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SOLAR THERMAL ELECTRICITY IN 1998: AN IEA/SolarPACES SUMMARY OF STATUS AND FUTURE PROSPECTS

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Abstract. Research and development activities sponsored by countries within the International Energy Agency's solar thermal working group, SolarPACES, have helped reduce the cost of solar thermal systems to one-fifth that of the early pilot plants. Continued technological improvements are currently being proven in next-generation demonstration plants. These advances, along with cost reductions made possible by scale-up to larger production and construction of a succession of power plants, have made solar thermal systems the lowest-cost solar energy in the world and promise cost-competitiveness with fossil-fuel plants in the future. Solar thermal technologies are appropriate for a wide range of applications, including dispatchable central-station power plants where they can meet peak-load to near-base-load needs of a utility, and distributed, modular power plants for both remote and grid-connected applications.

In this paper, we present the collective position of the SolarPACES community on solar electricity-generating technology. We discuss the current status of the technology and likely near-term improvements; the needs of target markets; and important technical and financial issues that must be resolved for success in near-term global markets.

1. INTRODUCTION

Since 1977, IEA/SolarPACES has pursued a focused program of research and development in the field of solar thermal power and chemical energy systems. Systematic development of three solar thermal technologies --troughs, towers, and dishes-- has led to the ever-increasing ability of these technologies to harness concentrated solar thermal energy for electricity production and other uses with efficiency, reliability and cost-effectiveness. Our vision within the IEA-SolarPACES community is that by 2010, solar thermal power technologies will be making a significant contribution to the delivery of clean, sustainable energy services in the world's sun-belt.

It is clear that the technologies are now nearing readiness for full-scale market introduction, and SolarPACES is poised to play a key role in this new phase. To facilitate the entry of solar thermal power to the international energy market, SolarPACES has broadened its focus. Looking ahead strategically, we will continue to cooperate closely on research and technology development in solar thermal power and solar chemistry, but we have also initiated activities to support project development, to overcome non-technical barriers, and to build world-wide awareness of the relevance of solar thermal power applications to current problems of energy and the environment.

Commercial applications of solar thermal power technologies from a few kilowatts to hundreds of megawatts are now feasible, and plants totaling 350 MW have been in operation in California since the 1980s. Plants can function in dispatchable, grid-connected markets or

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in distributed, stand-alone applications. They are suitable for hybrid operation with a variety of fossil fuels, or can include cost-effective storage to meet dispatchability requirements. They can operate in all global regions having high direct-normal solar insolation, including large areas of Africa, Australia, China, India, the Mediterranean region, the Middle East, the southwestern United States, and Central and South America. Commercial solar plants have achieved costs of about 12¢/kWh (the lowest cost of any solar technology), and the potential for cost reduction will ultimately lead to prices as low as 5¢/kWh. (All costs discussed in this paper are in U. S. dollars ($) or cents (¢).)

Recognizing both the environmental and climatic hazards to be faced in the coming decades and the continued depletion of the world's most valuable fossil energy resources, solar thermal technologies can provide critical solutions to energy problems within a relatively short time-frame and are capable of contributing substantially to CO_2 reduction efforts. Of all the renewable technologies available for large-scale power production today and for the next few decades, solar thermal (because of its relatively conventional technology and ease of scale-up) is one of few with the potential to make major contributions of clean energy. Nonetheless, the present-day potential of solar thermal electricity generation is not well known, even within communities concerned with renewable energy use. In this paper, we summarize the issues associated with making large-scale solar thermal contributions to the electric power market a reality.

2. STATUS OF THE TECHNOLOGIES

The architectures of the three main types of solar thermal power systems are shown schematically in Figure 1. **Trough systems** use linear parabolic concentrators to focus the sunlight along the focal lines of the collectors. The solar energy is absorbed in a working fluid (typically a heat-transfer oil, or in advanced systems, steam), which is then piped to a central location to power a conventional steam turbine system. In a **power tower system**, a field of two-axis tracking mirrors reflects the solar energy onto a receiver that is mounted on top of a centrally located tower. The solar energy is absorbed by a working fluid (typically molten salt or air) and then used to generate steam to power a convention turbine. Depending on the working fluid properties, the energy can be effectively stored for hours if desired to allow electricity production during periods of peak need, even if the sun is not shining. The third type of solar thermal system, the **dish/engine system**, uses a parabolic dish concentrator to focus the sunlight to a thermal receiver and a heat engine/generator located at the focus of the dish to generate power. More detailed descriptions of these technologies can be found in several references [1-3].

