SERI/TP-270-1465

November 1981

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W. Luft
J. Froechtenigt

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.00

SOLAR ENERGY CONTROLLED-ENVIRONMENT AGRICULTURE IN THE UNITED STATES AND IN SAUDI ARABIA

Werner Luft
Joseph Froechtenigt

Solar Energy Research Institute
Golden, Colorado

ABSTRACT

The work described aims to advance the technical and economic feasibility of commercial-scale, solar-powered, controlled-environment agriculture.

Conventionally-powered, controlled-environment agriculture facilities have been in operation for years. In 1977, there were approximately 92,000 hectares of such facilities throughout the world powered by the electric grid and/or fossil fuel. Benefits of controlled-environment agriculture include reduced fresh water consumption, protection from harmful external conditions (e.g., insects, sandstorm, cold weather), and improved quality and high yield of produce.

Conventionally-powered, controlled-environment agriculture is a worldwide activity that has been proven successful in many different climates. However, no significant efforts have been made to replace conventionally-powered, controlled-environment agriculture with completely self-sufficient, solar-powered, controlled-environment agriculture systems.

To accomplish the objective of the SOLERAS solar energy controlled-environment agriculture project, a three-phase activity is planned. From 15 proposals received for Phase 1, three companies have been awarded contracts. The water desalination technology being evaluated is reverse osmosis. The solar energy collection technologies include flat-plate thermal collectors, solar ponds, photovoltaics, and wind turbines. The greenhouse designs are specific for each system.

The significant results of this work will be levelized product cost projections based on a common analysis methodology and common data inputs for inflation, cost of capital, lifetime, etc.

1. BACKGROUND

In October 1977, Saudi Arabia and the United States signed a Project Agreement for Cooperation in the Field of Solar Energy (SOLERAS) under the auspices of the United States-Saudi Arabian Joint Commission on Economic Cooperation. The objectives of the agreement are to:

- cooperate in the field of solar energy technology for the mutual benefit of the two countries, including the development and stimulation of solar industries within the two countries;

- advance the development of solar energy technology in the two countries; and
- facilitate the transfer of technology developed under this agreement between the two countries.

The Solar Energy Research Institute (SERI), as the Operating Agent, is responsible for implementing the SOLERAS Program in accordance with directives of the SOLERAS Executive Board, which has approved a five-year technical program plan.

As part of this technical program plan, a project area of Rural/Agricultural Solar Applications for solar technology has been initiated. The objective of the Rural/Agricultural Solar Applications project area is to enhance the quality of rural life in hot, arid climates without negative effects on the environment by providing systems using renewable energy sources for domestic, communal, agricultural, and local industrial applications. These systems must provide power for water desalination, water pumping for irrigation, and controlled-environment cooling for growing selected fruit and vegetable crops.

Anticipated future demands for food production, coupled with rapidly depleting fossil fuel reserves, point to the need for food production concepts that utilize renewable energy sources. In many regions where large areas of land are available for agricultural use, the main constraint is the lack of irrigation water. These conditions exist in most of Saudi Arabia and in portions of the southwestern United States. Even in some areas of the United States where water is available for irrigation, the rising cost of fossil fuel used for pumping this water is making the cost of irrigation farming prohibitive. In such regions, controlled-environment agriculture affords an attractive means of increasing food production by controlling adverse environmental conditions with minimum water input.

Conventionally-powered, controlled-environment agriculture facilities have been in operation for years. In 1977, there were approximately 92,000 hectares of controlled-environment agriculture facilities throughout the world, powered by the electric grid and/or fossil fuel. Benefits of controlled-environment agriculture include reduced fresh water consumption, protection from harmful external conditions (e.g., insects, sandstorms, cold weather), and higher quality and larger yields of produce. As demonstrated at some of the controlled-environment agriculture facilities in the Middle East and southwestern United States, the ratio of yield per hectare of controlled-environment agriculture to open-field agriculture may range from 4:1 to 21:1, depending on the type of crop grown.

Since 1972, controlled-environment agriculture pilot plants have been established in Saudi Arabia, Kuwait, Abu Dhabi, Iran, and other arid or desert areas. High agricultural yields have been achieved in these locations by such means. In some of the projects, seawater is used for evaporative cooling, and desalinated seawater is used for irrigation.

