10% of the new starts after the year 2000 will be solar plants leading to 5% of the Nation's generating capacity in the year 2020.

No adverse environmental impact is expected except for the cooling problems similar to those of conventional power plants. Solar power

plants will be principally located in remote areas where the effects of appearance will be minimal.

Short-Range R&D

The recommended short-range research and development program (see Table 18) is geared to satisfying the first program goal of establishing cost competitiveness within about five years. The expected total effort planned over a 7-year period is estimated to cost \$25 million. A key feature of the program is to continue environmental life tests of the exposed optical elements and a system and heat storage analysis.

Long-Range R&D

The recommended long-range research and development program (see Table 19) consists of

Table 18. Solar Thermal Conversion Short-Range R&D Program (Feasibility Study and Component Development).

Task	Year						
	1	2	3	4	5	6	7
System analysis (concept definition, component integration, cost trade offs, power plant interface and environmental impact)	[Bar spanning years 1-5]						
Establish environmental test procedures and preliminary tests of components	[Bar spanning years 1-2]						
Heat storage							
Analysis and selection of approach	[Bar spanning years 1-2]						
Verification tests	[Bar spanning years 3-5] life test						
Concentrator development	[Bar spanning years 2-5] life test						
Heat transfer							
Analysis and selection of approach	[Bar spanning years 2-4]						
Verification tests							
Collector subassembly verification test	[Bar spanning years 2-3] life test						
Improved solar absorber coating development	[Bar spanning years 3-7]						

a pilot plant and demonstration plant design, construction and operation. The estimated program costs for these plants are \$100 million and as much as \$1,000 million, respectively. Industry may share the cost of the demonstration plant. The overall R&D program is laid out to meet the second program goal of making the solar thermal conversion power plant commercially available by 1990.

Phased Program Plan

The long and short ranged R&D plans are phased into three phases as shown in Table 20. Milestones are indicated where information will be available for making key decisions before the next larger and most costly tasks are initiated. The estimated funding for the total 15 year program is \$1130 million.

PHOTOVOLTAIC SOLAR ENERGY CONVERSION SYSTEMS

Concept Description

Photovoltaic conversion systems are based on the utilization of the photovoltaic effect in solid state devices. In these devices, absorption of light generates free electrical charges which can be collected on contacts applied to the surfaces of the semiconductor. The theoretical limit efficiency for the conversion process is about 25% for a single-semiconductor device operating at room temperature [33,34,35]. Device operation at lower temperatures results in increased efficiency [36], but operation below ambient temperature in the earth environment is energetically not advantageous.

The various proposals for photovoltaic systems to supply large amounts of electrical power for terrestrial consumption can be classified into three types:

1. Photovoltaic systems on buildings, with the converters attached to or incorporated into the building structures, and supplying energy to activities connected with the buildings;
2. Ground central systems [37], with large

contiguous or distributed, but connected photovoltaic collectors, serving either a distribution system or single large consumers; and

3. Central systems in space, with power transmission to central ground stations and subsequent distribution.

Status

Photovoltaic devices made from silicon have supplied essentially all of the power used by the spacecraft of all nations. Their performance and reliability in space is well established. In addition, small quantities of solar cells have been made and applied utilizing other semiconducting materials, predominantly cadmium sulfide, cadmium telluride, and gallium arsenide.

For terrestrial energy applications, solar cells are in use in the U.S., Great Britain, Japan, and other countries in form of small "packaged power" systems to energize transistor radios, various types of remote sensing devices, harbor and buoy lights, microwave repeater stations, highway emergency call systems, etc. [38]. Some of these systems have been in successful operation for over 9 years. However, large photovoltaic systems for terrestrial applications have not been built, although the basic technical capability exists.

Present annual U.S. production of silicon solar cells, manufactured nearly exclusively for the space program, amounts to 50-70 kw electric [39]. The average efficiency of present production cells is near 11 percent for space, 13 to 14 percent for terrestrial applications, with 13 to 13.5 percent for space and 15.5 to 16 percent terrestrial applications reported on recent laboratory cells [40]. To make extensive application of silicon solar arrays for terrestrial consumption economically feasible, their price will have to be reduced by a factor of at least 100 from present levels [41]. A significant part of this is expected to be gained through the required million-fold expansion of production rates and attendant automation. However, it is felt that new process approaches will have to be identified to provide for a continuous flow of

**Table 19. Solar Thermal Conversion Long-Range R&D Program
(Pilot and Demonstration Plant)**

Task	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Pilot plant															
Design				█											
Component fabrication					█	█	█								
Plant construction						█	█	█							
Plant operation								█	█	█	█	█			
Demonstration plant															
Design										█					
Component production										█	█	█	█	█	
Plant construction										█	█	█	█	█	
Plant operation														█	█

operations from the raw material to the completed array, possibly in part similar to integrated circuit fabrication. A number of ideas have been advanced for individual process steps which could be important to the establishment of such integrated processing. Foremost among these are methods for obtaining ribbons or sheets of single crystal or large crystal silicon by (1) edge-defined film growth [42], (2) dendritic growth [43], (3) rolling silicon [44], and (4) casting sheets with subsequent recrystallization through heated or molten zones [45]. Once such single or large crystal sheets are available, integrated solar arrays could be formed from them by possibly as few as 7 operations, e.g., vapor deposition, heating, and ion implantation in a continuous, flow through process. Optical filters with a comparable number of such operations are now quoted at \$0.40/ft.². Another approach consists of automated assembly of

small silicon spheres, produced by a modified shot tower method, into a large plastic encapsulated assembly. All of these approaches require experimental verification of technical feasibility. Several cost analyses have been provided which show possibility of reaching the economic goal of generating cost-competitive electric power [42,46]. Silicon itself is the second most abundant element in the earth's crust and is produced in the U.S. at the annual rate of 66,000 tons in metallurgical purity at \$600/ton [46], which is a sufficiently low basic material cost.

Thin film Cu₂S-CdS solar cells have been prepared in pilot line quantities (total 10 kw) for over 12 years, with efficiencies of 4 to 6 percent for terrestrial applications, and over 8 percent reported on development models [47]. The processes used for their fabrication appear readily amenable to low cost mass production

Table 20. Summary and Milestones--Solar Thermal Development Program.

Phases	Year																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Feasibility study and component development.	<div style="text-align: center;"> </div>																			
Pilot plant.	<div style="text-align: center;"> </div>																			
Commercial production.	<div style="text-align: center;"> </div>																			

Feasibility study and component development.

Pilot plant.

Commercial production.

Technical feasibility and economic viability decision.

Construction go-ahead decision

Des. Construction Operation
 Production decision.

methods. In the past, the thin film $\text{Cu}_2\text{S}-\text{CdS}$ solar cells have been plagued by degradation and low yields for long life [48].

Interest in the U.S. has been reawakened for terrestrial applications, and recently reported process changes are hoped to result in long life arrays [47,49]. A cost estimate for a system using $\text{Cu}_2\text{S}-\text{CdS}$ solar cells and including power conditioning, system protection, installation, and a 15% annual cost of capital, taxes, and maintenance, has arrived at a cost of 2 to 4¢/kwh of generated electricity [50].

Other semiconductor materials have not been sufficiently developed to be of interest for extensive solar energy applications at this time but research into new methods of solar energy conversion should be initiated [51].

Current R&D is primarily directed towards increasing size and decreasing weight of spacecraft power systems, increasing resistance against radiation in space, and increasing the efficiency of silicon solar cells towards 20 percent in space. This work is supported by NASA and the U.S. Air Force at a combined annual level of approximately \$3 million.

NSF under the RANN program and NASA under its Applications program have an interest in terrestrial applications, and are beginning to support R&D towards low cost photovoltaic approaches. During the last year, one company has started to develop reduced cost photovoltaic systems in an effort to expand the market in "packaged power" as a step towards large scale terrestrial applications of photovoltaic systems. Also, a group of companies has pooled capabilities to develop the concept of obtaining power from space.

Photovoltaic Systems on Buildings

CONCEPT DESCRIPTION

The application of photovoltaic arrays on buildings locates the generator at the place of the load, reducing the need for energy transmission and distribution with the associated losses and costs. The system thus matches the distributed nature of solar energy to the distributed pattern of energy consumption.

In this approach, photovoltaic arrays are

mounted on buildings or form part of their structures, the latter presenting economic and possibly aesthetic advantages. The basic installation does not differ from that of solar thermal collectors. A particularly attractive approach is to combine the photovoltaic array with a flat plate thermal collector [52,53], since most buildings require both thermal energy (hot water supply, space heating, absorption refrigeration, air conditioning, low temperature process heat, etc.) and electrical energy (lighting, motive power, electronics, high temperature process heat, etc.). In this case which is illustrated in Figure 13 the absorber surface of the thermal collector is formed by the solar array which converts a portion of the incoming solar energy into electrical energy, and permits collection of about 50% of the remaining energy in the form of heat. Although some of the efficiency of the solar array is traded off for thermal energy collection, this combination system provides advantages:

- up to 60 percent of the available solar energy can be utilized;
- the thermal collector uses the same land area as occupied by the buildings; and
- the components fulfill several functions, yielding a more cost effective system.

As in all terrestrial solar energy utilization systems, energy storage is required. In general it is considered uneconomical to provide local storage capacity for more than an average day's requirement [6]. Thus, auxiliary energy will be needed at times. The overall system concept shown in Figure 14 includes several subsystems: solar array, electrical power conditioning, energy storage, auxiliary energy, and possibly power line interfaces. Storage can be provided by batteries, electrolysis cell-fuel cell systems, flywheels, etc. [54,55,56].

