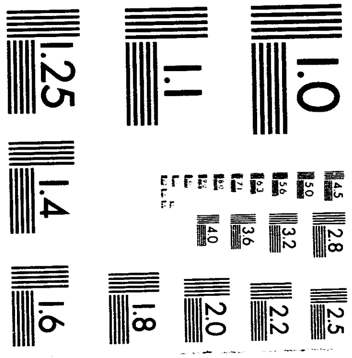
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EVALUATION OF SECOND-GENERATION CENTRAL RECEIVER TECHNOLOGIES

Gregory J. Kolb
James M. Chavez
Paul Klimas
Sandia National Laboratories
Albuquerque, New Mexico

Wolfgang Meinecke
Manfred Becker
Deutsche Forschungsanstalt
für Luft-und Raumfahrt (DLR) e.v.
Köln, Germany

Michael Kiera
Siemens/KWU
Bergisch Gladbach, Germany

ABSTRACT

This paper summarizes the results of a study performed by the US and Germany to assess the technical and economic potential of central receiver power plants and to identify the necessary research and development (R&D) activities required to reach demonstration and commercialization. Second generation power plant designs, employing molten-salt and volumetric-air receivers, were assessed at the size of 30 and 100 MW_e. The study developed a common guideline and used data from previous system tests and studies. The levelized-energy costs for the second generation plants were estimated and found to be competitive with costs from fossil-fueled power plants. Potential for further cost reductions exists if technical improvements can be introduced successfully in the long term. Additionally, the study presents results of plant reliability and uncertainty analyses. Mid- and long-term technical potentials are described, as well as recommendations for the R&D activities needed to reach the goal of large-scale commercialization. The results of this study have already helped direct research in the US and Europe. For example, the favorable potential for these technologies has led to the Solar Two molten-salt project in the US and the TSA volumetric receiver test in Spain. In addition, early analysis conducted within this study indicated that an advanced thermal storage medium was necessary to achieve favorable economics for the air plant. This led to the design of the thermal storage system currently being tested in Spain. In summary, each of the investigated receiver technologies has mid- and long-term potential for improving plant performance and reducing capital and energy costs (resulting in less than 10 cts/kWh given excellent insolation conditions) in an environmentally safe way and largely independent of fossil-fuel prices. Each central receiver technology described in the study has enough potential to justify its continued development.

INTRODUCTION

This paper summarizes the results of a US/German study of central receiver technologies for solar thermal power generation [1]. The study was performed by Sandia National Laboratories (SNL) in Albuquerque, NM (US), by the Solar Thermal Electric Technology Division and Deutsche Forschungsanstalt für Luft-und Raumfahrt (DLR) e.v. (German Aerospace Research Establishment) in Köln, Germany, by the Energy Technology Division. The analysis team comprising SNL, DLR and Interatom GmbH (today: Siemens/KWU) in Bergisch Gladbach, Germany, conducted the study over a 2-year period under the International Energy Agency's "Small Solar Power Systems" project. Funding was provided by the German Ministry of Research and Technology (BMFT) and the US Department of Energy.

The 10-MW_e Solar One Pilot Plant in Barstow, CA, was the largest demonstration of first-generation central receiver technology. During operation of the plant and after its shutdown, significant progress was made in the United States (US) and in Europe on more advanced second-generation central receiver designs. The primary difference between first- and second-generation systems as defined by this study is the choice of receiver

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heat-transfer fluid; Solar One [2] used water/steam, and the second-generation systems in the US and in Europe use molten salt and atmospheric air, respectively. Molten-salt is currently preferred by the US because it allows the incorporation of a cost-effective energy storage system. In Europe, researchers are pursuing the use of a volumetric receiver system using air because it is an inherently simpler system with the potential to be very reliable. Key features of the second-generation systems are depicted in Figures 1 and 2, for the molten salt and air systems, respectively. American and European industries and institutions have expressed interest in commercializing second-generation technology and have proposed building demonstration power plants. The PHOEBUS industrial consortium finished a feasibility study on air technology in 1990 [3] and two US utilities completed studies on salt and sodium technology in 1988 [4]. Currently, a team of US utilities plans to retrofit the 10-MW_e Solar One plant with molten-salt technology [5]. In Europe, the PHOEBUS consortium considered building a 30-MW_e atmospheric-air plant in Jordan. If the demonstration of second-generation technology is successful, commercial-scale plants in the range of 30 to 200 MW_e could then be built and deployed in sunny regions worldwide. Of course, the level of deployment will depend on their economic potential, i.e., the cost of energy from these plants and how they compare with other options for electricity generation.