In the United States, commercial controlled-environment agriculture facilities in Tucson, Arizona, and Cleveland, Ohio, have had successful operation for many years. Conventionally-powered, controlled-environment agriculture is a worldwide activity that has been proven successful in many different climates. Much effort has been exerted by the United States to use solar energy in support of agriculture; however, the objectives of these efforts have been directed toward one specific aspect of farm support, such as crop drying, heating of greenhouses or livestock shelters, or providing solar energy to power irrigation pumps. In Saudi Arabia, small research facilities for controlled-environment agriculture, powered by fossil-fuel generators, are being supported by the Ministry of Agriculture and Water.

Although conventionally-powered, controlled-environment agriculture activity is worldwide, no significant effort is being made to replace these facilities with completely integrated, solar-powered, controlled-environment agriculture systems.

2. DISCUSSION

The advantages of controlled-environment agriculture are:

(1) flexibility of location,
(2) protection from external stresses,
(3) conservation of water and nutrients,
(4) increased yield,
(5) higher quality produce,
(6) reliable continuous production,
(7) reduced agricultural pollution,
(8) reduced storage and transportation needs, and
(9) potential integration with other systems.

Let us discuss each of these advantages in turn:

(1) Controlled-environment agriculture systems can be located where their produce is required, for example, near cities and other urban centers. Such placement is made possible by the limited water needs and low growing area requirements of these systems. The low water demand is accomplished by recycling the water, and the relatively small area requirement is a consequence of the high yields achieved.

(2) The controlled-environment protects the produce from insects, dust, and adverse climate.

(3) Using closed systems significantly reduces the amount of fresh water and nutrients required.

(4) The annual yields per unit area can be increased by factors as high as 20, depending on the type of produce grown.

(5) Protection from the natural environment enhances the quality of the crops, which thus fetch top prices.

(6) Year-round continuous production is possible in controlled-environment facilities. The crops can be selected to complement the produce available from regular horticulture to maximize prices for the controlled-environment produce.

(7) The closed systems approach prevents the release of pollutants such as herbicides and high salt-content water into the environment.

(8) Continuous stable production eliminates great seasonal production peaks that require extensive storage for periods whose maximum length is determined by the type of crop. The ability to locate the controlled-environment system close to consumption centers reduces the need for long-distance transportation.

(9) The controlled-environment agriculture systems lend themselves to integration with systems for solar energy water desalination, for solar power generation, and for biomass power and carbon dioxide generation, thereby allowing relative self-sufficiency. Seawater or brackish water and plant nutrients must be provided, albeit only in limited amounts.

Table 1. Protected Cultivation in Some Countries

Country	Cultivated Area (ha)	Population (million)	Area Per capita (m^2)	Year of data
Belgium	1,600	9.8	1.6	1977
Britain	2,900	56	0.5	1977
France	20,000	53	3.8	1977
Israel	3,700	3.3	11.2	1973
Italy	14,800	57	2.6	1977
Japan	23,000	115	2.0	1977
Netherlands	7,900	14	5.7	1977
Soviet Union	2,200	255	0.09	1976
Spain	9,300	36	2.6	1976
Turkey	2,000	40	0.5	1972
United States	2,100	203	0.1	1969
West Germany	2,500	61	0.4	1977

The areas under controlled-environment cultivation are small compared to land areas used for conventional agriculture. Only high-priced selected crops can be grown economically in conventionally-powered, controlled-environment facilities.

Table 1 gives data on protected cultivating areas in various countries.

Common greenhouse vegetable crops are tomatoes, cucumbers, squash, peppers, lettuce, cabbage, eggplant, radishes, turnips, and okra. Typical annual yields for protected cultivation are 530 metric tons/ha for cucumber, 270 for tomatoes, and 170 for lettuce. (Note: 1 metric ton = 1000 kg = 1 Mg). The high yields achievable with controlled-environment horticulture as compared to high-yield field growth is illustrated in Table 2, where the yield at a controlled-environment facility at Khark Island in Iran is compared to a single-crop per annum high-yield, open-field growth in the United States.