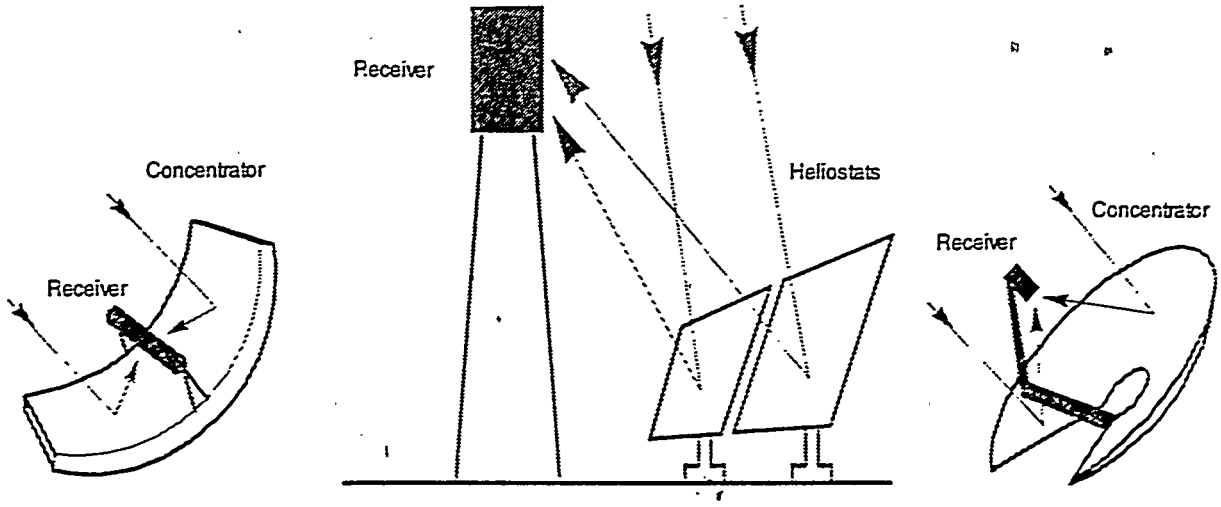

Figure 1. Trough, Power Tower, and Dish/Engine Systems

Typical solar-to-electric system conversion efficiencies and annual capacity factors for the three technologies are listed in Table 1 below. The values for parabolic troughs, by far the most mature technology, have been demonstrated in the field. The values for dish and tower systems are, in general, projections based on component and prototype system test data and the assumption of mature development of current technology. While system efficiencies are important, they are, of course, only one factor in the ultimate measure of competitiveness – cost.

Table 1: Characteristics of Solar Thermal Systems ((d) = demonstrated. (p) = projected)

System	Peak Efficiency	Annual Efficiency	Annual Capacity Factors
Trough	20 % (d)	10 to 12 % (d)	24 % (d)
Power Tower	23 % (p)	14 % to 19 % (p)	25 % to 70 % (p)
Dish	29 % (d)	18 % to 23 % (p)	25 % (p)

2.1 Trough Power Plants

With 354 MW_e of SEGS-parabolic trough power plants currently connected to the grid in Southern California, USA, since the mid-1980's, parabolic troughs represent the most mature solar thermal technology. To date, there are over 90 plant-years of experience from the nine operating plants, which range in size from 14 MW to 80 MW. No new plants have been built since 1991 because declining fossil-fuel prices in the USA resulted in unattractive economic predictions for future plants. The plants are located at three sites near Barstow, California, in the Mojave Desert: Daggett (I, II), Kramer Junction (III - VII), and Harper Lake (VIII, IX).