Benefits of the use of photovoltaic systems on buildings are:

- Minimal effect on the ecology through use of land areas already being used for other purposes.
- About three times the present average household consumption of electric power can be collected from average-size family residences, even in the northeastern U.S.

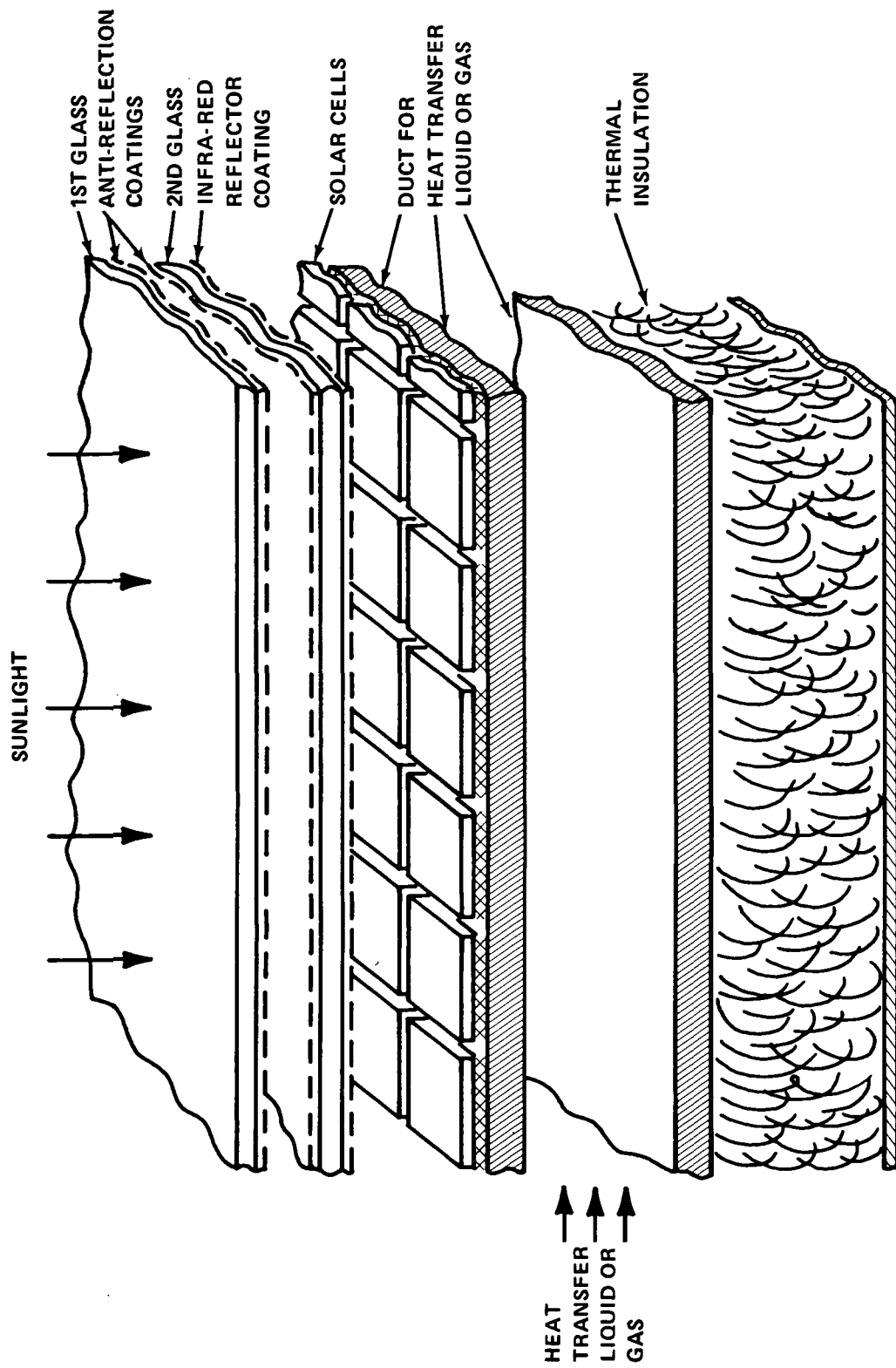


FIGURE 13. STRUCTURE OF COMBINATION THERMAL-PHOTOVOLTAIC SOLAR COLLECTOR

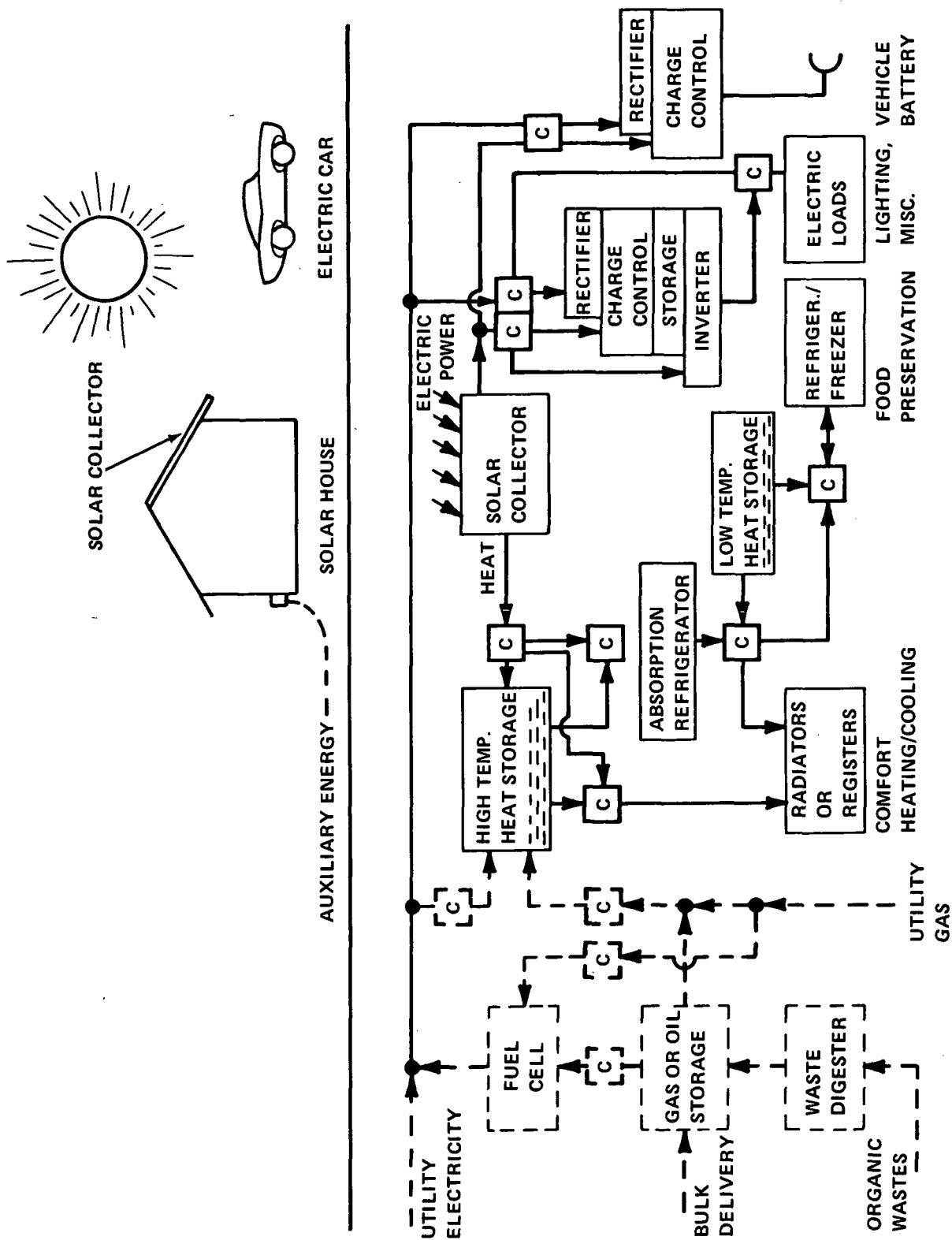


FIGURE 14. SCHEMATIC OF SOLAR ENERGY SYSTEM FOR RESIDENTIAL BUILDING

Assuming the energy storage problem solved, this energy surplus may make the electric automobile feasible.

- Invulnerability to breakdowns in energy distribution or centralized generation systems.
- The small size of the individual unit makes prototype testing and demonstration relatively inexpensive, and will help to attract consumer oriented industries.

STATUS

Systems larger than the "Packaged Power" systems have not been built, although the technology and the components are available. Only preliminary feasibility studies have been performed on combination thermal/photovoltaic systems.

LIMITATIONS AND KEY PROBLEMS

The maximum installable array area approximately equals the ground area covered by buildings. Attention will have to be paid to the orientation, location and shading of buildings in the same manner as for thermal collectors. This will make most existing buildings unsuitable for retrofitting. The introduction will therefore generally be limited to new construction. Further, only up to 90% of the new buildings will be suitable for solar energy collection. In addition, the highly fractionated nature of the construction industry will result in slow market growth, taking 20 years or more to reach saturation.

