SOLAR TWO TECHNOLOGY FOR MEXICO

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Solar power towers, based on molten salt technology, have been the subject of extensive research and development since the late 1970s. In the mid 1980s small experimental plants were successfully fielded in the USA and France that demonstrated the feasibility of the concept at a 1 to 2 MW_e scale. Systems analyses indicate this technology will be cost competitive with coal-fired power plants after scaling-up plant size to the 100 to 200 MW_e range. To help bridge the scale-up gap, a 10 MW_e demonstration project known as Solar Two, was successfully operated in California, USA from 1996 to 1999. The next logical step could be to scale-up further and develop a 30 MW_e project within the country of Mexico. The plant could be built by an IPP industrial consortium consisting of USA's Boeing and Bechtel Corporations, combined with Mexican industrial and financial partners. Plausible technical and financial characteristics of such a "Solar-Two-type" Mexican project will be discussed in the paragraphs that follow.

TECHNOLOGY DESCRIPTION

In a molten-salt solar power tower, liquid salt at 290 °C is pumped from a 'cold' storage tank through the receiver where it is heated by the heliostat field to 565 °C and then on to a 'hot' tank for storage. When power is needed from the plant, hot salt is pumped to a steam generating system that produces superheated steam for the turbine/generator. From the steam generator, the salt is returned to the cold tank where it is stored and eventually reheated in the receiver. Figure 1 is a schematic diagram of the primary flow paths in a molten-salt solar power plant. Determining the optimum storage size to meet power-dispatch requirements is an important part of the system design process. Tanks can be designed with sufficient capacity to power a turbine at full output for up to 13 hours.

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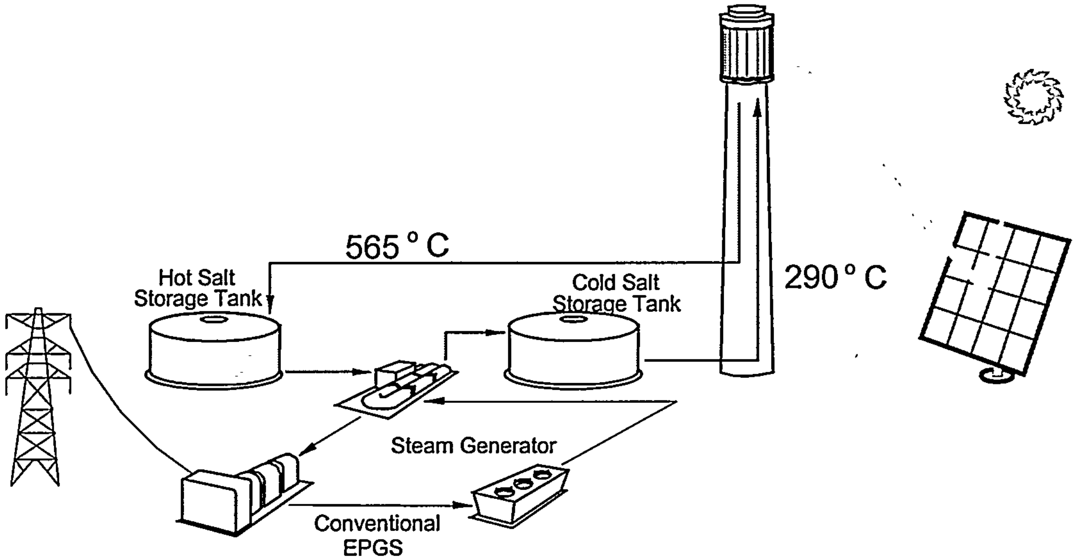

Figure 1: Molten-salt power tower (Solar Two, baseline configuration)

The heliostat field that surrounds the tower is laid out to optimize the annual performance of the plant. The field and the receiver are also sized depending on the needs of the utility. In a typical installation, solar energy collection occurs at a rate greater than that required to provide steam to the turbine. Consequently, the thermal storage system can be charged at the same time that the plant is producing power at full capacity. The ratio of the thermal power provided by the collector system (the heliostat field and receiver) to the peak thermal power required by the turbine generator is called the solar multiple. With a solar multiple of ~3, a molten-salt power tower can be designed for an annual capacity factor of ~70%. Consequently, the power tower could potentially operate for 70% of the year without the need for a back up fuel source. Without energy storage, solar technologies are limited to annual capacity factors near 25%.