GOALS AND OBJECTIVES

An evaluation of the technical and economic potential of these second-generation central receiver plants was the primary goal of the study. Objectives were to investigate:

1. technical characteristics (efficiencies, annual energy yield, etc.),
2.- levelized energy costs (LEC),
3.- reliability of the plant and its subsystems,
4. uncertainty of technical and cost data.

A secondary goal was to identify the potential of these systems and research that is needed to improve the performance and reduce the cost of central receiver systems.

METHODOLOGY

DLR and SNL formed a set of consensus guidelines, which dictated many parameters that would be treated identically for all second-generation technologies. The major agreements are summarized below.

1. Focus on two different plant sizes
   a. 30 MW_e in solar and hybrid modes with annual capacity factors of 30% and 40%, respectively.
   b. 100 MW_e in solar-only mode with a capacity factor of 40%.
2. Choose glass heliostats for the 30-MW_e plants with an area of 150 m^2 and a cost of \$130/m^2. Choose stretched-membrane heliostats for the 100-MW_e plants with an area of 150 m^2 and a cost of \$96/m^2. Costs are based on vendor quotes obtained during the utility study mentioned previously [4].
3. Define the second-generation plant to be the fifth in a small series.
4. Use the same cost, performance, and reliability for identical balance-of-plant equipment.
5. Use solar data collected at Barstow, CA, in 1976 [6].
6. Use the same analytical methods to analyze cost, performance, and reliability of the power plants.

The primary sources for technical information and costs for components and subsystems were the PHOEBUS Feasibility Study and the US Utility Studies. In general, costs were based on single-vendor quotes for the first plant. These costs are conservative relative to what a fifth plant would cost, considering the effects of competitive bidding and technology improvements. Since the understanding of longer term economic potential was of interest, the cost data bases were modified to represent a fifth plant. Competitive bidding was assumed to reduce costs by 10%, and advancements in receiver design were assumed to occur that allowed the flux limit to be raised by 20%. Where possible, information was also obtained from the solar parabolic trough systems built by LUZ [7] to check the validity of the cost estimates and to understand cost reductions that are possible when multiple plants are built.

The SOLERGY computer code [8] was used to simulate plant performance throughout an entire calendar year. Technical justification for input parameters to the code were documented in detail [1]..

Two additional analyses were also performed; they were attempts to quantify the reliability of the plants and to rank the uncertainties in terms of their effects on the LEC. Information gained in both of these areas will help identify and prioritize future energy research needs.