Table 2. Comparison of Controlled Environment and Open-Field Yields [1]

Crop	Controlled Environment (tons/ha-yr)	Open Field (tons/ha-yr)	Ratio
Cucumber	570	27	21
Tomato	318	67	4.7
Lettuce	168	24	7
Cabbage	172	27	6.4

The water requirements of a closed, controlled-environment system for vegetable production in central Chile are, for example, 5,000 m^3/ha-yr (14 m^3/ha-day) compared with 10,000-15,000 m^3/ha-yr of water (27-41 m^3/ha-day) for open field production in the same locality [2].

The amount of labor required for greenhouse cultivation is relatively high, ranging from 11 persons/ha (7 for cultivation, 2 for packing, and 2 for support/maintenance) to 30 persons/ha.

The power and water requirements for controlled-environment agriculture vary with location. Estimates for greenhouses in the Middle East are:

- 110 to 120 kW/ha in electric power for pumps, fans, and light;
- 47 to 74 m^3/ha-day of desalted water for irrigation; and
- 28 m^3/ha-day of brackish water for year-round evaporative cooling [1].

A number of greenhouse designs have been proposed for use in hot climates to reduce the temperature by essentially passive means. However, active cooling may be required, since passive design features alone are generally insufficient to maintain an adequately low temperature regime in hot climates.

Figure 1 shows a schematic design for brackish water evaporation for space cooling and simultaneous fresh water production. The water vapor condenses against the transparent roof, and the condensate is collected. Such system results in high humidity levels within the greenhouse that may cause problems with certain crops [2]. The design in Fig. 2 [3] reduces the amount of sunlight that enters the greenhouse. It uses latent heat

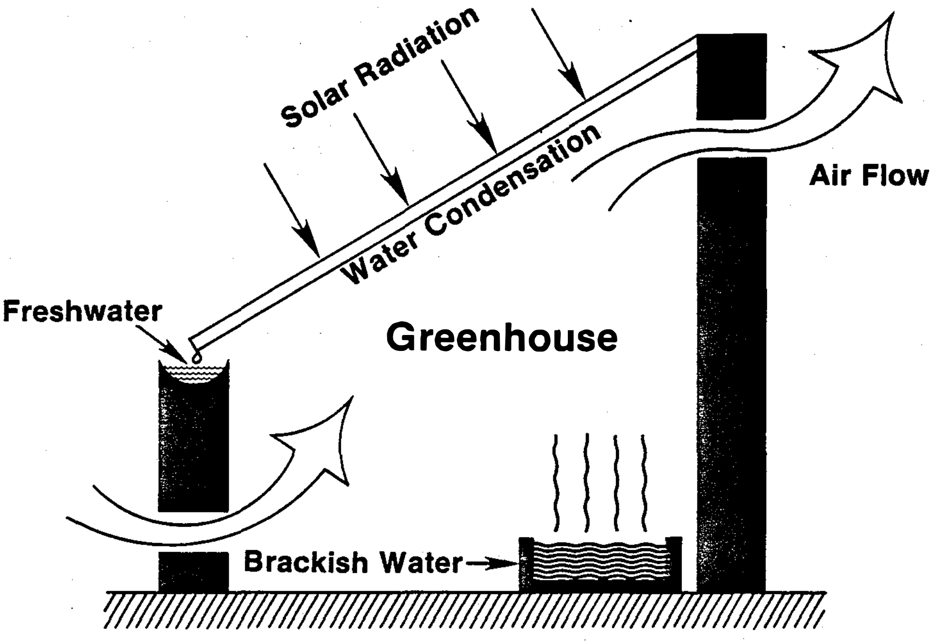

Fig. 1. Schematic Design of Greenhouse for Hot Climates Using Simple Evaporative Cooling and Solar Still