The ability to dispatch electricity from a molten-salt power tower is illustrated in Figure 2. The figure shows solar intensity, energy stored in the hot tank, and electric power output as functions of time of day.

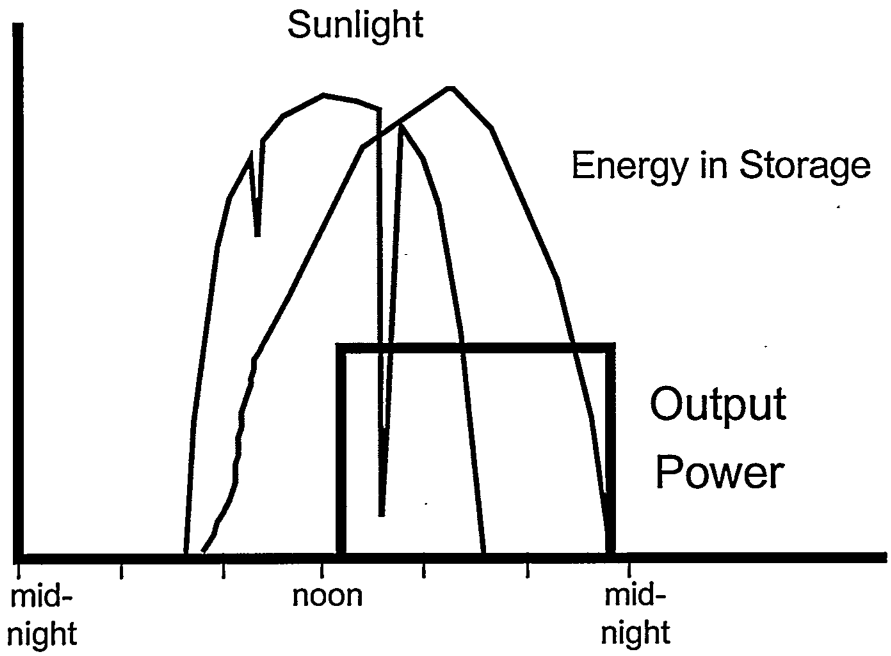

Figure 2 Dispatchability of molten-salt power towers

In this example, the solar plant begins collecting thermal energy soon after sunrise and stores it in the hot tank, accumulating energy in the tank throughout the day. In response to a peak-load demand on the grid that extends well past sundown (like in Mexico), the turbine is brought on line at 1:00 p.m. and continues to generate power until 11 p.m. Because of the storage, power output from the turbine generator remains constant through fluctuations in solar intensity and until all of the energy stored in the hot tank is depleted. Energy storage and dispatchability are very important for the success of solar power tower technology, and the USA believes that molten salt is the key to cost effective energy storage. Molten salt energy storage is low cost relative to battery methods of storing solar energy and also has a very high storage efficiency. Table 1 compares some key aspects of energy storage systems.

Economic studies have shown that levelized energy costs are reduced by adding more storage up to a limit of about 13 hours (~70% capacity factor). While it is true that storage increases the cost of the plant, it is also true that plants with higher capacity factors have better economic utilization of the turbine, and other balance of plant equipment. Since salt storage is inexpensive, reductions in LEC due to increased utilization of the turbine more than compensate for the increased cost due to addition of storage.

Table 1: Comparison of solar-energy storage systems

	Installed cost of energy storage for a 200 MW plant ($/kWhr$_e$)	Lifetime of storage system (years)	Annual round-trip storage efficiency (%)	Maximum operating temperature (C°)
Molten-salt power tower	30	30	99	600
Photovoltaic system with battery storage	150	6	80	Not Applicable

Solar Two

To encourage the development of molten-salt power towers, a consortium of utilities led by Southern California Edison joined with the United States Department of Energy to retrofit the Solar One[1] plant with a molten-salt heat-transfer system. The goals of the redesigned plant, called Solar Two, were to validate nitrate salt technology, to reduce the technical and economic risk of power towers, and to stimulate the commercialization of power tower technology. Solar Two produced 10 MW_e electricity with enough thermal storage to continue to operate the turbine at full capacity for three hours after the sun set.

The conversion of Solar One to Solar Two required a new molten-salt heat transfer system (including the receiver, thermal storage, piping, and a steam generator) and a new control system. The Solar One heliostat field, the tower, the turbine/generator, and the control system required modest modifications. Solar Two was first connected to the utility grid in early 1996 and was shutdown in the spring of 1999, after the successful completion of its test program. The plant was shutdown because lack of budget prohibited longer term operation and the very low price paid for power on the California grid precluded using power sales to pay for plant operating expenses.