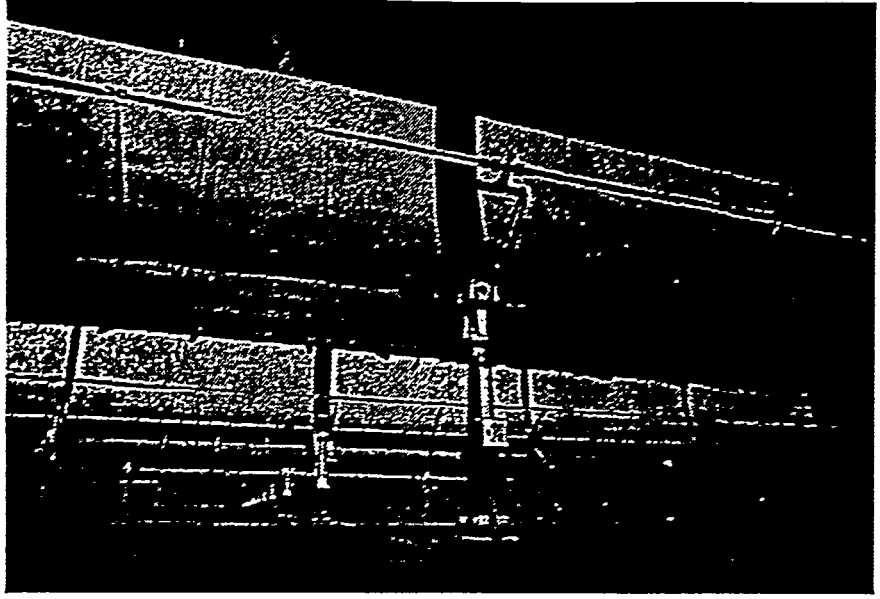

Figure 2. KJC Trough Plant

The performance of these power plants continues to improve. The Kramer Junction site has achieved a 30% reduction in O&M costs over the last five years. This is the result of major improvement programs for collector design and the O&M procedures, carried out in collaboration between the Kramer Junction Company (KJC) Operating Company and Sandia National Laboratories. In addition, key component manufacturing companies in the field of solar energy have made advances: for example SOLEL in Israel has improved the absorber tubes and Pilkington (formerly FLAGSOL), the German reflector producer, has developed improved process know-how and system integration, as well as working to initiate new projects in the world's sunbelt. We estimate that new plants, utilizing current technology with these proven enhancements, could be built for about 10 to 12c/kWh.

To reduce costs still further, the following improvements represent the expected next generation of improvements in trough collector technology:

- improvements in the collector field due to better optical and thermal properties of the mirrors and receivers, lighter and tilted structures, lighter mirrors, and better controls;
- improvements in the process by substituting water for synthetic oil as a one-cycle/two-phase heat-transfer medium between the solar collector field and the power block, known as Direct Steam Generation (DSG);
- improvements in system integration by reduction of parasitic loads, optimization of start-up procedures, and a better control strategy;
- development of advanced solar/fossil hybrid schemes, especially the coupling with combined-cycle power plants.

These improvements will be implemented through on-going research activities such as the German/Spanish project DISS and the new Euro Trough project. New receiver configurations and reflectors for parabolic trough applications are currently being developed in the parabolic trough experiment (PAREX) at the DLR in Germany. Prototypes of new receiver configurations will be tested on the PSA in Spain as soon as the new trough test facility becomes available in 1998.

2.2 Power Tower Plants

In over fifteen years of worldwide experimental evaluation, power tower plants have proven to be technically feasible in projects using different heat transfer media (steam, air, sodium and molten salts) in the thermal cycle and different heliostat designs. American and European industries have expressed interest in commercializing second-generation power tower technology and have recently constructed demonstration power plants. At Barstow, California, USA, a 10-MW_e pilot plant (Solar One) operated with steam from 1982 through 1988 and is presently operated as Solar Two with molten salt as the heat transfer and storage medium, after modification of the complete plant in 1996. In parallel, European activities have demonstrated air as a transfer fluid, with heat transfer into tubes replaced by direct radiation into a porous, volumetric receiver, where the solar energy is absorbed on a fine mesh and immediately transferred to the air working fluid. Extensive validation of this concept has been demonstrated by the Phoebus Technology Program Solar Air Receiver (TSA) tests conducted over the past few years in Almeria, Spain.