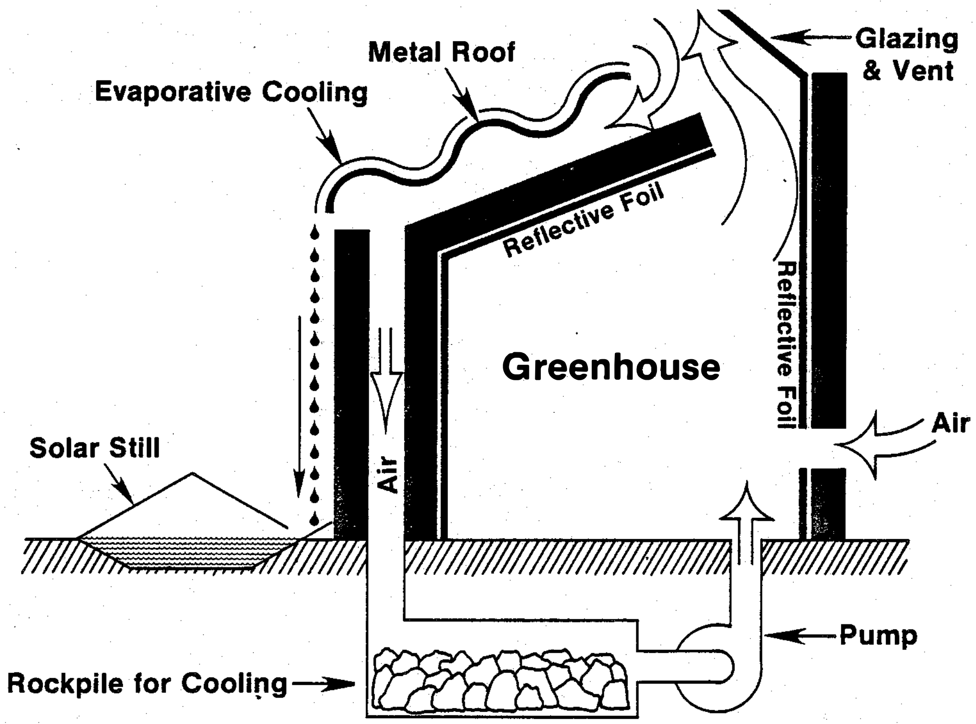

Fig. 2. **Greenhouse Design with Evaporative Cooling and Rock-Bed Cooling for Hot Climates**

storage in a rockpile to reduce the daytime and nighttime temperature variations. Evaporative cooling of the roof is used for daytime temperature reduction in the greenhouse. The drainage from the water sprayed on the roof is used for fresh water production in a free-standing solar still. The light is distributed uniformly within the greenhouse by means of reflective foil on the walls and ceiling. Convective air-flow assists in maintaining low temperature in the greenhouse.

Other design concepts make use of the fact that only 48% of the solar spectrum is usable for photosynthetical processes, namely the spectrum from 0.39 to 0.72 μm wavelength (see Fig. 3).

Examples of design concepts using spectrum cutoffs are shown in Figs. 4 and 5. The first of these 2 figures shows a design using an absorption filter in the transparent roof to reduce the amount of heat entering the greenhouse and to evaporate seawater to generate fresh water. Seawater trickling down over the warm surface incorporating the absorption filter is evaporated and condenses against the upper transparent layer. The condensate is collected and used for irrigation. The second design uses an absorbing liquid in the roof to reduce the amount of heat entering the controlled environment. The absorbing liquid could be a 2.5% $CuCl_2$ and water mixture [2]. The heat absorbed in the fluid could be stored for nighttime heating of the greenhouse or could be used for fresh water production.