Low cost (\$0.50 to \$3.50 per ft.² for combination systems, less for others based on \$0.02/kWh credit for the energy supplied by the system) and long life of solar arrays (minimum: 10 to 20; goal: 20 to 40 years) in the earth environment are the key problems to be solved for reaching commercial readiness. For Si solar arrays, cost reduction is the primary task. For Cu₂S—CdS solar arrays, the major tasks appear to be increases in both life and efficiency. It is estimated that the development goals can be attained with adequate effort within 10 years.

Development of energy storage devices of sufficiently low cost and long life is the second key problem. Again, multiple approaches are under investigation. The remaining subsystem

and system problems such as inexpensive DC to AC conversion equipment, require engineering development.

GOALS AND PROJECTED IMPACTS

The key problem areas, status and goals for photovoltaic systems on buildings are outlined in Table 21. An estimated schedule to demonstration of commercial readiness is shown in Figure 15. Since confidence in reaching the key component goals is high, and subsystem and prototype systems are relatively small and inexpensive, it is recommended that subsystem development and system testing be undertaken in parallel with the component development. This approach will cut time to start of introduction approximately in half. The projected impacts are shown in Table 22.

Ground Central Stations

CONCEPT, STATUS, IMPACTS

Significant areas in regions of adequate insolation would be covered with photovoltaic arrays to feed power into a distribution grid in the manner of a utility power plant [37]. Many variations have been proposed, including arrangement of the arrays for partial shading to permit agricultural activities beneath, or distributed arrangement of the arrays interconnected to form a central station [50]. Since solar arrays without concentrators accept diffuse radiation, significant amounts of power can be generated even on overcast days.

The basic technology required for photovoltaic ground central stations does not differ significantly from that of the systems on buildings, except for scale and for site preparation and installation.

Because of the commonality in technology, and the smaller unit size of the systems on buildings, the emphasis should initially be placed on technology development for the latter system type, with simultaneous feasibility studies and subsequent systems definition for the ground central stations.

The projected impacts are shown in Table 22.

Table 21. Key Problem Areas and Required Action for Photovoltaic Systems on Buildings

Key Problem Area	Present Status	Development Goal	Basis for expectation of success	Required Action
I. Solar Array				
1. Cost (\$/ft ²)	70 for ground arrays Si 1,000-8,000 for space arrays Cu ₂ S-CdS —	3.5 or less 0.5 or less	Millionfold production increase, new approaches Estimates from lab. processes	Process develop't. automation, quantity production Automation, quantity production
2. Life (years)	Si >9 (no degradation) Cu ₂ S-CdS 2 (50% degradation)	20-40 10-20	Data, existing technology Prelim. data on few cells	Array design, life testing R&D, extensive life testing, array design
3. Cell efficiency (%)	Si 13 space; 15.5 GNO Cu ₂ S-CdS 5-8	20 10	Theory Laboratory experience	R&D R&D
II. Energy Storage				
1. Cost (\$/kW from each cycle at proper depth of discharge)	~100	≤50	Lead-acid batteries	R&D on batteries of abundant materials (Li, Na, S, Cl), fuel cells and on flywheels etc.
2. Life (cycles) (years)	<3000 5-7	>4000 >10	Industrial Experience	"
III. Other Subsystems (Power Conditioning, Charge Control, etc.)				
1. Cost (\$/kW)	N/A	50	Existing Technology	Engineering Development
IV. System				
1. Data Acquisition				
a. Solar Input	N/A	Spectral Distribution-statistics	N/A	Development of sensor systems.
b. Use pattern	N/A	N/A	N/A	Instrumenting sample and prototype houses
2. Optimization	N/A	N/A	N/A	Engineering analysis

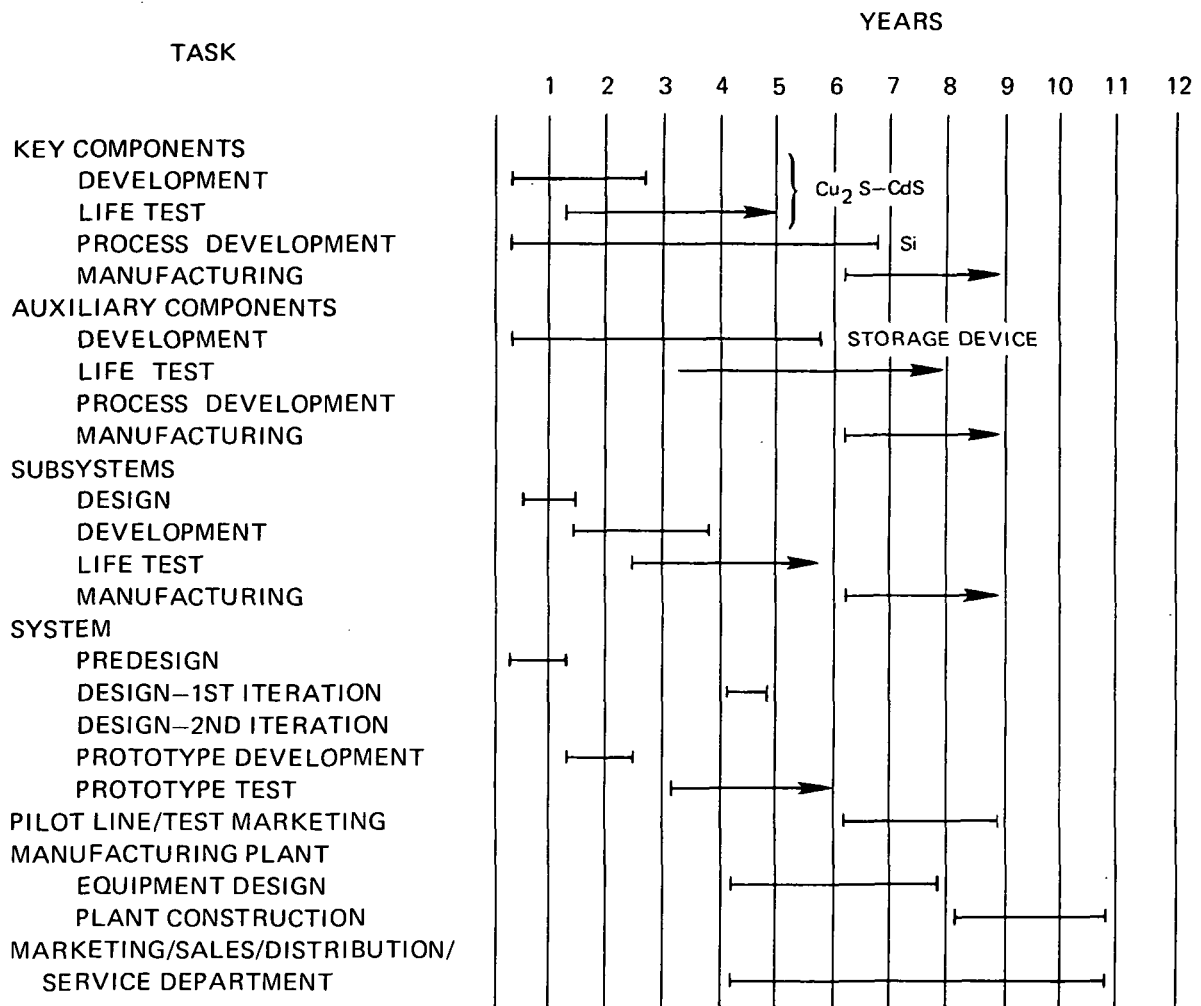


FIGURE 15. MILESTONES FOR PHOTOVOLTAIC SYSTEMS ON BUILDINGS.

Electric Power From Space

CONCEPT DESCRIPTION

A satellite in synchronous orbit around the earth's equator receives solar energy for 24 hours a day, except for brief periods around the equinoxes. In this orbit, a satellite receives six to ten times the amount of solar energy available in suitable terrestrial locations in the U.S. As illustrated in Figure 16 the dc power generated in space by such a satellite would be beamed via microwaves to the ground and there reconverted to high voltage dc or ac power to meet base or demand load needs. In addition such satellites could serve as communications or observation bases.

The use of microwaves at a frequency near 3GHz for power transmission from the satellite to earth provides minimum loss in the ionosphere and troposphere. This loss has been estimated to average 6 percent and to remain moderate even in severe rainstorms. To obtain adequate beam definition at this frequency, a transmitting antenna of approximately 1 km diameter is needed. The transmission efficiency is expected to be in the 55 to 75 percent range from dc in space to dc on earth [57].

The transmitting antenna diameter determines the economical system size, which ranges from 4,000 to 15,000 MW power output on earth. The system as initially conceived utilizes 2 mil thick silicon solar cells to form two solar

Table 22. Impact of Electric Power Generation by Conversion of Solar Energy

Impacts	Residential/commercial	Large industrial & ground central stations	Space station
Initial impact (1%)			
Growth	1980 earliest 1985 probable	1990	
Total	1985 earliest 1995 probable	2000	1990-2000
Significant impact (10%)			
Growth	1985 earliest 1995 probable	2000	2000-2010
Total	1990 earliest 1995 probable	2020	2020-2030
Resources			
Materials	Non-critical if Si Adequate if CdS	Non-critical if Si Adequate if CdS	Undetermined
Environmental (operation only)			
Land use	None	2002: $3 \times 10^2 \text{mi}^2$ 2020: $3 \times 10^3 \text{mi}^2$	2000: 30mi^2 2020: 300mi^2
Air	None	None	Rocket exhaust from launch
Water	None	None	Undetermined
Radioactivity	None	None	None
Noise	None	None	Restricted to launch
Visual	Minimal, may require larger roof angle	Dark surfaces observable	Undetermined
Safety	None	None	Low intensity microwave radiation
Waste	None	None	None
Thermal	None beyond conventional dark roofs	Possible development of heat islands	10-20% above consumable energy is added to terrestrial heating burden.