The Solar Two receiver, which is shown in Figure 3, was designed and built by Boeing's Rocketdyne division. It comprised a series of panels (each made of 32 thin-walled, stainless steel tubes) through which the molten salt flowed in a serpentine path. The panels formed a cylindrical shell surrounding piping, structural supports, and control equipment. The external surfaces of the tubes were coated with a black Pyromark™ paint that is robust, resistant to high temperatures and thermal cycling, and absorbs 95% of the incident sunlight. The receiver design was optimized to absorb a maximum amount of solar energy while reducing the heat losses due to convection and radiation. The design, which includeed laser-welding, sophisticated tube-nozzle-header connections, a tube clip design that accomodated tube expansion and contraction, and non-contact flux measurement devices, allowed the receiver to rapidly change temperature without being damaged. For example, during a cloud passage, the receiver could safely change from 290 to 570 °C in less than one minute.

The salt storage medium was a mixture of 60 percent sodium nitrate and 40 percent potassium nitrate. It melts at 220 °C and is maintained in a molten state (290 °C) in the 'cold' storage tank. Molten salt can be difficult to handle because it has a low viscosity (similar to water) and it wets metal surfaces extremely well. Consequently, it can be difficult to contain and transport. An important consideration in successfully implementing this technology at Solar Two was the identification of pumps, valves, valve packing, and gasket materials that worked with molten salt. Accordingly, Solar Two was designed with a minimum number of gasketed flanges and most instrument transducers, valves, and fittings were welded in place.

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[1] Solar One was a 10 MW_e power tower that successfully operated from 1982 to 1988. In Solar One, steam was directly generated in the solar receiver and a oil/rock thermal storage system was used. Thermal storage for this plant was costly and inefficient. Because of this, the USA decided to develop molten-salt power towers.