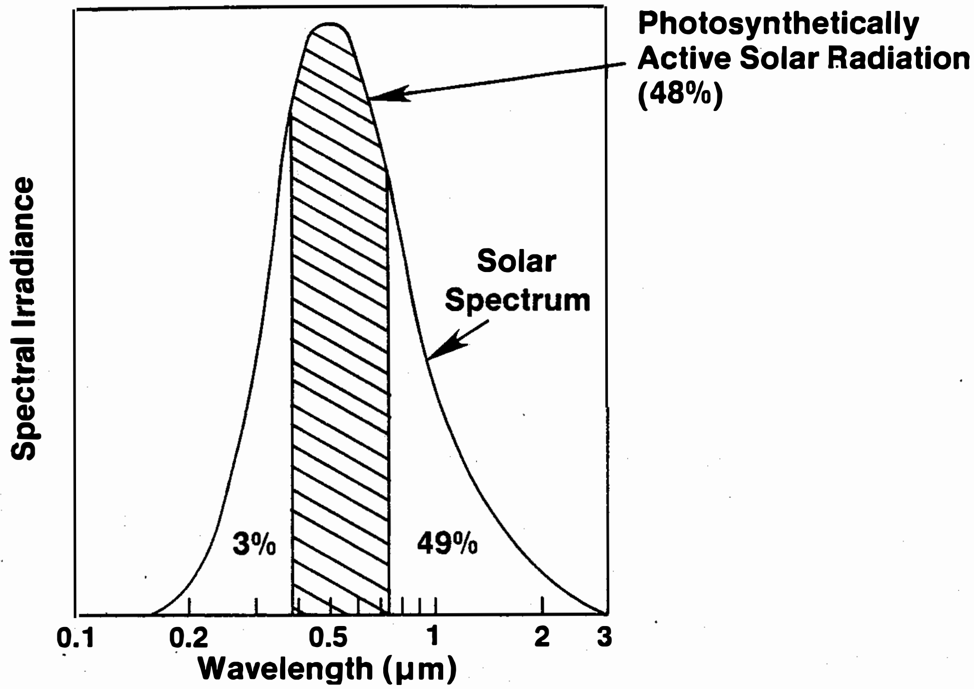

Fig. 3. Photosynthetically Active Solar Radiation

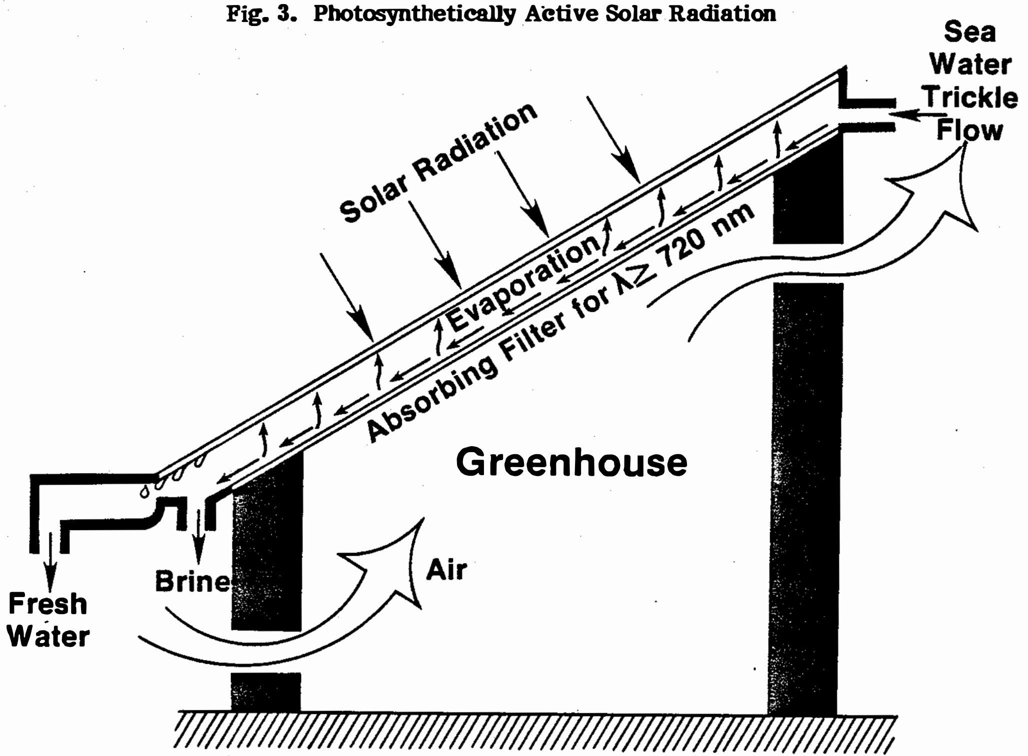

Fig. 4. Greenhouse Design for Hot Climates with Absorbing Filter and Solar Still to Reduce Temperature

