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Characterization of Alternative Hybrid Solar Thermal Electric Systems

Tom A. Williams

Abstract: Hybrid power towers offer a number of advantages over solar-only power tower systems for early commercial deployment of the technology. These advantages include enhanced modularity, reduced financial and technical risks, and lower energy costs. With the changes in the domestic and world markets for bulk power, hybrid power towers are likely to have the best opportunities for power projects. This paper discusses issues that are likely to be important to the deployment of hybrid power towers in the near future. A large number of alternative designs are possible, and it is likely that there is no single approach that can be considered best or optimal for all project opportunities. The preferred design will depend on the application, as well as the unique objectives and perspectives of the person evaluating the design.

1. INTRODUCTION

The Solar Two plant is currently demonstrating the technical viability of molten-salt power towers at a 10-megawatts (MWe) level. Following successful demonstration, the next step is deployment of the technology in a commercial application. The question is what type of application, and how should the technology be designed for that application. A scale-up of the system to a much larger capacity (30-100 MWe) is one alternative. Another alternative is to use the basic solar technology demonstrated at Solar Two in a hybrid solar/fossil configuration.

The expanding interest in developing early commercial solar plants using hybrid systems is driven by the requirements of the marketplace, not by any specific developments in solar thermal or hybrid system design. The utility market is moving rapidly toward deregulation. Utility ownership of all power plants is rapidly being replaced by Independent Power Producers (IPP) building, owning, and operating plants. And the most widely held perceptions are that fossil energy prices should remain fairly stable for some time to come. Hybrid systems have many potential advantages over solar-only systems in this type of market environment.

The purpose of this paper is to articulate the issues that are likely to lead to selection from among different types of hybrid options for early deployment of commercial molten-salt power tower plants. Based on the market environment described above, the paper develops perspectives on the issues that are likely to drive the selection of preferred project configurations. These perspectives are used to identify alternative project scenarios, and then to consider how the various technology options might align with these scenarios.

2. EVALUATION CHARACTERISTICS FOR HYBRID PROJECTS

Although it is typical in the solar literature for studies to speak of “optimizing” the plant design, in most cases the optimization consists of simply minimizing the levelized energy cost (LEC). It also is typical that studies constrain the optimization to a particular plant size or design. There is nothing intrinsically wrong in this approach, but it can easily lead to overly strong conclusions that a particular design is “best” or “optimal.” In any project there are a number of important attributes that go into the selection process. To complicate matters further, most projects involve a number of decision-makers. The prospective of a research, development, and deployment (RD&D) agency may differ greatly from that of a financial institution, leading to very different judgements of what is important in project selection and design.

There are several classes of decision-makers that can be expected to be involved in the decision to build a solar thermal power plant. *Owners* of the plant are the equity investors who sell the energy services from the plant to recover their investment and earn suitable return. In the past the owners were typically expected to be utilities, but power restructuring worldwide now makes the ownership more likely to be an IPP, or a utility that will operate more like an IPP and less like a traditional utility. *Financial organizations* lend money for the project, and are most interested in the project being financially stable, ensuring return of the principal with interest. *Grant organizations* have interests in promoting solar technologies, and are generally interested in playing a catalytic role that buys down the cost of initial plants with the expectation that future plants would be built without grants. *RD&D organizations* (which may be governmental or private companies) want to develop and demonstrate advanced technologies that have the potential to be superior to existing options. *Public interests* reflect a stakeholder group rather than part of the decision-making group, but in many projects may have a strong impact on what is judged acceptable.

The following subsections describe the more important characteristics in the selection of the preferred hybrid option for a particular application, and the importance of these characteristics to the different members of the decision-making group.

2.1 Economic Factors

Economic factors are of most importance to owners, but are also very important to financial organizations. They may be of moderate to high importance to the other members of the decision-making group.

The levelized energy cost of a hybrid plant is an important screening variable for owners and the public. The LEC can be calculated on an overall basis for the plant (where solar energy is blended with fossil fuel energy), or with the solar LEC separated from the fossil LEC. The overall basis of calculation is popular with technology advocates, because blending the solar energy with low-cost fossil fuels yields a lower LEC value. The use of the solar LEC provides a better comparison of the solar economics, and is particularly important for comparing alternative hybrid systems [1,2].