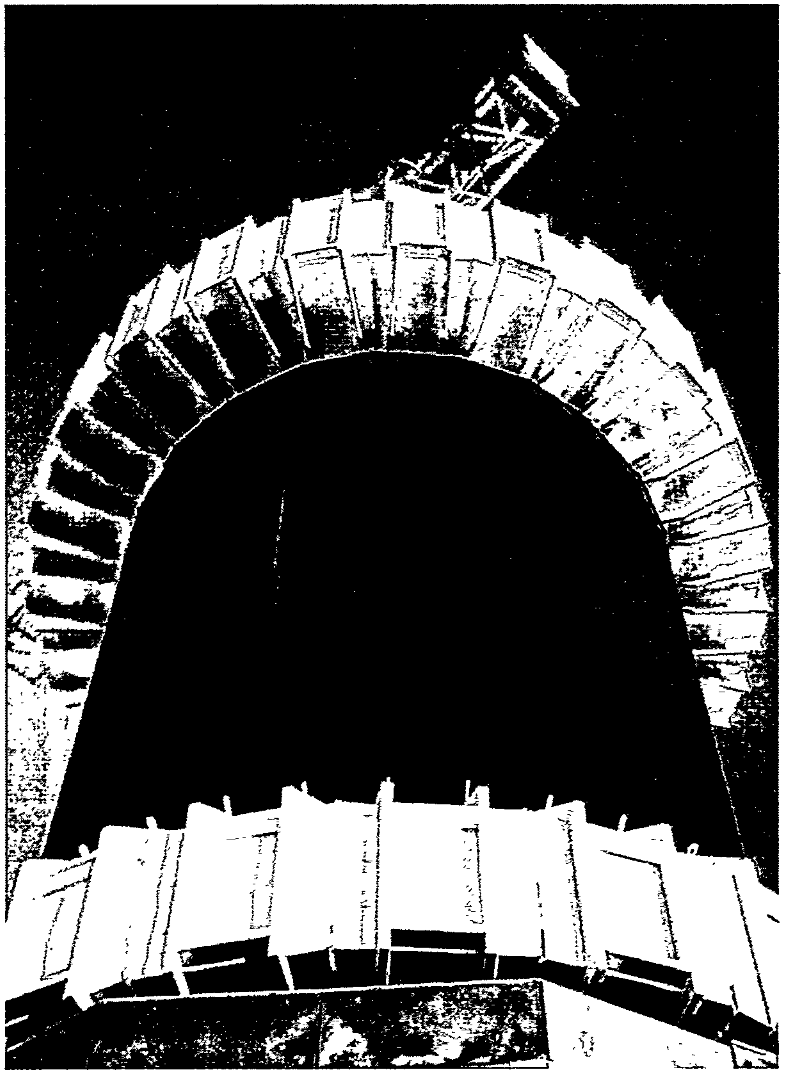

Figure 3 The molten-salt receiver at Solar Two

The energy storage system for Solar Two consisted of two 875,000 L storage tanks which were fabricated on-site by Pitt-Des Moines. The tanks were externally insulated and constructed of stainless steel and carbon steel for the hot and cold tanks, respectively. A natural convection cooling system was used in the foundation of each tank to minimize overheating and excessive dehydration of the underlying soil.

All pipes, valves, and vessels for hot salt were constructed from stainless steel because of its corrosion resistance in the molten-salt environment. The cold-salt system was made from mild carbon steel. The steam generator system (SGS) heat exchangers, which were constructed by ABB Lummus, consisted of a shell-and-tube superheater, a kettle boiler, and a shell-and-tube preheater. Stainless steel centrifugal cantilever pumps transported salt from the hot-tank-pump sump through the SGS to the cold tank. Salt in the cold tank was pumped with multi-stage turbine pumps up the tower to the receiver. The 'core' area of Solar Two, which included the storage tanks, the steam generator, salt pumps, and piping, is shown in Figure 4.

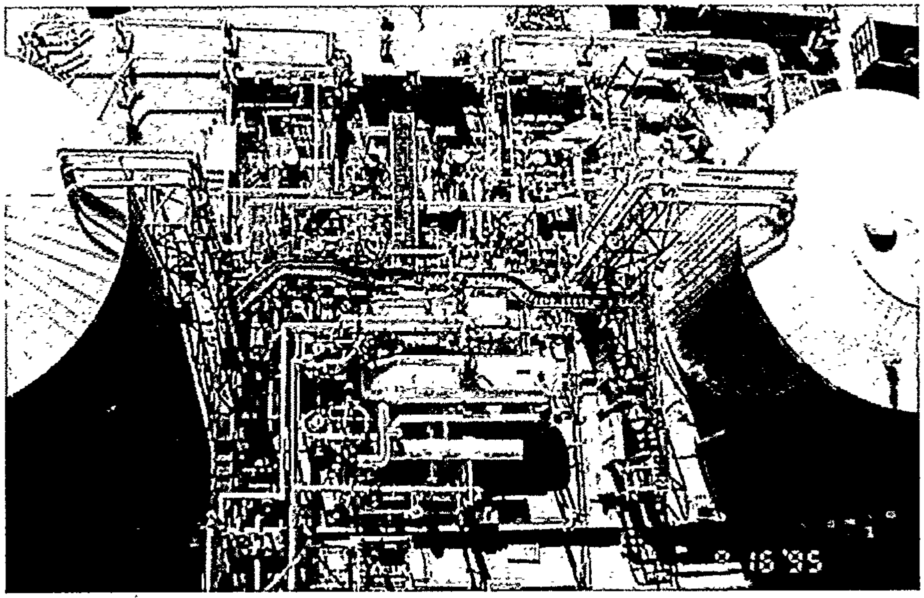

Figure 4: Core area at Solar Two

Data showed that the molten salt receiver and thermal storage tanks perform as predicted during design. For example, data revealed that the receiver absorbed 39.8 MW_t, which is 93% of the design value. Considering the fact that the mirror field had significant problems, due to the use of old Solar-One-type heliostats, this is as good as could be expected. The thermal storage system also exhibited excellent thermal characteristics. Figure 5 depicts a month-long cooldown of the hot storage tank when it was filled with molten salt. It can be seen that the tank cools very slowly (about 75°C over one month) and the measured thermal losses are within about 10% of the design prediction.