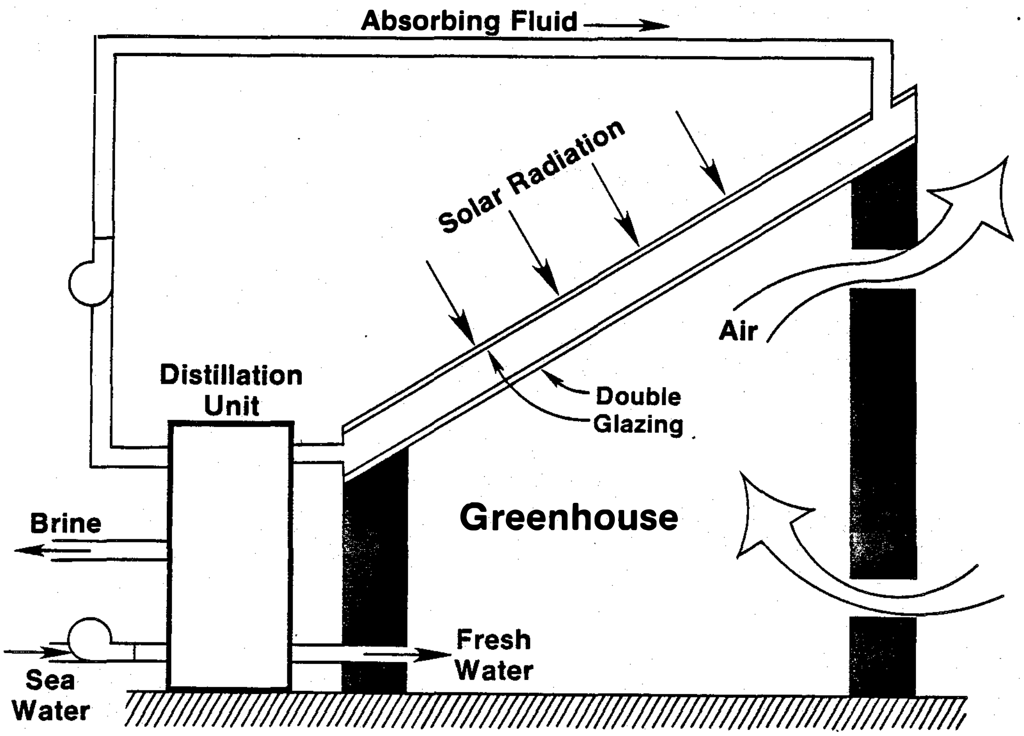

Fig. 5. **Greenhouse Design for Hot Climates with Double Glazing and Absorbing Fluid**

Some examples of conventionally-powered, controlled-environment horticulture systems are described in Table 3.

3. PROJECT PLANS

To accomplish the objective of the SOLERAS solar-powered, controlled-environment agriculture, a three-phase activity is planned. The phases are as follows:

Phase 1: Preliminary System Design and Cost Analysis
Phase 2: Detailed Pilot Plant Design and Construction
Phase 3: Pilot Plant Operation and Training of Personnel

Phase 1: System analyses and economic analyses will be performed by several companies for solar-powered, controlled-environment systems with growing areas in the range from 0.4 to 1.0 ha to establish a baseline system for each company. The systems will be optimized to minimize produce cost and technological risk. The main criterion for the analysis will be the levelized crop cost. Levelized cost means the total cost (capital, operation, and maintenance) of the system over its lifetime divided by the total production output over the same time span (e.g., \$/kg of tomatoes). Each system will be designed for a specific site and application. The site, application, and technology will have broad applicability to needs in either the United States or in Saudi Arabia. It is the intent of this project to encourage innovation without unduly affecting performance and

Table 3. Performance Data of Selected Systems

	Puerto Penasco, Mexico	Khark Island, Iran	Sadiyat Island, Abu Dhabi	Tucson, Arizona, USA
System completion date	—	1974	1972	—
Greenhouse area (m^2)	1,700	8,100	20,000	37,000
Vegetable yield (ton/ha-yr)	—	307	270[a]	368[a]
Fresh water production (m^3/ha-day)	53	—	133	—
Maximum fresh water consumption (m^3/ha-day)	32	57	—	740
Active evaporative cooling	yes	yes	yes	—
Diesel-motor generator	yes	—	yes	no
Power (kW)	180	—	866	—
Power consumption (kW/ha)				
Electric	1059	—	433	325
Thermal	—	—	—	3000
Maximum greenhouse temperature (° C)	35	—	24	29
Labor (persons/ha)	—	15	—	15

[a] Tomatoes.

reliability. Crop yield and cost projections will be made for a number of different crops. A development plan for Phase 2 will be generated including detailed cost estimates for the design and construction of an integrated, solar-powered controlled-environment agriculture pilot plant using the technology of the baseline system.