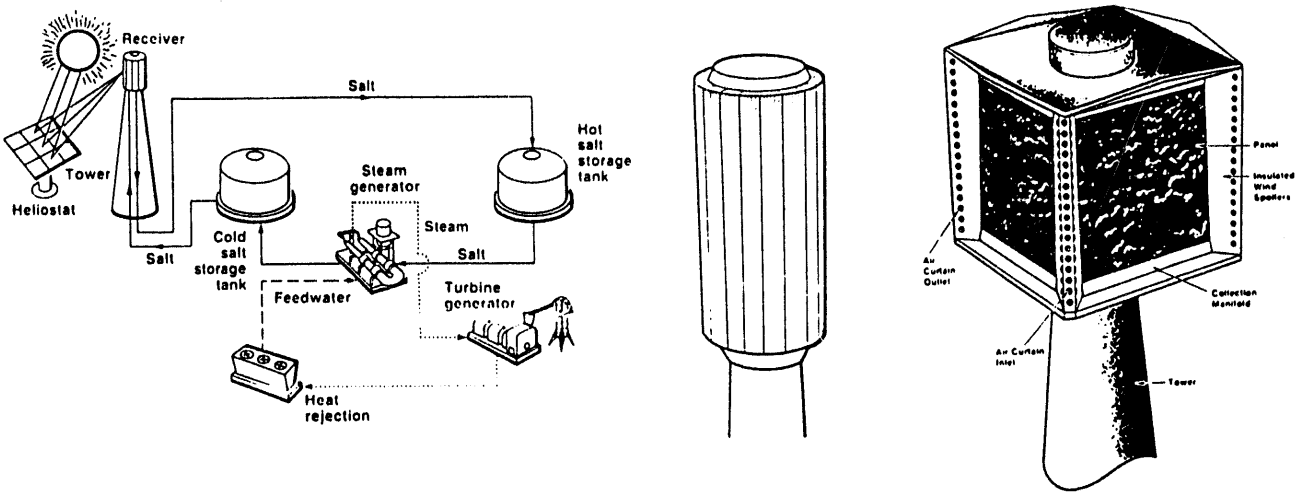

Figure 1 Schematic of a molten-salt power plant. Molten salt is heated to 565°C within a tubular-type (SIT) or film-type (DAR) receiver and pumped to the hot storage tank. After making steam, molten salt at 288°C is returned to the cold tank and pumped back to the receiver. In a SIT receiver (left), solar energy is absorbed by the salt through the tube walls. In a DAR (right), solar energy is absorbed by the salt directly as it flows on the outside surface of four flat panels.

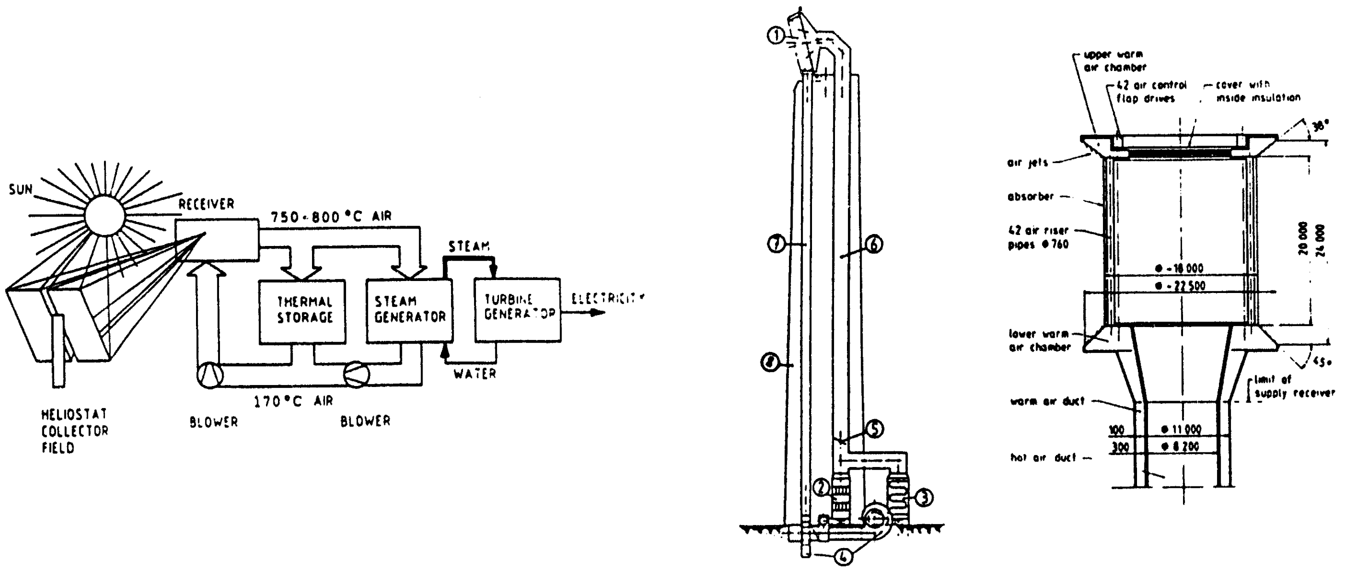

Figure 2 Schematic of atmospheric-air power plants. Air is heated to 750°C within volumetric-type receiver (VR) and fans move the air directly to the steam generator and/or thermocline storage system. After making steam, warm air at 170°C is mixed with atmospheric air and reintroduced to the receiver inlet. In a volumetric receiver, solar energy is absorbed within the volume of a wire-mesh pack that is several centimeters thick. For small plants (30 MW, left), one flat absorber is preferred. For large plants (100 MW, right), economic tradeoffs favor a cylindrical receiver.