POSSIBLE FUTURE POWER TOWERS IN MEXICO AND ELSEWHERE

To date, the largest power towers ever built are the 10 MW_e Solar One and Solar Two plants. Now that Solar Two has successfully demonstrated molten salt technology at a reasonable scale, the first commercial plants will scale up the technology by a factor of 3 to 10 in size for utility-grid-connected applications in the Western United States and/or international power markets such as Spain[2] or Mexico. New peaking and intermediate power sources are needed today in many areas of the world. As the technology matures, plants with up to a 400 MW_e rating could be built. Low-cost energy storage will allow plants to be designed and built with a range of annual capacity factors (20 to 70%). Total market penetration should be much larger for this technology than for an intermittent solar technology without storage. This is due to the combination of high capacity factors and the fact that energy storage will allow power to be brought onto the grid in a controlled manner. In other words, the inclusion of storage reduces electrical transients and results in a more stable overall utility grid. For example, EPRI has estimated that total possible market penetration by a solar technology without storage will be limited to only 10% of total grid capacity.

Proposed Initial System Application in Mexico - To reduce the financial risk associated with the deployment of a new power plant technology and to lower the cost of delivering solar power, initial commercial-scale power towers would likely be hybridized with conventional fossil-fired plants. Many hybridization options are possible with combined cycle and Rankine-cycle plants, but the option that appears to make the most sense for Mexico is depicted in Figure 6.

[2] A first-commercial project is currently being pursued in Spain by Bechtel, Boeing, Spanish companies, and Sandia National Laboratories. If financing can be found, this project could be online by 2003. Currently plans call for a receiver that is 3 times larger than Solar Two and an energy storage system that is 5 times larger.