Phase 2: Of the several systems designed in Phase 1, one or more systems will be chosen for pilot-plant construction. The criteria for selection will include levelized cost per unit of produce for the commercial-size plant, design, and construction cost for the pilot plant, consistency in cost between the commercial-size plant and the pilot plant, maturity of system design, and projected plant reliability. Each pilot plant will have a growing area in the range of 0.4 to 1.0 ha. The pilot plants will be designed in detail and constructed on specific sites.

Phase 3: The pilot plants will be operated and evaluated to provide the information essential for designing large-scale, integrated, solar-powered, controlled-environment agriculture systems. Personnel will be trained in the operation and maintenance of the facilities.

The schedule for Phase 1 is July 1981 to January 1982. Phase 2 is expected to start in March 1982, with the pilot-plant construction completed by July 1983. Phase 3 will begin at the completion of Phase 2 and will continue until the end of 1983.

4. PHASE-1 IMPLEMENTATION

The combinations of water desalination and solar technologies that were covered in the 15 proposals received for the Phase-1 definition study are shown in Table 4. This table shows solar energy technologies and desalination technologies that were represented by the proposals. The numbers in Table 4 indicate the number of proposals incorporating each of the solar energy/desalination technology combinations. Since some proposals offered a coupling of several solar technologies or of several desalination technologies, the total number (17) shown in this table is higher than the number of proposals received.

Table 4. Matrix Showing Combination of Desalination and Solar Energy Technologies for Solar-Controlled Environment Agriculture

	Solar Energy Technology					
Desalination Technology	Photovoltaics	Wind	Line Focus, Thermal	Point Focus, Thermal	Solar Pond	Total
Reverse osmosis	5	2	1	1	1	10
Solar still	—	—	1	—	2	3
Electrodialysis	2	1	—	—	1	4
TOTAL	7	3	2	1	4	17

Table 5. Contractors for Phase 1

Prime Contractor	Team Members
Battelle Columbus Laboratories	U.S. Agro Systems, Inc. The Consulting Center of Riyadh Ramada Energy Systems Kellam and Smith Engineers National Greenhouse Co. DSET Laboratories, Inc. Saudi Investment and Development Center
Science Applications, Inc. (McLean, Virginia)	Texas A&M Agricultural Experiment Station University of Texas McCormack Corp. Geiger Berger Assoc. Robert E. McKee, Inc.
Saudi Engineering Solar Energy Applications	Agwad Alfassi Trading Association ESMIL International B.V. Nutriculture, Inc. Kinetics Technology International

The most frequently proposed solar energy technology was photovoltaics, particularly in combination with reverse osmosis. Solar ponds were the second most frequent option.

The three companies that have been awarded contracts for Phase 1 and their team members are shown in Table 5. The technologies involved in the four systems, the water type, and projected plant locations are given in Table 6. Table 6 shows that these four contracts represent three greenhouse technologies and four different solar energy technologies.

Table 6. Plant Locations and Technologies for Three Systems

	Prime Contractor		
Parameter	Battelle	SAI	SESEA
Site	Saudi Arabia	United States	Saudi Arabia
Climate	Hot-dry	Hot-dry	Hot-dry
Water Source	Brackish well water	Brackish well water	Brackish well water
Greenhouse Design	Transparent roof with channels for fluid of variable opacity	Double pane glass roof with fluid between panes; inner pane tinted	Air-inflated double polyethylene on steel frame with outside moveable shade
Cooling Method	Absorption chiller, evaporative cooling, and shading	Ground water and shading	Evaporative cooling and shading
Solar Energy Collectors	Photovoltaics and flat-plate thermal collectors	Photovoltaics and wind	Solar pond
Energy Conversion	Photovoltaics	Photovoltaics and wind-driven electric generator	Organic Rankine-cycle turbine
Energy Storage	Electric storage battery	Electric storage battery	Solar pond
Desalination Process	Reverse osmosis	Reverse osmosis	Reverse osmosis
Innovation	Roof design	Roof design	Outside shade cover

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