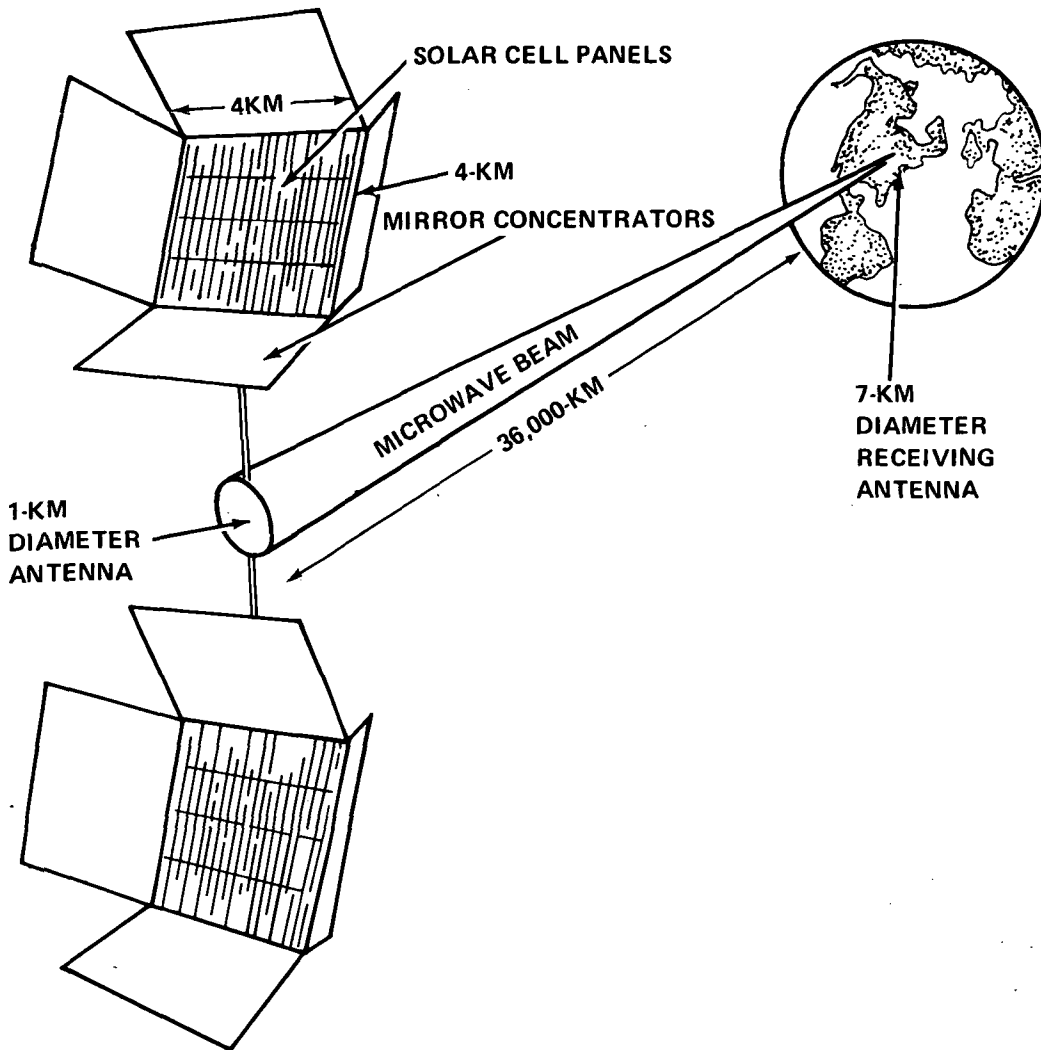


FIGURE 16. SPACE STATION CONCEPT TO PRODUCE 10,000 MW.

collectors capable of providing about 10,000 Megawatts on earth. For economy, lightweight mirrors would reflect solar energy onto the solar cells to achieve a concentration ratio of approximately 3. The 25,000 ton station would be transported in parts to low earth orbit by 300 to 1,100 flights of a second generation space shuttle, and from there to synchronous orbit by ion propulsion.

STATUS

Since 1963, over 50 satellites of the U.S. have been placed in synchronous orbit. They have been powered by silicon solar cells, with a combined capacity of approximately 7 kW, and

the power systems of some have functioned for more than 5 years. Through them, a considerable amount of information on photovoltaic power system performance and on attitude control in synchronous orbit is available. The Air Force has successfully flown a 1.5 kW rollout array of 22W/lb. [58], while designs of a 100 kW capacity system for the NASA Manned Space Station are being prepared. Present prices for space flight qualified solar arrays range from \$1,000 to \$8,000 per ft.².

A partially reusable space shuttle is under development, designed to provide transportation to low earth orbit for \$100 per pound. Solar powered ion propulsion has been demonstrated

in space through the NASA SERT program. Both of these systems can form the technology basis for the space power station transportation system.

Microwave generators with more than 5 kW output and 76 percent efficiency have been demonstrated. Highly directional, self-steering (retro-directive) antenna arrays have been developed by the Air Force for radar and communications purposes. For the receiving antenna system, rectifier diodes with 75 percent efficiency are available.

For the space power station system which will be 100,000 times larger than the Manned Space Station, only preliminary concept studies have been carried out.

LIMITATIONS AND KEY PROBLEMS

Demonstration of commercial readiness assumes availability of the presently planned space shuttle. Installation of the operational system would require a second generation shuttle, with an estimated development cost of \$10 billion, which would be capable of providing transportation to low earth orbit at a cost of \$50/lb. At an annual average introduction rate of 3.5 stations, up to 11 shuttle starts per day may be required, excluding flights for servicing. With a 2 to 3 day turn-around time, approximately 30 shuttles (\$100 million each) would be needed, with adequate service and launch facilities and noise buffer zone.

Chemical pollution could be minimized through use of hydrogen-oxygen fueled shuttles, but the influence of the additional water in the upper troposphere requires study. The microwave safety and radio frequency allocation/interference questions require answers, which are expected to be found in a planned Office of Telecommunications Policy Program.

At a projected cost for the commercial system of \$20 billion per station (\$2,000/kW), including transportation and ground station costs, the cost of the generated electric power would be near 38 mills/kWh. With 52 percent of the projected station cost attributable to the solar arrays, achievement of a solar array cost reduction to \$32/ft.² or less assumes special importance. Special engineering problems to be

solved include the large weight reduction for the solar arrays and their deployment in extremely large structures of low weight, combined with the requirement for orientation and attitude control. The interaction of large flexible systems with the attitude control operation requires special investigation. Methods for assembly of large, flexible systems, composed of many parts, by automated or man assisted methods in space would need to be developed, as well as low cost transportation to synchronous orbit. The microwave transmission system requires engineering development based on existing technology. This task is expected to be eased through repetitive use of few component types in benign operating modes. Demonstration of commercial readiness of the system would require a major national commitment, comparable to the "Peaceful Uses of Atomic Energy" and "Man on the Moon" programs. However, such a commitment is not required during the first 10 years of the project, during which technology development of general usefulness would be carried out.

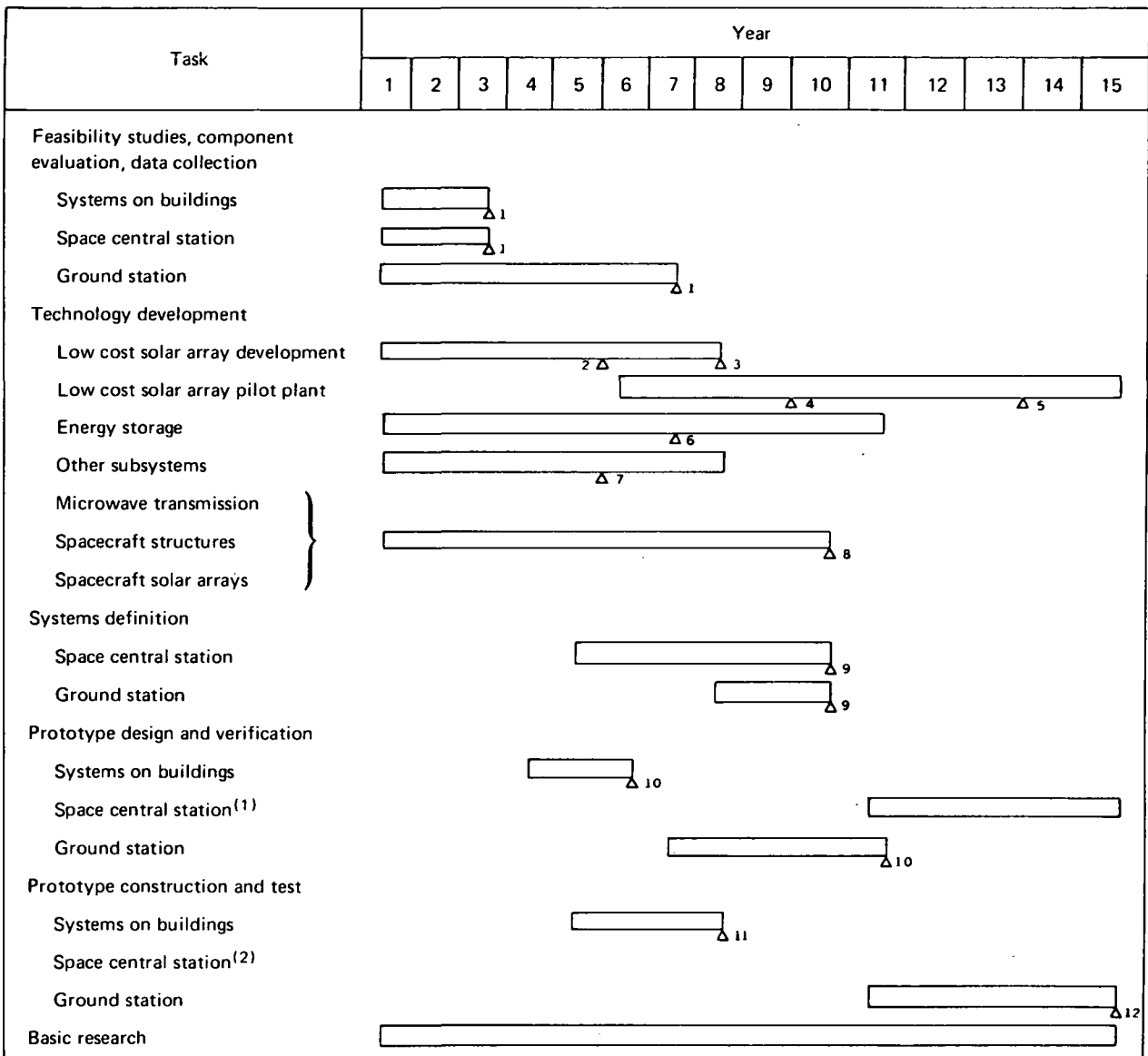
The development tasks, with status and goals, are outlined in Table 23. Development of the system depends on successful completion of most of these tasks. It would therefore be difficult to assign, at this time, a success probability higher than low to the entire system. Through component and subsystem technology development and systems studies in the first phase of the proposed program, this uncertainty would be stepwise decreased in the early years and should be essentially removed before a decision on commencing the second phase is made, which includes the major national commitment.