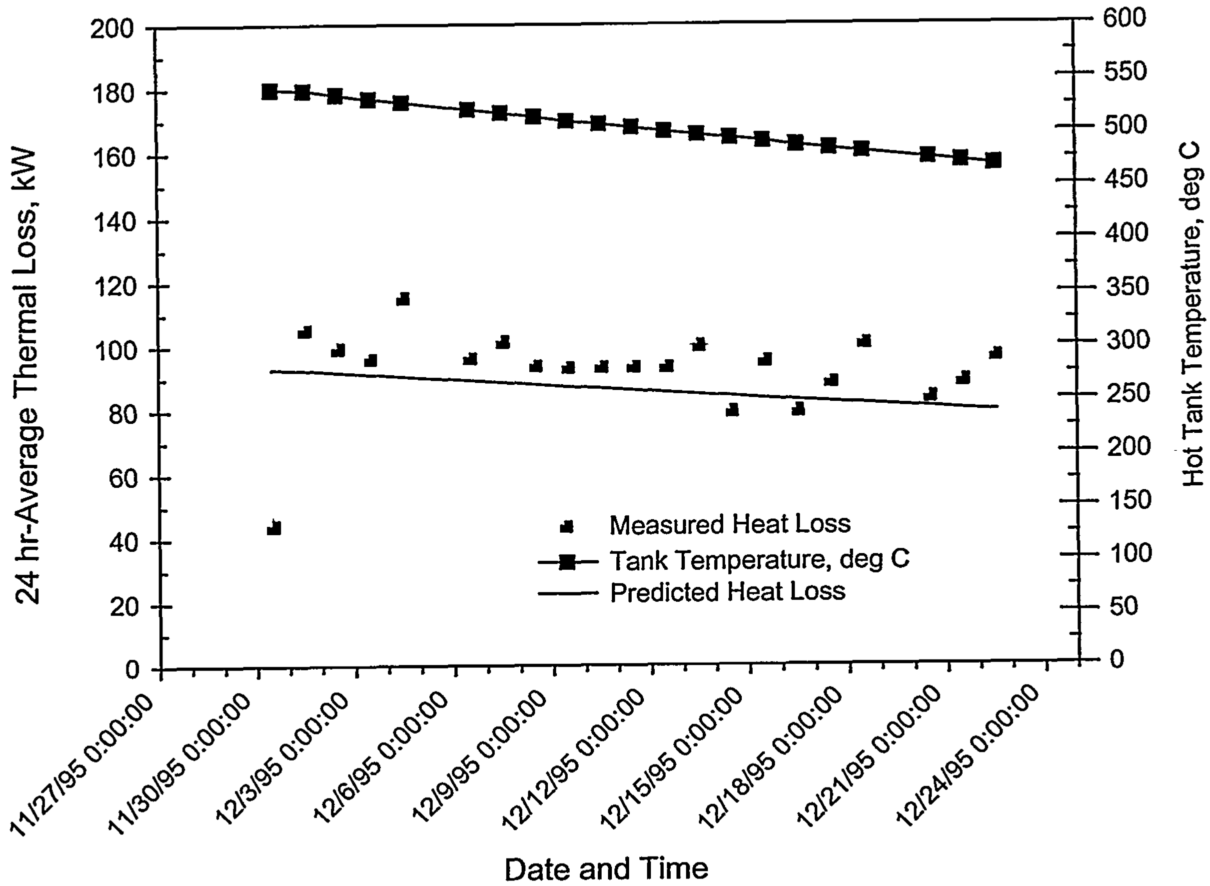

Figure 5: Cooldown of hot storage tank at Solar Two

In the hybrid plant, the solar energy is used to boost the power output of the steam turbine. Typical daily power output from the hypothetical "power boost" hybrid power plant is depicted in Figure 7. From the figure it can be seen that in this plant we have, in effect, "piggybacked" a solar-only plant on top of a base-loaded fossil-fueled plant.

In the power boost hybrid plant, additional electricity is produced by over-sizing the steam turbine contained within the Rankine plant so it can operate on full fossil and solar energy when solar is available. In this plant, solar contributes about 25% of the peak power output from the plant. Designing plants with a relatively modest solar fraction reduces financial risk because the majority of the electricity is derived from proven fossil technology and steady payments for power sales are assured.

Plausible Technical and Financial Characteristics of Mexico's First Power Tower

The first power tower plant in Mexico is assumed to be hybrid and is comprised of a 105 MW base-load combined-cycle plant fired with natural gas combined with a 30 MW solar power tower. Hybrid parabolic trough plants with approximately this split between gas-fired combined cycle and solar power have been proposed for funding by the Global Environmental Facility in India, Egypt, and Morocco. The solar capacity factor for the proposed power plant is selected to be ~40%[3]. The solar tower will therefore provide evening peaking power as well as some intermediate load power. To achieve these solar specifications, the sizes of the heliostat field, receiver, storage, and steam generator should be similar to those listed in Table 2.

Also listed in the table is the cost of the solar components. It should be noted that the costs listed for the turbine/generator and O&M are *incremental* amounts associated with adding 30 MW to the base load plant. If one were to compare these 2 amounts with the same categories for a 30 MW solar-only plant, they would see that they are reduced by ~50%. This is the primary reason why the cost of solar power in a hybrid solar plant is less than in a solar-only plant. The cost of the heliostats is likely to be the most controversial item listed in the table. The assumed cost is $160/m^2. This is based on a 1996 study by the USA SOLMAT program. This value along with others obtained from additional sources is plotted in Figure 8.

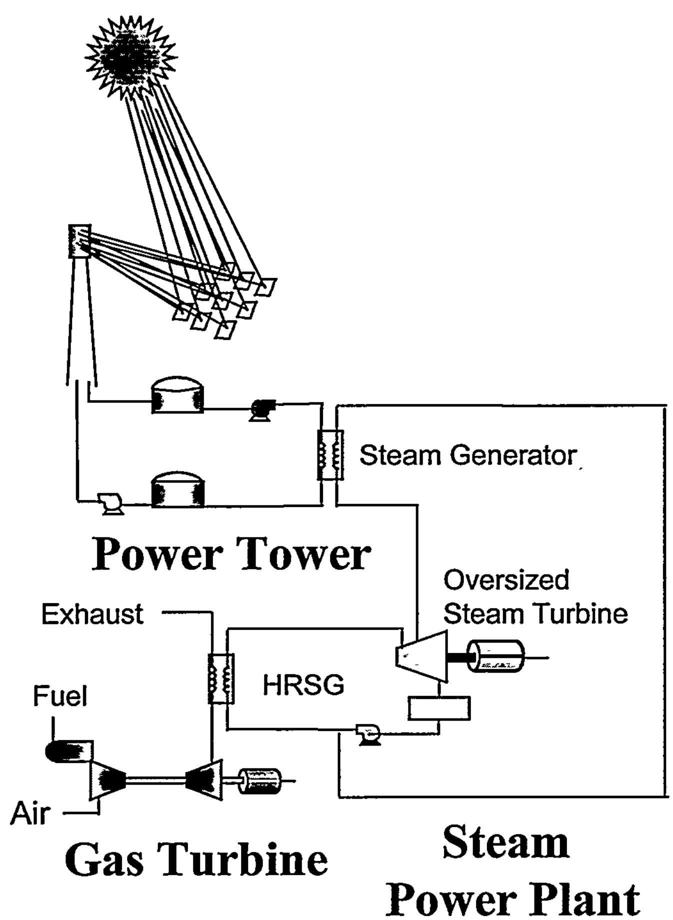

Figure 6: Power tower hybridized with gas-fired combined-cycle plant. Steam from the solar steam generator is blended with steam from the heat recovery steam generator before entering the steam turbine.