Greg Kolb

RESULTS OF LEC CALCULATIONS

The results of the LEC calculations following the common guideline for the second-generation central receiver plants are presented in Table 1. These calculations are based on a constant dollar (inflation removed) fixed-charge rate of 10.5%. This value is typical for an investor-owned utility in the U.S. and does not include the effect of any solar tax credits. Whereas the 30-MW_e plants may reach 15 to 16 cents/kWh in pure solar operation (13 cents/kWh in solar/fossil hybrid operation with 25% of fossil energy share of the total thermal energy given to the electricity generating system), the 100-MW_e plants may have the potential of generating electricity for less than 10 cents/kWh under excellent insolation conditions (2800 $kWh/m^2/yr$). This electricity cost is competitive with today's fossil power plants and would be reduced further if environmental adders were added for fossil plants and/or if tax relief could be included for solar plants.

The following paragraphs discuss the LEC results for the salt and air plants in some detail in order to better assess the differences analyzed by this study.

The results in Table 1 indicate that the salt plants have lower LEC figures than the air plants. When judging these differences, the uncertainties of the technical and cost data as well as the remaining differences in the design layout should be taken into account. The difference for the 30-MW_e plants is within the margin of uncertainties for this study; however, some technical and cost differences give the 100-MW_e SIT plant an advantage over the 100-MW_e air plant. These reasons are mainly due to the cost of providing large thermal storage capacities and in different annual plant efficiencies.

The cost of the thermal storage system for the air plant is significantly more than for the salt plant. Including indirects and interest during construction, the 8 hrs storage for the 100-MW_e air plant costs $53 M (19% of total capital cost), whereas the 7 hrs storage for the 100-MW_e salt plant is $26 M (11% of total). Since the 30-MW_e plants had significantly less storage (4.5 hrs for salt and 3 hrs for air) than the 100-MW_e plants, the difference in storage costs did not impact the LEC nearly as much. In the longer term, a less costly and more advanced energy storage system may be expected to be available for the air plant.

In addition, the 100-MW_e SIT plant has a higher annual plant efficiency than the air plant (0.165 versus 0.150, assuming 100% plant availability). This efficiency advantage helps reduce the LEC of the salt plant because fewer heliostats and a smaller receiver are used, which results in the same capacity factor as the air plant. Comments on the major efficiency differences are given below.

This analysis predicts that the SIT receiver is more efficient than the air receiver. However, a detailed review of the study results indicated that the geometry of the 100-MW_e air receiver did not appear to be optimized as well as the geometry of the salt receiver. Future studies will likely define improved geometries for the air receiver, which should make it comparable to the salt receiver. Another advantage of the 100-MW_e salt plant is a higher annual efficiency for the Rankine cycle (.419 versus .401), because its feedwater temperature is 120°C higher. The air plants use a lower feedwater temperature to reduce mixing losses at the receiver inlet (note in Figure 2 that air is reintroduced at the receiver inlet). Development of an effective air curtain will reduce these mixing losses and make it possible to raise the feedwater temperature and hence, improve the Rankine efficiency.

Table 1 indicates the direct-absorption receiver (DAR) salt plant may be able to achieve a lower LEC than the SIT plant. The primary reason is that the DAR is predicted to have a higher annual efficiency than the SIT receiver (0.885 versus 0.803); the DAR power plant, therefore, employs fewer heliostats and a smaller receiver to achieve the same capacity factor as the SIT plant. The LEC reduction is not as great as predicted by previous studies [9] because the SIT receiver used in this analysis is more advanced than the SIT receiver used in previous comparisons. In addition, it should be emphasized that of all technolgies considered in this study, the DAR has had the least development (a 4 meter DAR panel was built at Sandia but testing was suspended before obtaining meaningful on-sun test results). Because of this fact, the predicted LEC improvement is suspect until further testing is completed.

Based on comparisons with data from existing LUZ plants and Solar One, the LEC predictions of this study appear plausible. Additional reductions in LEC, beyond those presented here, may be achieved in the long-term by introducing further technical improvements, increasing the plant capacity factor by larger storage capacities (if economically reasonable), and increasing plant size to larger than 100 MW_e. For example, other studies performed in the US indicate that the LEC of an SIT plant will be reduced ~30% by increasing plant size from 100 to 200 MW_e and increasing storage from 6 to 13 hrs [10].