GOALS AND PROJECT IMPACTS

The impacts are listed in Table 22 and the phasing and milestone schedule is shown in Table 23. This schedule has been designed to allow for:

1. Sufficient systems/technology assessments to determine its true potential before proceeding to system development or demonstration.

Table 23. R&D Summary and Milestones for Photovoltaic Electric Generation.



Notes: (1) Includes flight experiments for verification.
 (2) Initiated after 15 years.

- Milestones:
- ▲₁ Technical and economic feasibility of system evaluated.
 - ▲₂ Technical feasibility and cost potential of process established.
 - ▲₃ Processes further improved.
 - ▲₄ Pilot plant constructed and operation initiated.
 - ▲₅ Process sufficiently refined and evaluated to justify construction of large scale production plant.
 - ▲₆ Feasibility of long-life, low-cost storage subsystems established.
 - ▲₇ Basic engineering development of other subsystems complete.
 - ▲₈ Technology adequately developed to permit systems development.
 - ▲₉ Results of systems definition indicate feasibility for prototype design.
 - ▲₁₀ Prototype design and component/subsystem verification tests justify prototype construction.
 - ▲₁₁ Prototypes successfully demonstrated, justify test marketing.
 - ▲₁₂ Prototype tests successful, justify test marketing of small systems, demonstration plant for large systems.

2. Sequential reviews where major programmatic go-no go decisions/commitments can be made.
3. Flexibility for the nation's decision makers to permit exercising this power system option, when and if needed.

Recommended Research Program for all Photovoltaic Systems

The proposed research programs are designed to demonstrate technical and economic feasibility on the component and subsystem level before entering into costly systems demonstrations. Systems feasibility studies should be carried out simultaneously to provide direction to the technology development work, and to prepare for ensuing decisions on systems development. These studies may have to provide the necessary input for feasibility analysis and later system design.

The main development required is the production of very low cost arrays, regardless of what ultimate photovoltaic system is used. Therefore, work should be continued at an accelerated rate in materials, processes, and system design to make low cost solar arrays available. Their use in future space programs and specialized ground applications is assured even if they could not be produced economically enough for large scale solar power stations. As soon as it becomes evident that a low cost solar array of adequate life and performance is attainable, a pilot plant should be designed, built and operated to prove the process.

During the first 3 program years, the emphasis should be almost completely on component and subsystem development and feasibility studies. As a possible exception, low cost prototype development could be started on photovoltaic systems for buildings to facilitate early introduction.

In the following 7 years, the photovoltaic systems for buildings should proceed to prototype evaluation, pilot line operation and test marketing, assuming the technology development having progressed satisfactorily. The space power station would continue in technology development and in systems definition, which

should also commence for the ground central stations. It may be noted that the low cost solar array process development is equally applicable to all three systems. The space power station however, requires modification to achieve especially low weight and radiation resistance.

In the time span beyond 10 years, the system design and development of the space power station prototype and transportation system could take place, followed by system demonstration. The photovoltaic systems for buildings should then be in commercial status, and design and test of the first ground central station could proceed.

A detailed schedule and milestone chart has been included for the pacing item, the Low Cost Solar Array Research and Development task (see Figure 17).

A number of approaches should be pursued under each schedule item. The milestones form decision points for continuing or shifting efforts.

Table 23 presents a milestone plan, arranged in program phases for each of the major system types. The transition points from one phase to the next form the major milestones which are the key decision points in the individual programs. The estimated funding for the overall photovoltaic R&D program is \$780 million.

WIND ENERGY CONVERSION

Concept Description

Solar energy sustains the winds [59]. It is calculated that the power potential in the winds over the continental U.S., the Aleutian arc and the Eastern seaboard is about 10^{11} kilowatts electric. Winds are remarkably repeatable and predictable. The momentum in moving air can be extracted by momentum-interchange machines located in suitable places such as plains, valleys and along the continental coastal shelves [60].

A desirable windpower system incorporates its own storage and its own peaking capability as shown in Figure 18. It is thus able to span between variable wind to patterned electricity consumer demand. This system could be nearly pollution-free. The electrical energy generated