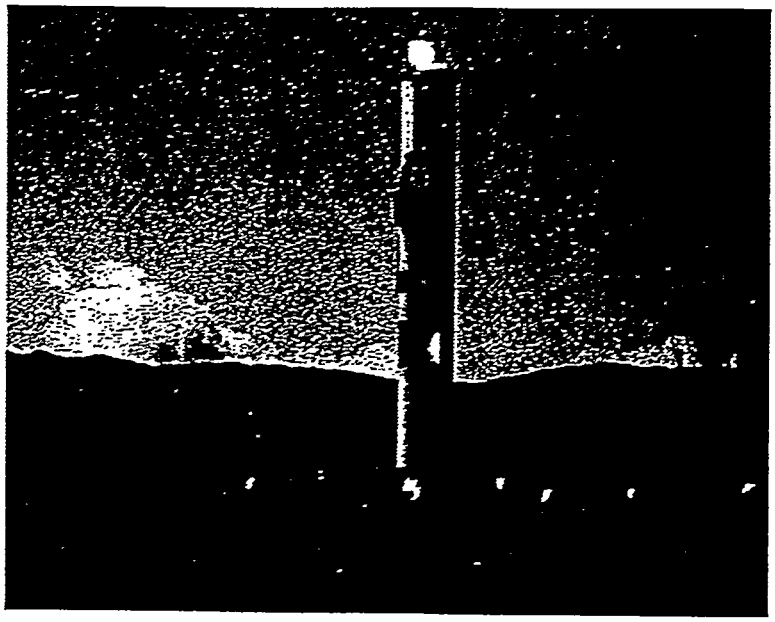

Figure 3. Power Tower Testing at the PSA

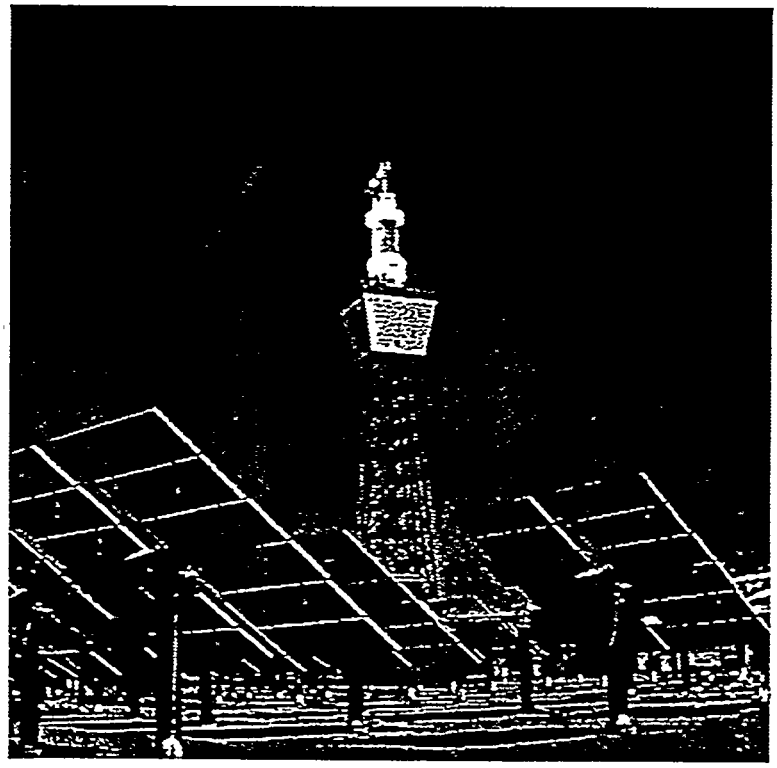

Figure 4. Solar Two

The following efforts in the USA and in Europe (mainly in Germany and Spain) are targeted to achieve power tower technology at a cost less than 10c/kWh by means of:

- improvements in the heliostat field and receiver due to better optical properties, lighter mirrors and structures, as well as better control. New heliostat design activities include the 150-m² and 170-m² heliostats developed by Advanced Thermal Systems (ATS) and Science Applications International Corporation (SAIC), respectively, under the U. S. SolMaT program; the 150-m² stretched-membrane ASM-150 heliostat of Steinmüller (under license of SBP) in Germany; and the 105-m² glass/metal GM-100 heliostat of

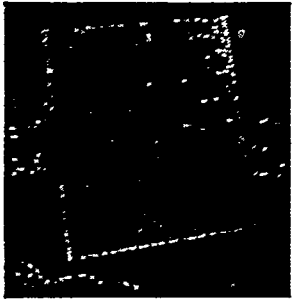

Figure 6. ATS 150-m² Heliostat

Spanish companies. The latter two heliostats were developed within the framework of the Spanish/German Heliostat Technology Program.

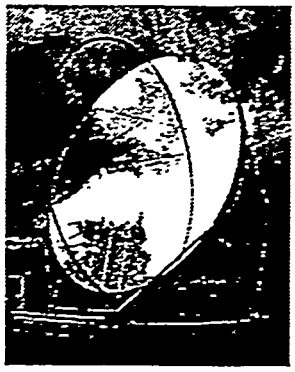

Figure 5. Steinmuller 150-m² Heliostat

- improvements in heat transfer media and receiver concepts. The current experiments on new receiver concepts include the 42.2 MW_t molten salt receiver at the Solar Two plant near Barstow, CA, USA; the 25-MW_t water/steam receiver for the Colon Solar cogeneration plant project in Huelva/Spain; and three open or closed volumetric receiver experiments, in Europe (PSA/Spain) and Israel (WIS): 200 kW_t CorRec and 200 kW_t HITREC of DLR; 350 kW_t REFOS-Receiver of DLR; 60 kW_t DIAPR-receiver of WIS/Rotem Ind.
- improvements in system integration by reduction of parasitic loads, optimization of start-up procedures, and better control strategies.
- development of solar/fossil hybrid schemes, especially the coupling with conventional combined-cycle power plants. One concept under investigation in Israel includes using a secondary reflector on the tower top to beam the solar energy to ground level for collection at high temperature for use in a gas turbine or combined cycle.

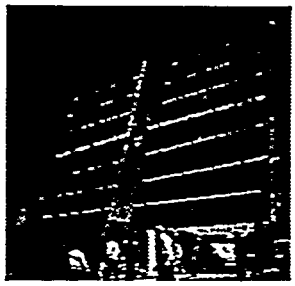

Figure 7. Spanish 100-m² Heliostat

2.3 Dish-Engine Power Plants

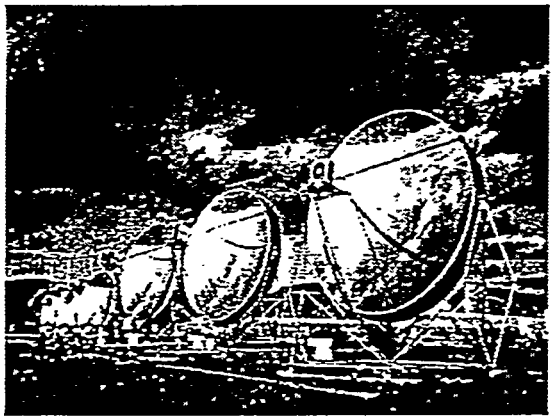

Figure 8. SBP Dishes at the PSA

Several dish-engine prototypes have successfully operated over the last ten years (including 7- to 25-kW units developed by Advanco, McDonnell Douglas Corporation, Cummins Engine Company, and others) but large-scale deployment has not yet occurred. Currently, in Spain, six units with a 9- to 10-kW_e rating are now successfully operating. They were developed by the German Company Schlaich, Bergermann and Partner (SBP) and were erected in conjunction with the German companies Steinmüller (collector system) and SOLO Kleinmotoren (Stirling engine). Three of these dishes have been continually operated with great success since 1992, accumulating over 30,000 hours of operating experience.

At the same time in the USA, SAIC is installing the first of five second-generation 25-kW dish/Stirling prototypes for extended testing at utility sites throughout the southwest USA. These systems will incorporate cost-reduction features, hybridization, and exhibit higher system reliabilities than current prototypes to qualify them for mass production and commercialization.