Table 1 Summary of Cost Estimates and LEC Calculations Using LEC Equation from Common Guidelines

2nd Generation C.R. Technology	Cap. Cost 1) ($M)	Ann. Cap. Cost ($M)	Ann. O&M Cost ($M)	Total Ann. Cost ($M)	Ann. Net Electric. Energy 2) (GWhe)	Availi-bility (%)	Capacity Factor (%)	LEC 2) (cts/kWhe)
* 30 MW_e SIT, Solar-Only Solar Multiple = 1.4, 4.5h-Stor.	95.3 (77.6)	9.9	2.6	12.6	81.7	91.0	31.1	15.4
* 30 MW_e SIT, Hybrid (25%) SM = 1.4, 4.5 h-Stor.	99.5 (81.0)	10.4	3.5	13.9	109.0	91.0	41.5	12.8
* 30 MW_e Air, Solar-Only SM = 1.2, 3h-Stor.	99.4 (81.0)	10.4	2.5	12.9	78.9	91.5	30.0	16.4
* 30 MW_e Air, Hybrid (25%) SM = 1.6, 7h-Stor.	101.3 (82.6)	10.6	3.2	13.9	105.2	91.5	40.1	13.2
* 100 MW_e SIT, Solar-Only SM = 1.6, 7h-Stor.	227.7 (182.7)	23.9	4.5	28.5	336.3	91.0	38.4	8.5
* 100 MW_e Air, Solar-Only SM = 1.8, 8h-Stor.	272.7 (218.7)	28.6	4.4	33.0	335.6	91.5	38.3	9.8
* 100 MW_e DAR, Solar-Only SM=1.5, 9h-Stor.	211.9 (169.9)	22.2	4.3	26.5	340.4	91.5	38.9	7.8

1) In brackets: direct capital cost

2) Includes plant availability

RESULTS OF RELIABILITY ANALYSES

The PHOEBUS and Utility Studies did not include an analysis of equipment reliability. However, since the conclusion of these studies, considerable effort in collecting and analyzing relevant failure data has been done by the study group. This is the first time such an analysis has been performed for central receiver systems, and it can be defended with a good degree of confidence. Data sources are (1) the tests of commercial-scale molten-salt pumps and valves completed in 1990, (2) salt receiver and other salt-component tests conducted in France and the US, (3) power block and steam generator data from solar-trough plants and the US utility industry, and (4) control system and other applicable data from Solar One.

Using the UNIRAM computer code [11] the analysis predicts the availability of the SIT plant, during hours of sunshine, to be 91% and the DAR and air plant to be 91.5%. The availability prediction appears plausible based on comparisons with availabilities actually achieved at Solar One during its last operating year (95%) and routinely achieved at LUZ plants (>90%). The top three contributors to forced outages at all plants were predicted to be the master control system, the turbine-generator, and the flow-control valves/dampers contained within the solar receiver. The analysis of the SIT plant was described in detail in a previous ASME paper [12].

RESULTS OF UNCERTAINTY ANALYSIS

The parameters employed in the analysis of cost, performance, and reliability are not known precisely. Therefore, a study was performed to analyze the LEC calculations in order to identify the system parameters that contribute most to the uncertainty in these costs. Since the purpose of research and development (R&D) is to reduce uncertainty, the resulting importance ranking can help prioritize future central receiver research.

Using average estimates with +/- tolerances, both backed by experimental evidence and expert judgment, a Monte Carlo sampling approach was applied to the 100-MW_e SIT plant LEC calculations. The analysis indicated that LEC ranged from 0.075 to 0.10 $/kW-hr and that the cost of stretched-membrane heliostats was the most important parameter. The following seven parameters were one-half to one-third as important as heliostat costs: (1) operation and maintenance (O&M) costs, (2) repair time for controls, (3) receiver absorptance, (4) receiver thermal losses, (5) electric parasitics, (6) heliostat cleanliness, and (7) tube leak repair time. To our knowledge, this is the first time such an importance-ranking technique has been applied to a solar power plant.

The uncertainty analysis has helped to prioritize future R&D. For example, the two most important uncertainty issues, (1) heliostat costs, and (2) O&M costs, are currently being addressed in the US. To reduce the uncertainty associated with heliostat costs, the National Renewable Energy Laboratory (formerly SERI) is testing currently available films and working with industry to develop advanced reflective films with a longer life. To reduce O&M costs, SNL has embarked on a multi-year program with KJC Operating Company (formerly LUZ) at solar electric generating systems (SEGS) operating solar plants. SEGS parabolic trough plants and central receiver plants have many common subsystems and are faced with many similar O&M problems. It is expected that this collaborative project will not only help current SEGS plants but will improve the study predictions of O&M costs for future commercial-scale central receiver plants.