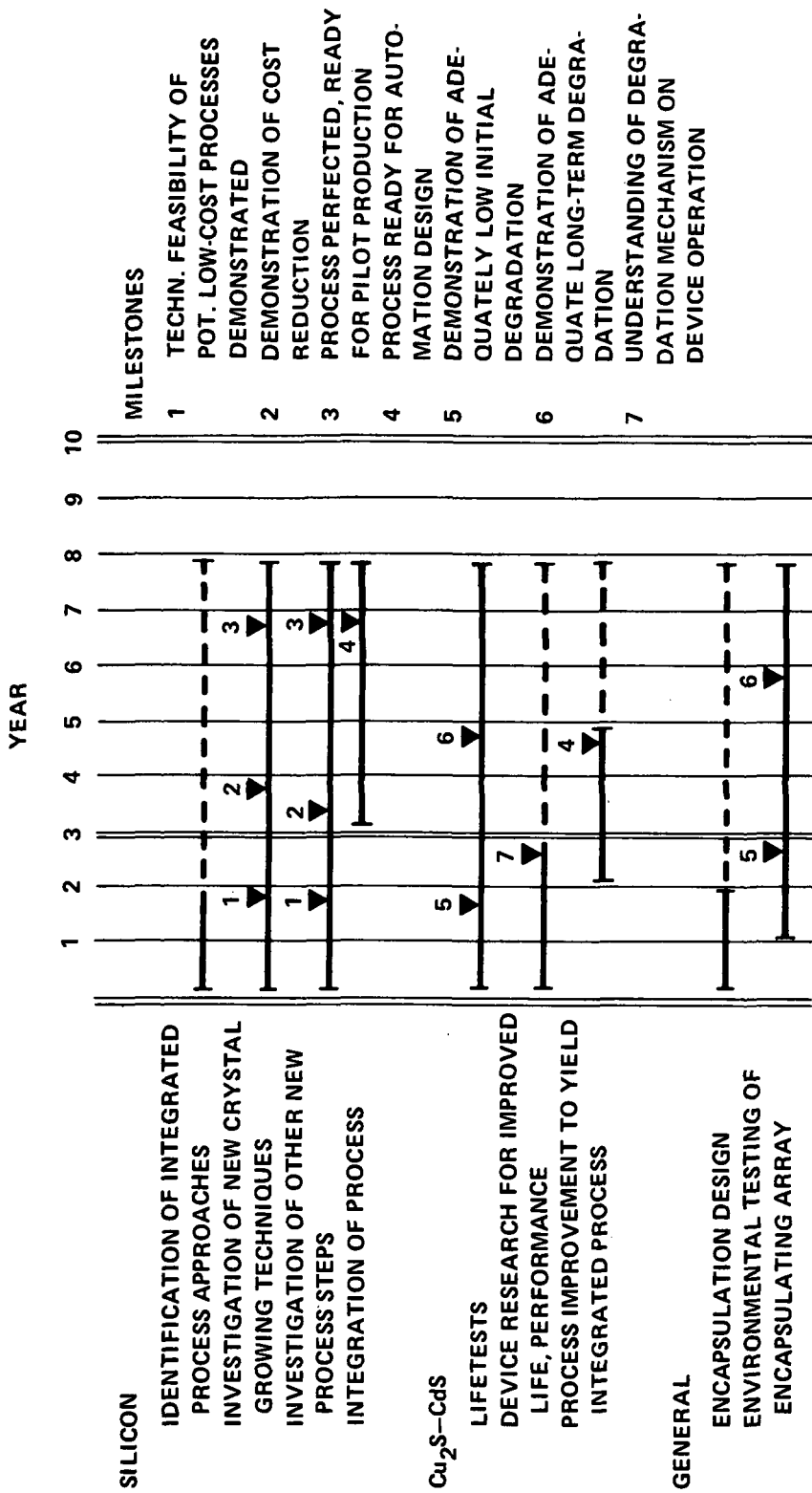


FIGURE 17. PLAN FOR LOW COST SOLAR ARRAY TECHNOLOGY DEVELOPMENT

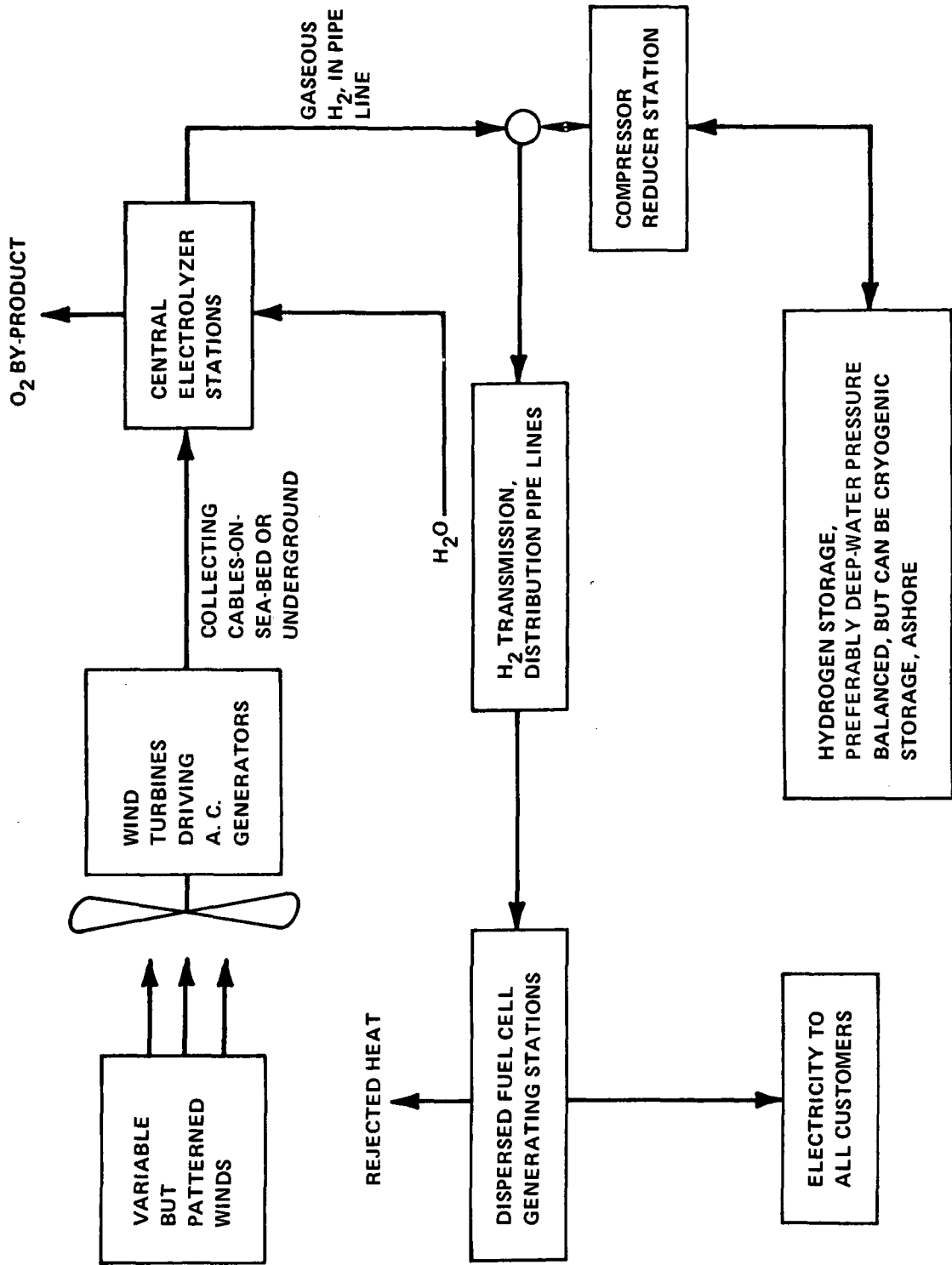


FIGURE 18. BLOCK DIAGRAM OF ONE PROPOSED WIND CONVERSION SYSTEM

by the aeroturbines located off-shore is used to electrolyze water. The hydrogen thus produced is transmitted by pipeline to shore or compressed and stored for use during calm periods. In such a manner hydrogen can be supplied on a continuous basis to fuel cell or thermal electric generating stations. It should be emphasized that the offshore-hydrogen storage approach is only one of several worthy of exploration.

Status

There was a mature technology for windpower sixty years ago. Steady improvement was made through the 1950's directed toward large-scale applications. In 1915, 100 Mw of electricity were being generated by windpower in Denmark. Today electricity brought in by cable from Sweden's hydroelectric plant is less expensive. In the 1940's a 1.25 Mw machine was built and operated at Grandpa's Knob, Vermont [61], but was shut down by a materials failure of the blade. A conceptual design using aeroturbines to produce 160 billion kilowatt hours of electricity per year has recently been completed for the offshore New England region [62]. This preliminary study shows that the electrical power when used to produce hydrogen which is then piped onshore for consumption in power plants is cost competitive with conventional methods of producing electrical power.

Limiting Factors and Recommended Approaches

The limiting factors in the large scale application of windpower are a combination of available wind energy and weather modification. The effect of large numbers of closely spaced windmills has not been assessed. There are no known technological limitations to the application of windpower.

The windpower program should start with a Federally financed research and development program which would include among its first tasks: (1) examination of global and local limitations on the extraction of kinetic energy from the winds with emphasis on possible weather modification, and (2) a study of legal constraints against the large-scale use of windpower.

Goals and Project Impact

It is proposed that windpower be developed in the regions described in Table 24. The maximum generating capacities are also shown in this table. The maximum total energy generated by conversion of wind power is about 19% of the year 2000 annual electricity production. The annual capacity in each site was calculated using available wind velocity-duration data, at specified heights, impinging that wind against either 200 ft. diameter (2 Mw) or 60 ft. diameter (100kW) wind turbines.

Short Range R&D Program

A 3-year program is set forth in Table 25. A large fuel cell development program is included because some of the most attractive concepts require efficient (>50%) and inexpensive (<\$115/kW) fuels cells. The same need for a fuel cell program can be found in many of the other Solar Energy and Ocean Energy Programs, however. Any energy scheme which produces hydrogen, methane or an alcohol fuel should be equally interested in this major task.

Long Range (4th through 10th year) R&D Program

A recommended program phasing is presented in Table 26. The estimated funding for this 10 year program is \$610 million.

POWER FROM OCEAN THERMAL DIFFERENCES

Concept Description

Between the Tropics of Cancer and Capricorn where the intensity of incoming solar energy reaches its peak, 90 percent of the earth's surface is water. That surface layer is in thermal equilibrium at a temperature that never drops below 82°F. To the far North and South the intensified summer insolation melts down the previous winter's accumulation of frozen precipitation. That meltdown slides to the depths of the oceans and slowly moves toward the equator, forming the cold water ways of the

Table 24. Maximum Electrical Energy Production From Wind Power

Site	Annual power production	Maximum possible by year
(1) Offshore, New England	159 × 10 ⁹ kWh	1990
(2) Offshore, New England	318 × 10 ⁹ kWh	2000
(3) Offshore, Eastern Seaboard, along the 100 meter contour, Ambrose shipping channel south to Charleston, S.C.	283 × 10 ⁹ kWh	2000
(4) Along the E-W Axis, Lake Superior (320 m)	35 × 10 ⁹ kWh	2000
(5) Along the N-S Axis, Lake Michigan (220 m)	29 × 10 ⁹ kWh	2000
(6) Along the N-S Axis, Lake Huron (160 m)	23 × 10 ⁹ kWh	2000
(7) Along the W-E Axis, Lake Erie (200 m)	23 × 10 ⁹ kWh	2000
(8) Along the W-E Axis, Lake Ontario (160 m)	23 × 10 ⁹ kWh	2000
(9) Through the Great Plains from Dallas, Texas, North in a path 300 miles wide W-E, and 1300 miles long, S to N. Wind Stations to be clustered in groups of 165, at least 60 miles between groups (sparse coverage)	210 × 10 ⁹ kWh	2000
(10) Offshore the Texas Gulf Coast, along a length of 400 miles from the Mexican border, eastward, along the 100 meter contour	190 × 10 ⁹ kWh	2000
(11) Along the Aleutian Chain, 1260 miles, on transects each 35 miles long, spaced at 60-mile intervals, between 100 meter contours. Hydrogen is to be liquefied and transported to California by tanker.	402 × 10 ⁹ kWh	2000

Estimated Total Production Possible: 1.536 × 10¹² kWh by year 2000

Table 25. Recommended Tasks, Short Range (3 Year) R&D Program for Windpower Development

1. Conduct technology review and economic feasibility studies.
2. Investigate global and local implications of large scale extraction of kinetic energy from the atmosphere.
3. Study institutional constraints against large scale windpower schemes.
4. Review and advance pertinent aerodynamic, structural, mechanical, and electrical theory and applicable design practice.
5. Assess environmental impact on marine, forest and plains ecology.
6. Study and advance marine architectural and pipeline theory.
7. Investigate and plan for least-cost large-scale production of components and subsystems.
8. With NOAA, establish and carry out a program for identification and quantification of "especially windy sites." Give emphasis to Great Plains and Rocky Mountains.
9. Design an appropriate set of demonstration units.
10. Start a large scale fuel-cell R&D program aimed at low-cost long-life hydrogen-oxygen and hydrogen-air mini-substation fuel cells.

oceans. It is thus possible under several hundred million square miles of ocean to find a nearly infinite heat sink at 35 to 38°F; at a level as little as 2,000 ft. directly beneath a nearly infinite surface heat reservoir at 82 to 85°F [63]. Both heat reservoir and heat sink are replenished annually by solar energy. A heat engine operating across a 50°F temperature difference in an 85°F heat source would be able, theoretically, to convert to useful work, 9 percent of the heat flowing across it.