[3] This capacity factor has been selected to demonstrate the ability of molten salt technology to meet the evening peak in Northern Mexico. The optimum capacity factor for Northern Mexico may be higher or lower than this, depending on the results of detailed economic studies.

Figure 7: A hypothetical power profile from a "power-boost" hybrid plant. In this case, thermal storage is used to dispatch the solar electricity late in the day to meet an evening peak that lasts well into the night (a pattern that is common in Mexico).

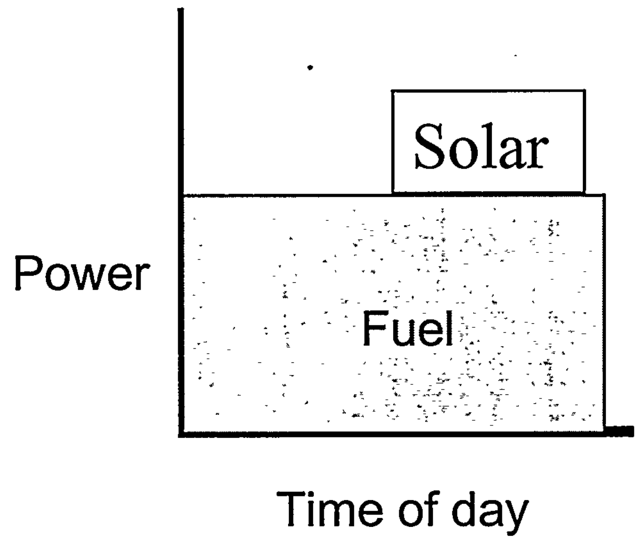

Table 2: Specifications for Hybrid Solar Power Tower Plant Using Molten Salt Technology

Plant Design	**Power Booster**
Maximum solar and fossil power	135 MW_e
Maximum fossil-only power	105 MW_e
Solar receiver thermal rating	145 MW_t
Number of heliostats	1850
Total heliostat area	275000 m^2
Thermal storage size	550 $MWhr_t$
Solar steam generator size	80 MW_t
Solar-specific turbine/generator size	30 MW_e
Performance	
Annual output from fossil energy	737000 $MWhr_e$
Annual output from solar energy	113000 $MWhr_e$
Total annual output	850000 $MWhr_e$
Annual direct normal insolation	2.7 $MWhr/m^2/yr$
Solar Capital Cost	
Structures & improvements	3.5 $M
Heliostats	44 $M
Receiver & tower	18 $M
Thermal storage	11 $M
Steam generator	5.3 $M
Turbine/generator & Balance of plant	12.5 $M
Control	1 $M
Engineering/construction management	10 $M
Contingency (15% of above)	15.8 $M
Total	121 $M
Annual Solar O&M Cost	~1.5 $M