Research and development work in Australia has demonstrated the 400-m² "big dish" of ANU Tech in Canberra with the participation of Pacific Power. The objectives of the project are currently being redefined because of changes in the Australian utility environment.

The use of dishes for stand-alone installations seems to be the application that will reach the most attainable near-term goals, a cost of less than 15¢/kWh. This will be achieved through:

- improvements in mirror and receiver, including better optical properties of the mirrors; lighter mirrors and structures; improved hybrid heat-pipe receivers; and development of a control system for fully automatic operation;
- improvements in the system by using solarized Stirling and Brayton engines with advanced heat-pipe and volumetric receivers;
- improvements in system integration by reduction of parasitic loads, optimization of start-up procedures, better control strategies, and hybrid operation of the Stirling and Brayton engines.

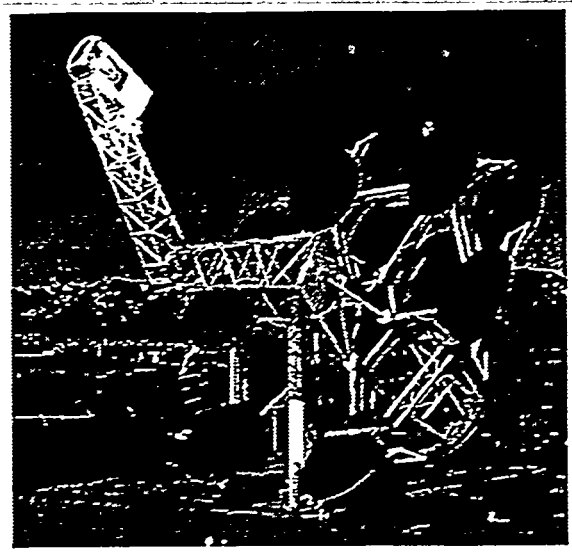

Figure 9. SAIC 25-kW Dish/Stirling System

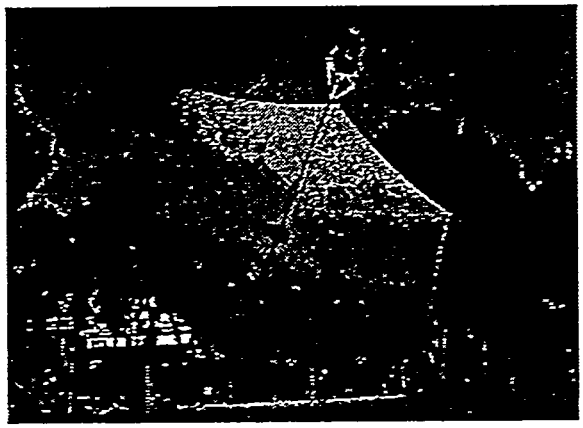

Figure 10. 400-m² Dish in Canberra

3. THE MARKETS

Solar thermal technologies are capable of meeting the requirements of two major electric power markets: large-scale **dispatchable markets** comprised of grid-connected peaking and base-load power, and rapidly expanding **distributed markets** including both on-grid and remote applications.

3.1 Dispatchable Power Markets

Dispatchable power markets are dominated by fossil-fuel-fired electricity distributed over central utility grids. Power must be produced "on demand" in order to meet changing loads and command the highest value. Low life-cycle costs are the primary driver of investment decisions in this market, and gas-fired combustion turbines and combined-cycle power plants represent the modern conventional technologies serving this market.

Using storage and hybridization capabilities, dispatchable trough and power tower technologies can address this market. They currently offer the lowest-cost, highest-value solar electricity available and have the potential to be economically competitive with fossil energy in the longer term. The lowest energy costs are generally achieved in the 100 MW and greater size range, although more modular designs (30 MW and below) are feasible and may offer advantages in some applications.

These technologies face a number of challenges in meeting developer, investor, and customer needs. With large-scale performance and reliability demonstrated at the SEGS plants in the USA, the most significant challenge in dispatchable applications is that the levelized energy cost (LEC) is still higher than competing conventional technologies. Technology enhancements underway throughout the world will help reduce the capital cost of solar components and enable higher annual efficiency (both leading to lower LEC). Furthermore, advanced system development will lead to substantial cost reductions through innovative designs, advanced materials, and improved operations. Additional development of hybrid systems will enable increased modularity, reduced risk, and reduced cost.