The Gulfstream carries 1,000 and 1,500 million cubic feet per second of near-tropical sea water through the Gulf of Florida [64]. The stream can be said to flow in a path about 20 miles wide. Within a 500 mile length of that path, the thermal difference between the surface and the depths range from 27.5°F to 39°F [65]. That heat difference occurring at a surface temperature of 71.5°F, would permit a theoretical maximum conversion of heat into useful work of 5%. An overall practical efficiency of 2% can be expected. If one BTU from each pound of the warm Gulf Stream flowing through heat engines could be converted into useful work, an annual energy production of 700×10^{12} kWh would result. A collection system of units moored on one mile spacings along the length and across the breadth of that stream are thought capable of an annual energy production of 26×10^{12} kWh. In a suggested design, each unit would resemble a vertical axis spar buoy of about 100 feet diameter with an overall height of 220 feet. In one version, the hot-side heat exchanger would project outward to either side from a huge underwater kite. The total wing span (beam) for such a 400 MW unit is on the order of 400 feet.

A method for converting sea thermal difference into electrical power is shown in Figure 19, the Claude cycle [66]. One modification of the Claude cycle interposes an intermediate working fluid (e.g., propane) between the heat source and the heat sink. The expansion turbine operating on a hydrocarbon or fluoro-carbon fluid would be a fraction of the size of the turbine using vaporized sea water and the degassing ejectors could be eliminated in that cycle. However, the hot-side heat exchanger might be far more expensive than the flash evaporator which it replaces, so a trade-off will have to be made. For economy of energy transport, the electrical power can be conducted to electrolytic cells to make hydrogen fuel for use in fuel cells.

A preliminary estimate of the capital cost of each of these concepts is in the \$200 to \$400 range per kW of capacity; further information is needed for confident appraisal.

Table 26. Proposed Windpower R&D Program.

Task	Year												
	1	2	3	4	5	6	7	8	9	10	11	12	
1. Execute the tasks proposed to confirm windpower technical and economic feasibility (Table 25).	[Bar]			△1									
2. Plan for large-scale component and system acquisition.		[Bar]											
3. Provide continuing R&D support for windpower development.													
4. Design, build, install, and operate windpower components and pilot plants.													
5. Development of fuel cells for use with aeroturbines.													
6. Construct, emplace, and operate several complete 100 Mw wind systems.													

△1 Decide if pilot plant should be started.

△2 Begin production of adequate prototype fuel cells and/or other storage devices for the 100 Mw wind system.

△3 Start detailed design purchasing and fabrication of several 100 megawatt wind units complete with energy storage and delivery systems.

① First demonstration units operable.

Status

In 1929 the Claude cycle was successfully demonstrated in Cuba; 22 kW of useful power were produced in an engine whose actual overall efficiency was less than 1 percent. Two experimental units of 3,500 kW net output, each working in the Claude cycle were installed off the Ivory Coast in 1956 by the French. Due to mechanical failure and other problems the plants were abandoned after a short time. There is a small continuing French R&D effort in this field at the time and the NSF has just funded a feasibility study in the U.S.

Limiting Factors: Recommended Approach

Large-scale use of the ocean thermal differences process could be limited by a combination of technical and economic problems.

The possible technical and economic problems require analysis. At least three competitive concepts, three heat engine cycles, and two energy transmission systems should be analyzed in enough detail, separately and in various combination, until credible cost estimates can be made.

1. The concepts to be investigated:

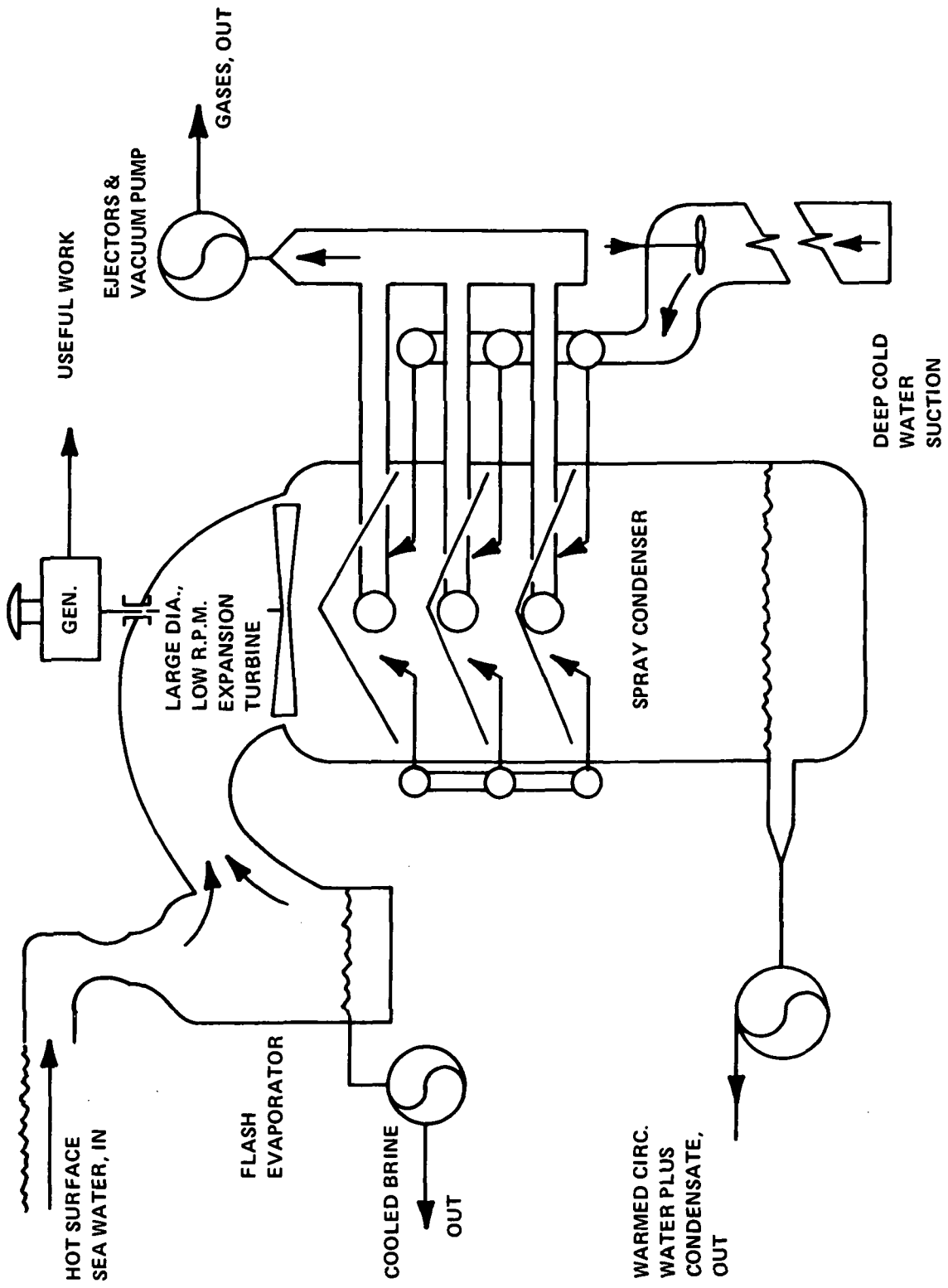


FIGURE 19. THE CLAUDE OCEAN THERMAL DIFFERENCES PROCESS

- a. Afloat units, well out in the moving water of the Gulf Stream.
 - b. Afloat units, near shore in nearly stagnant water in the Gulf Stream.
 - c. Afloat units, well out in the Gulf of Mexico at the shelf's edge, in essentially stagnant water.
2. The cycles to be investigated:
 - a. Rankine cycle, sea water working fluid.
 - b. Rankine cycle, distilled water working fluid.
 - c. Rankine cycle, hydrocarbon or fluorocarbon working fluid.
 3. The Energy Transmission Systems to be investigated:
 - a. ac or dc electricity transmission via cable.
 - b. On-site electrolytic generation of hydrogen, energy transmission via pipeline gas.

The analyses would get down to a configuration for each subsystem and component, adequately described and specified as to permit careful cost estimation. Verification of technical feasibility and determination of costs would go hand-in-hand.

There is no social limiting factor seen to large-scale ocean thermal differences use. None of these plants will be visible from the beach.

It is anticipated that the large-scale use of this process would best meet socio-economic-political approval if it includes economical distribution of energy throughout the country. A new concentration of industry and population near the Gulf and southeast Atlantic Coast might not be acceptable. Pipeline distribution of energy as hydrogen gas seems to be an answer.