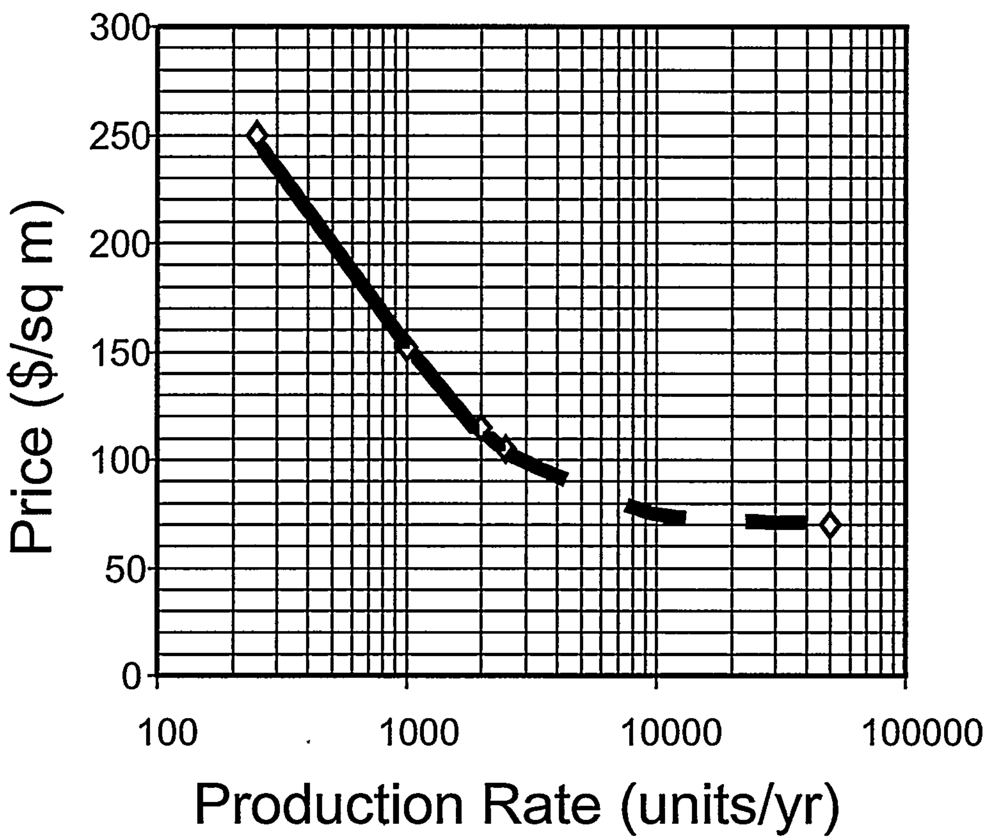

Figure 8: Heliostat price as a function of annual production volume. These prices apply to a heliostat with a surface area of 150 m^2 and is similar in design to those tested at Sandia National Laboratories. Solid portion of curve is based on estimates by USA manufacturers. Dashed portion is a reasonable extrapolation.

Using the direct-normal insolation file for Blythe, California (close to Mexicali, B.C.), the SOLERGY computer code was used to predict the solar capacity factors and net solar-electricity delivery as a function of time of the day and month of the year. The result of this analysis is presented in Table 4. The solar plant is assumed to be out for maintenance for 30 days per year; a 3 week scheduled outage is assumed for December and 9 days the rest of the year.

It can be seen that the energy storage feature of the molten-salt power tower allows high capacity factors to be obtained during the evening and afternoon periods.

Table 4: Predicted Capacity Factors (%) as a Function of Time for a 30 MW Solar Power Booster Operating in Northern Mexico

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1700-2200h Evening Power	95	74	91	91	97	96	94	94	100	93	97	17
1300-1700h Afternoon Power	78	48	71	81	84	89	84	87	90	73	87	10
2200-1300h	6	9	22	29	33	41	30	25	26	16	9	0
# of Maintenance Outage Days	0	2	0	2	0	2	0	2	0	1	0	21

SUMMARY AND CONCLUSIONS

Studies by the Department of Energy's national laboratories, major U.S. utilities, and the World Bank have identified molten-salt power towers as the technology that may be able to achieve the lowest solar-electricity cost for power plants in the 30- to 400-MW_e size range (World Bank, 1999, Electric Power Research Institute, 1997). In addition, the integral low-cost energy storage system provides functional features that are unique among solar technologies: (1) plants with high annual capacity factors (~70%) are economically practical and (2) power can be dispatched to the utility grid when the demand is the highest, even at night. These promising findings led to the construction and operation of the Solar Two power tower from 1996 through early 1999. This 10-MW_e plant demonstrated the viability of molten-salt technology at a reasonable size, which will allow a low-risk scale-up to a commercial size in the next plant. The positive findings of the Solar Two project (Pacheco, et.al, 2000) have led to the current promotion of a first-commercial plant in Spain. Mexico would also be an excellent site for an early deployment of this technology. Because the people who developed Solar Two are in "Mexico's backyard," business relationships between American and Mexican industry to build the plant could be readily formed.

REFERENCES

Electric Power Research Institute and U.S. Department of Energy, 1997, *Renewable Energy Technology Characterizations*, EPRI TR-109496, Palo Alto, CA. (The report may be downloaded at website "http://www.eren.doe.gov/power/techchar.html".)

Pacheco, J. E., H. E. Reilly, G. J. Kolb, and C. E. Tyner, "Summary of the Solar Two Tests and Evaluations," *Proceedings of the Renewable Energy for the New Millennium, Solar Thermal 2000 International Conference*, March 8-10, 2000, Sydney, Australia.

World Bank, 1999, *Cost Reduction Study for Solar Thermal Power Plants, Final Report, May 5, 1999,* contact: Richard Spencer, Washington, D. C.