Solar thermal systems are currently candidates for dispatchable demonstrations in major international markets, with high-value green markets possibly providing openings for early commercial plants or technology validations. In the long term, the development of power parks will reduce costs through economies-of-scale and further help the technology grow. With continued development success and early implementation opportunities, we expect dispatchable system costs to drop to 8-10¢/kWh within 5 years and to 4-6¢/kWh by 2010.

3.2 Distributed Power Markets

The current emphasis in distributed power applications is to develop technologies that can operate reliably for loads ranging from 10 kWe to several MWe. The majority of these applications are currently for remote power (such as water pumping and village electrification) where there is no utility grid. In these applications, diesel engine generators are the primary current competition. Also of growing interest to utilities are grid-connected applications in which the solar generator is sited at critical points on the transmission and distribution (T&D) system, providing value not simply from the energy produced but also in postponing T&D infrastructure upgrades to meet load growth. Small gas-turbine systems will also compete with solar thermal and other renewable energy technologies for this market. Key market criteria for distributed power applications are reliable unattended operations, minimal (and low technology) service requirements, and competition with the cost of alternatives (which are typically quite high).

The technology appropriate for distributed applications is the dish/engine system. Each dish/engine module (10 to 50 kW, depending on the design) is an independent power system designed for automatic startup and unattended operation. Multiple dish/engine systems can be installed at a common site to provide as much power as required, and the system can easily be expanded with additional modules to accommodate future load growth. The systems can be designed for solar-only applications, can be easily and cost-effectively hybridized with fossil fuels to allow power production without sunlight, or can be deployed with battery systems to store energy for later use. The high value of distributed power (as high as 50c/kWh and above for some remote applications) provides ample opportunities for commercial deployment early in the technology development.

There are several critical issues facing the development of dish/engine systems. The first and foremost is reliability, as measured by both Mean Time Between Failure (MTBF) and operation and maintenance (O&M) costs. The second issue is system cost, although this issue is currently less critical because commercial sales can occur in high-value markets at current costs if reliability and O&M are improved.

The future for distributed solar thermal applications appears bright. The technology enhancements necessary to achieve high reliability and reduce O&M costs are well understood. As technology development proceeds, there will be numerous opportunities for field validations that will build on the high value of energy for remote applications and the low cost for system demonstration (because of the small module size). With continued development success, we expect distributed system costs to drop to 12-15¢/kWh within about 5 years and to 5-7¢/kWh by 2010.

4. CHALLENGES AND REALISTIC GOALS

Electrical power is a strategic asset, essential to maintain and create wealth in both industrial and developing nations. In order to attain sustainable growth, the expected increase in demand for electricity in the lesser developed countries of the sun belt means that they should use their available renewable resources, especially solar energy.

In addition to the technical achievements on which R&D efforts have been focused for the past two decades, researchers are facing numerous non-technology-related barriers to solar thermal's making wide-spread contributions to sustainable energy and a cleaner environment. To achieve the vision of the SolarPACES group, several obstacles and challenges will have to be overcome. We must:

- Establish appropriate market entry incentives, including, for example, equitable taxation relative to conventional energy products; carbon taxes or renewable energy tax credits; and Global Environmental Facility (GEF) support.
- Remove legislative and regulatory barriers to supplying solar thermal power to the grid.
- Develop of effective tools for assessing the true value of renewable technologies, including externalities.
- Improve the attractiveness of investment opportunities for solar thermal technologies.

Bringing a new technology such as solar power plants into the marketplace requires their being attractive to investors. From the viewpoint of profit and technical/financial risks, solar power is not yet attractive to today's investors. For this reason, we have expanded our role in SolarPACES from one that has focused largely on technology development to including activities to overcome barriers to commercialization of solar thermal technologies. One objective of these activities is to support market development in order to reduce financial, political, market and institutional hurdles. Research and development activities and market development are items that have to be carried out in parallel during the next one-to-two decades to ensure progress from the present state-of-the-art to advanced generations of solar thermal components/systems and to successfully establish these technologies in the energy marketplace of sunbelt countries within an accelerated time frame.