CONCLUSIONS AND RECOMMENDATIONS

Future (second-generation) central receiver technologies will be represented by the following two technologies:

- The molten-salt cooled system using a tubular receiver (later potentially a molten-salt film receiver) and salt thermal storage: this system is backed by the successful experience with a commercial-scale molten-salt loop, and medium-scale tests of a receiver (5 MW_t), storage (7 MWhr), steam generator (3.1 MW_t) at Sandia in Albuquerque, NM (US), as well as the French 2-MW_e experimental plant, Themis. A retrofit of the 10-MW_e Solar One Pilot Plant (the Solar Two Plant) using the molten-salt technology is currently planned for the site in Barstow, CA (US).

- The air-cooled system using a volumetric-air receiver and a solid ceramic material thermal storage: this system is backed by several small-scale receiver tests in Spiez, Switzerland; Lampoldshausen, Germany; Almeria, Spain; and Albuquerque, NM (US), as well as by some plant project studies (by SOTEL, PHOEBUS-Consortium) in Europe and by industrial experience concerning components and subsystems derived from proven conventional technologies; high-temperature gas ducts, blowers and dampers in chemical processing;

waste heat boilers in modern power plant technologies; high-temperature storage units in steel making processes; and high-temperature technologies from combined-cycle power plants). A 2.5-MW_t volumetric-air receiver system test (PHOEBUS Technology Program Solar Air Receiver Program TSA) has been successfully conducted in Almeria, Spain, in 1993. This facility comprises a complete medium-scale system: receiver, ceramic storage, steam generator, blowers, dampers, hot ducts, controls, etc.

From the results of this study, it is concluded that both the salt and air technologies have mid- and long-term potential for improved plant performance and reduced capital and energy costs. In the long term, the potential exists for generating electricity for less than 10 cts/kWh in an environmentally safe way, largely independent of fossil-fuel prices, and under excellent insolation conditions as found in Barstow, CA (US) or in South Jordan.

This fact makes it mandatory to further develop the technologies of central receiver power plants. The huge potential of solar energy warrants the development of more than one technology. Past experience has shown the developments did profit from each other, because large parts of the plant, such as the heliostats, are independent of the specific technology.

The molten-salt system using a tubular receiver (SIT) has the highest level of development of central receiver systems today. Plants utilizing SIT technology can be improved in the mid- and long-term by increasing performance through use of more advanced designs and higher solar fluxes. Potential for reduced capital costs and improved performance may be available with the molten-salt film receivers (DAR) once more development work has been completed on film stability. Reduced energy costs may also be obtained using an SIT receiver that is coated with a low emissivity surface similar to the cermet surface used in LUZ plants (not analyzed here).

The results of this study cannot predict whether the molten-salt or the air technology will offer better benefits in the future. While the molten-salt technology has an economic advantage over air systems in the 100-MW_e size, air systems promise to be simpler to operate and maintain, and therefore, may be better suited to developing countries, especially to sites with a poor industrial infrastructure. Additionally, the volumetric-air receiver system has potential for improved system performance once further development has been conducted in the long-term--particularly on the combined gas and steam turbine cycle aspect (not analyzed here).

The short-term status, mid-term expectations, and long-term potential for all the systems were assessed by the study group.

Short-term status of the systems comes from the study group's assessment of the level of the technology today. Many of the components in each of the systems are currently available. A plant utilizing an SIT receiver and glass-metal heliostats is the best available system today.

Mid-term expectations for central receiver systems come from an assessment considering possible improvements during the next 5 to 10 years. The study group defined goals for each system, which are its assessment of each system's potential. Many of the anticipated advances depend on the success of upcoming tests, which include the 10-MW_e Solar Two Plant project in California and the 2.5-MW_t volumetric-air receiver system test (TSA) in Almeria, Spain, as the main projects known today.

Long-term potential is the study group's prediction of how the various systems could look in more than 10 years from now. This is an assessment of the technology improvements that can be made to make central receiver systems competitive with conventional generating technologies. (Other favorable conditions may also be needed, e.g., environmental adders for fossil-fuel plants and/or tax relief for solar plants.) In the long term, each of the studied systems may have sufficient potential to be developed into a commercial system.