There are no anticipated adverse environmental effects associated with large-scale use of the ocean thermal differences process, but possible effects on marine life and shipping would need

to be studied. There is potential for improvement of the marine environment by the equivalent of natural upwelling of cold bottom water, rich with nutrients, into the photic zone.

Once technical and economic feasibility have been established by analysis, the development of components, subsystems, and prototypes should be undertaken.

Goals and Projected Impact

In the concept description it was estimated that 26 trillion kilowatt hours/year of energy could be recovered from the Gulf Stream off the U.S. southeast coast. If that energy is converted and transported as hydrogen gas, subsequently reconverted to electricity in fuel cells, about half to two-thirds of the energy would be recovered. If to that one adds a small portion of the energy that could come from the Gulf of Mexico, at shelf edge and beyond, the total annual production could exceed the year 2000 projected total energy demands.

A Recommended Short Range (3 year) R&D Program

A 3-year program of study oriented toward problem definition, concept feasibility, preliminary design, and economic evaluation is first recommended. Distribution of effort by activity is indicated in Table 27. At the conclusion of this program, data for a decision on continuing the development should be available. The merits and prospects of this system should be compared with others under investigation and with conventional methods. Part of the study outlined above has already been initiated with NSF support.

The Proposed 15 Year R&D Program

The 15 year R&D program, outlined in Table 27 is estimated to cost \$530 million.

Table 27. Electrical Power From Ocean Thermal Differences: 10 Year R&D Program.

Task	Year														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Conduct technology and economic feasibility studies.	[Bar]		▲1												
2. Conduct oceanography review of selected sites; establish and monitor ecological base line.				[Bar]			▲2								
3. Design, fabricate, and test key subsystems and components.				[Bar]			▲3								
4. Prepare contract design, specifications, and bid package for large-scale plant acquisition.					[Bar]										
5. Design, build, install, and operate a 10 megawatt pilot plant.								[Bar]				▲4			
6. Demonstration plant (400 Mw).												[Bar]			

- ▲1 Determine if oceanography review and subsystem development should start.
- ▲2 Make selection of best-suited components for demonstration plant.
- ▲3 Determine if 10 Mw pilot plant should be built.
- ▲4 Determine if 400 Mw demonstration plant should be built.

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APPENDIX A

PROPOSED R&D FUNDING

Table 1. Proposed Funding for Thermal Energy for Buildings (\$M)

Development*	76
Demonstration	24
Total	100

*Collectors, storage, coolers, system engineering, product engineering, and architecture.

Table 2. Proposed R&D Funding for Photosynthetic Production of Organic Materials and Hydrogen (\$M)

Activity	Research	Development	Pilot plant	Total
Production of low cost fuels				
Improve crop yields				
Water plants (algae and floating plants)	1	1	2	4
Investigation of plant harvesting				
Land plants	1	1	4	6
Water plants (algae and floating plants)	3	2	6	11
Investigation of crop transport				
Land plants and solid waste	2	1	3	6
Water plants	1	1	3	5
Production of hydrogen	11	17	—	28
Total	19	23	18	60

Table 3. Proposed R&D Funding for Conversion of Organic Materials to Energy (\$M)

Activity	Feasibility study	Component development	Pilot plant	Demonstration plant	Total
Combustion of organics	1	10	30	28	69
Combustion of solid wastes	1	10	30	28	69
Total	2	20	60	56	138

Table 4. Proposed R&D Funding for Conversion of Organic Materials to Fuels (\$M)

Activity	System or laboratory studies	Pilot plant	Demonstration plant	Total
Bioconversion to methane	9	23	29	61
Pyrolysis	2	12	35	49
Chemical reduction	3	18	41	62
Total	14	53	105	172

Table 5. Proposed Funding for Solar Thermal Electric Generation (\$M)

Feasibility studies and component development*	30
Pilot plants	100
Demonstration plant**	1000
Total	1130

*Collectors, storage, energy transfer, and system engineering.

**Amounts represent total government and private funds on a cost-share basis.

Table 6. Proposed Funding for Photovoltaic Electric Generation (\$M)

	Feasibility study	Technology development	Systems definition	Phototype testing	Total
Low cost solar array development		40			40
Low cost solar array pilot plant		170			170
Ground/building subsystems		30			30
Spacecraft subsystems		70			70
Systems for buildings	1			5	6
Ground stations	2		4	70	76
Space central stations	3		45	340	388
Total	6	310	49	415	780

Table 7. Proposed R&D Funding for Wind Energy and Ocean Thermal Gradient Conversion (\$M)

Activity	Feasibility study	Component development	Pilot plant	Demonstration plant*	Total
Wind conversion	4	96	20	490	610
Ocean thermal gradient	2	43	55	430**	530
Total	6	137	75	920	1140

*Amounts represent total government and private funds on a cost-share basis.

**One 400 Mw ocean plant.

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APPENDIX B

MEMBERSHIP OF SOLAR ENERGY PANEL

EXECUTIVE COMMITTEE

Dr. Paul Donovan
National Science Foundation
1800 G St., N.W.
Washington, D.C. 20550

Mr. William H. Woodward
NASA Headquarters
Code: RP
Washington, D.C. 20546

Mr. William R. Cherry
Code 760
NASA Goddard Space Flight Center
Greenbelt, Md. 20771

Dr. Frederick H. Morse
Department of Mechanical Engineering
University of Maryland
College Park, Md. 20742

Dr. Lloyd O. Herwig
NSF-RANN
1800 G St., N.W.
Washington, D.C. 20550

Prof. Raymond Bauer
Harvard Business School
Boston, Mass. 02163

Prof. Samuel Z. Klausner
University of Pennsylvania
4025 Chestnut Street
Philadelphia, Pa. 19104

Dr. James J. McKenzie
Mass. & National Audubon Society
36 Fabyan Street
Arlington, Mass.

Mr. Paul Rappaport
David Sarnoff Research Center
Princeton, N.J. 08540

Mr. Milton Searl
Resources for the Future, Inc.
1755 Massachusetts Ave., N.W.
Washington, D.C. 20036

BIOCONVERSION

Chairman

Dr. Martin D. Kamen
Department of Chemistry
University of California
La Jolla, Calif. 92037

Members

Dr. George L. M. Christopher
United Aircraft Research Labs.
East Hartford, Conn. 06108

Dr. Bessel Kok
RIAS Inc.
7212 Bello Ave.
Baltimore, Md.

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Department of Microbiology
Case Western Reserve University
Cleveland, Ohio

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University of California
Department of Sanitary Engineering
and Public Health
Berkeley, Calif.

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113 Towne Building
University of Pennsylvania
Philadelphia, Pa. 19104

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Energy Conversion Program
University of Delaware
Newark, Delaware 19711

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Arthur D. Little, Inc.
20 Acorn Park
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Mr. Paul Goldsmith
TRW Systems, Inc.
1 Space Park
Redondo Beach, Calif.

Mr. Peter A. Iles
Centralab Semiconductor Division
4501 N. Arden Drive
El Monte, California

Dr. Sheldon E. Isakoff
Engineering Physics Lab.
DuPont Co.
Wilmington, Delaware 19898

Prof. J. J. Loferski
Division of Engineering
Brown University
Providence, R.I. 02906

Dr. Remo Pellin
Monsanto Chemical Co.
860 N. Lindberg Blvd.
St. Louis, Mo. 63166

Dr. Nicholas F. Yannoni
Air Force Cambridge Research Lab.
Bedford, Mass. 01730

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Environmental Quality Lab.
California Institute of Technology
Pasadena, Calif. 91109

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Solar Energy Laboratory
University of Wisconsin
Madison, Wisc. 53706

Dr. George Löf
Colorado State University
Fort Collins, Colo.

Lt. Robert Reines
3415 Anderson SE
Albuquerque, N.M. 87106

Mr. P. Richard Rittlemann
610 Mellon Bank
Butler, Pa.

Prof. Richard Shoen
School of Architecture
UCLA
Los Angeles, Calif.

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Bell Telephone Laboratories
555 Union Blvd.
Allentown, Pa. 18103

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Dept. of Mechanical Engineering
University of Minnesota
Minneapolis, Minn. 55455

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Energy & Kinetics Department
UCLA
Los Angeles, Calif. 90024

Prof. William Gouse
Carnegie Mellon University
Pittsburgh, Pa. 15213

Dr. L. I. Maissel
IBM Corporation
Boardman Road
Poughkeepsie, N.Y. 12602

Dr. Aden B. Meinel
Optical Sciences Center
University of Arizona
Tucson, Ariz. 85721

Dr. L. T. Papay
Southern California Edison Co.
P. O. Box 800
2244 Walnut Grove Ave.
Rosemead, Calif. 91770

Prof. E. M. Sparrow
Dept. of Mechanical Engineering
University of Minnesota
Minneapolis, Minn. 55455

Mr. R. M. Van Vliet
4057 Rushton Drive
Dayton, Ohio 45431

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Dept. of Electrical Engineering
University of Florida
Gainesville, Fla. 32601

Members

Mr. J. Hilbert Anderson
1615 Hillock La.
York, Pa. 17403

Dr. Erich A. Farber
Solar Energy Laboratory
Dept. of Mechanical Engineering
University of Florida
Gainesville, Fla. 32601

Prof. William F. Heronemus
Dept. of Civil Engineering
University of Massachusetts
Amherst, Mass. 01002

Dr. George C. Szego
InterTechnology Corp.
Warrenton, Va. 22186