To help overcome some of these barriers, the Global Environmental Facility (GEF) was established (as an outgrowth of 1992 Climate Change Convention, Rio de Janeiro) to provide grant funding to develop projects that reduce global warming. The solar thermal community is in discussions with the GEF to develop initial projects in Egypt, India, and elsewhere. Solar thermal electricity generation has been shown to be an economically attractive method of reducing carbon dioxide (CO_2) emissions (i.e., less than $30/tonne of CO_2). In addition, CO_2 emissions generated during plant construction and operation are insignificant relative to the CO_2 generated during the life of a fossil-fuel plant. Because of this and the fact that land

usage by solar thermal plants is considerably less than most hydro projects and coal-fired plants (when land use for mining is considered), the World Bank has established the Solar Initiative to help promote solar thermal projects worldwide.

One barrier that often stands in the way of solar project development is taxation policy. Recent studies indicate that if a solar thermal plant in the USA is taxed at the same rate structure as an equivalent fossil-fuel plant, the solar plant will pay much more tax per kilowatt hour during its lifetime. These studies show that if tax equity is achieved, levelized electricity cost from the solar plant can be reduced by approximately one third. Achieving tax equity can do as much for improving the economic competitiveness of solar thermal plants than technological breakthroughs.

Recently, a detailed proposal of a market-introduction program was worked out by the DLR in Stuttgart [9]. This proposal shows that solar thermal power stations based on parabolic troughs can soon become a competitive option in the world's electricity market, if the market extension of this mature technology is supported by a concerted, long-term program capable of combining the forces of industry, finance, insurance and politics. Technical improvements based on the experience of over ten years of successful operation, mass-production and economies of scale will lead to a further cost reduction of 50% and to electricity costs of less than 6¢/kWh for hybrid steam cycles and less than 4c/kWh for hybrid combined cycles, respectively. By 2010, a capacity of 7 GW could be installed, avoiding 16 million tons of carbon dioxide per year at an avoidance cost of $2.50/tonne of CO_2.

The external funding necessary to bring down the cost of electricity during the program is on the order of $1 billion distributed over a period of eight years, starting with 30% for the first plants and reducing to zero in 2008. In all, the subsidized funding corresponds to only 6% of the overall investment of $16 billion.

The additional funding may come from diverse financial and political support, such as grants from public funds, tax-incentives, governmental guarantees and funds covering risks, low insurance fees for emission-free power, and low interest rates for capital used for pollution-free power generation. Tradable certificates for avoided carbon dioxide emissions in the frame of Activities Implemented Jointly (AIJ) can generate additional income for solar thermal power plants, offsetting the additional costs.

The measures for financial support listed above show that each one alone is sufficient to fund a market introduction program. A combination of those measures, sharing the financial burden among several players from industry, financial institutions, insurance and government, and the long-term frame of the program will create a particularly attractive environment for private investors. The additional funds needed for the start-up period are relatively small; thus the chance of success is particularly high.

5. CONCLUSIONS

To fully exploit environmentally friendly solar-thermal power, broader cooperation between government, electric utilities, and private industry is needed. Government support for research, technology development, and demonstration projects, though necessary, is not sufficient. In addition, market incentives must be created to overcome barriers in the user and financial communities that exist because solar thermal technologies are new, potentially risky,

and viewed as a possible threat to existing technologies and interests. Finally, the major investments needed to properly develop and market solar technology must be supported by stable long-term regulatory policies, which can only be provided by legislative and governmental supports.

A recent study on a market-introduction program shows that a combination of novel measures to share the financial burden among industry, financial institutions, insurance and government could create an attractive environment for private investors and help establish solar thermal power generation in the marketplace within the next one to two decades.

The IEA SolarPACES group is evaluating many of the technical and non-technical issues discussed in this paper. For more information regarding on-going projects, the reader should consult the SolarPACES annual reports and other papers presented at the International Conference on Solar Thermal Concentrating Technologies in Odeillo/France, June 1998.

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