In order for the assessed expectations and potential of these central receiver power plants to be realized, the study group recommends that a number of activities be undertaken including:

1. Updates to and expansions of this study.
2. Future R&D on:
    - SIT receiver system
    - Volumetric-air receiver system
    - Molten-salt film receiver systems
    - Heliostats.
3. System demonstrations such as:
    - "Solar Two" - a 10-MW_e SIT receiver system
    - 2.5-MW_t volumetric-air receiver system test
    - "Solar Three" - 40-MW_t volumetric-air receiver system or molten-salt film receiver
    - PHOEBUS - 30-MW_e volumetric-air receiver

system (120 MW$_t$)
- "Solar 100" - 100-MW$_e$ SIT plant.

The expansions of the study will use recent data and provide a more solid evaluation and comparison of the systems. The recommended R&D will provide the data for the expansions of the study, prove the engineering feasibility of the systems, and demonstrate each system's potential. The system demonstrations are necessary to validate the system's performance and reduce the risks in scaling up to the first commercial plant. Each central receiver technology described here has sufficiently high potential to justify its continued development.

REFERENCES

1. Chavez, J. M., G. J. Kolb, W. Meinecke, Becker/Klimas (Eds.), *Second Generation Central Receiver Technologies: A Status Report,* Sandia National Laboratories, Deutsche Forschungsanstalt fur Luft-und Raumfahrt, Verlag C. F. Muller Karlsruhe, 1993, ISBN 3-7880-7482-5.

2. Radosevich, L. G., *Final Report on the Power Production Phase of the 10 MWe Solar Thermal Central Receiver Pilot Plant,* SAND87-8022, Sandia National Laboratories, Livermore, CA, March 1988.

3. PHOEBUS Consortium, *A 30-MW$_e$ Solar Tower Plant for Jordan, Phase 1B, Feasibility Study,* Executive Summary, *Volume 1: Main Results, Volume 2: Technical Details,* edited by Fichtner Development Engineering, Stuttgart, March 1990.

4. Pacific Gas & Electric Company, *Solar Central Receiver Technology Advancement for Electric Utility Applications, Phase 1 Topical Report,* Report No. 007.2-88.2, San Francisco, CA, September 1988.

   Arizona Public Service Company, *Utility Solar Central Receiver Study,* Report No. DOE/AL/38741-1, November 1988.

   Alternate Utility Team, *Utility Solar Central Receiver Study,* Report No. DOE/AL/38741-2, September 1988.

5. Southern California Edison, et. al., *Solar Two Proposal to the Department of Energy,* June 1992.

6. Randall, C. M., *Barstow Insolation and Meteorological Data Base,* Aerospace Report No. ATR-78 (7695-05)-2, The Aerospace Corporation, El Segundo, CA, March 1978.

7. *Application for Certification for SEGS III, SEGS IV, SEGS V, SEGS VI, SEGS VII,* Prepared for California Energy Commission by Luz Engineering Corporation, Doc. No. P-E503-000, January 6, 1987.

8. Stoddard, M. C., S. E. Faas, C. J. Chiang, and J. A. Dirks, *SOLERGY - A Computer Code for Calculating the Annual Energy from Central Receiver Power Plants,* SAND86-8060, Sandia National Laboratories, Livermore, CA, May 1987.

9. Kolb, G. J., J. M. Chavez, "An Economic Analysis of a Quad-Panel Direct Absorption Receiver for a Commercial-Scale Central Receiver Power Plant," *Proceedings of the Twelfth Annual ASME International Solar Energy Conference*, Miami, FL, April 1-4, 1990.

10. Sandia National Laboratories, *Today's Solar Power Towers,* SAND91-2018, Sandia National Laboratories, Albuquerque, NM, October 1992.

11. Gardner, N., *User's Guide for the UNIRAM Availability Assessment Methodology: Version 1.1,* EPRI Publication AP-3956-CCM, Electric Power Research Institute, April 1985.

12. Kolb, G. J., "Reliability Analysis of a Salt-in-Tube Central Receiver Power Plant," *Proceedings of the Second ASME-JSES-JSME International Solar Energy Conference*, Reno, Nevada, March 17-22, 1991.

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