Solar investment costs relate to the specific capital investments in the plant that are required for the solar plant and the equipment to integrate the solar energy with fossil energy. Depending on the plant design, solar investment costs represent most or all of the project funds that are at risk because of new technology. Interviews with IPP indicate that in some cases solar investment costs may be more important than the solar LEC, and because they drive subsidy requirements they are very important to grant organizations. Solar investment costs are linked to the modularity of the system design and to the unit costs of the specific solar hardware required.

The final economic evaluation of the project should be based on discounted cash flow analysis that includes all financial benefits, including capacity payments and grants. Capacity payments (and load profiles) in particular can have a significant impact on the choice of the most economic hybrid technology, and should therefore be identified early in the evaluation [3].

2.2 Technology Factors

The solar fraction measures the percentage of energy on an annual basis that is supplied by solar energy. Solar fraction has been an issue of considerable debate within the RD&D community, with the arguments centered around whether a critical level of solar fraction should be required to justify investment of solar energy RD&D funding. Solar fraction also has been a concern of grant organizations. After much public input, the California Energy Commission (CEC) established a requirement that solar projects have a minimum solar fraction of 75% to receive production subsidies. There is at least some public concern that plants with low solar fractions are not “real” solar plants. It is too early to tell how the solar fraction will ultimately enter into the decision-making processes of these groups, but clearly it is an issue that must be considered.

Technology risk is the uncertainty in the operation, efficiency, or lifetime of the solar system. Technology risk clearly affects the financial risk of a project, so it is important to owners and financial organizations. Although promising new technologies always have a higher level of risk than established technologies, technology risk is not always negative to an RD&D organization--it may even be a positive attribute. Grant organizations generally have an intermediate tolerance for technology risk, with less aversion than owners but more than RD&D organizations.

2.3 Operating Factors

It is important to owners that the hybrid plant is able to dispatch and follow load as well as competing fossil-fueled plants. This ensures maximum revenues for both energy and capacity payments. It is also important that loss of the solar component of the plant not significantly affect plant operations, either in terms of losing rated capacity or degrading the plant fossil-mode efficiency.

Environmental impacts of plant operation may be very important to any group, but are particularly important to grant organizations. Solar hybrid systems will generally carry net environmental benefits due to the offset of fossil fuel emissions, including carbon dioxide.

3. EARLY COMMERCIAL APPLICATIONS

A wide range of early commercial applications for power towers can be envisioned, each with different characteristics that will influence the selection process. This section discusses a range of these applications, and describes how they might be expected to differ in project preferences. To be inclusive, the options discussed here include market applications that have not yet emerged, as well as applications that are of interest to the solar community but which may have limited markets in the near-term. It should be noted that all of the applications are described from the perspective of the most likely preferences; certainly, other preferences may influence the decision making process in any given project.

Development applications can occur when a governmental organization or company intentionally subsidizes the deployment of a specific technology with technology risk in order to realize improvements in the technology. An example would be a government-sponsored project, or a project sponsored by a regulated utility. The main influences on the project structure would come from the sponsoring organization (an RD&D perspective), the public, and the plant owners. The most important factors in this type of project would be expected to be the solar LEC, solar investment costs, and environmental benefits. The overall plant LEC also would be important, and it appears likely that (for the time being) solar fraction would be of some importance.

Commercial demonstrations also have subsidies, but differ from the above applications because they are designed to address economic rather than technical risk. Grants may be supplied to buy down the above-market cost of the solar energy, and preferred power purchase agreements may be included. Commercial demonstrations generally don’t stipulate a specific technology but would leave this decision to the private sector. In these projects the organizations providing the grants will have the most influence on the project design, followed by the plant owners and the organization (RD&D interest) promoting the demonstration. The fact that this application is more market driven than the previous one would lead to some changes in project priorities. Solar investment costs, project risk, and solar LEC are likely to be the dominant drivers for the project, followed by plant LEC and operating characteristics.

Environmental markets could be created by legislation assigning a value to emissions from fossil fuel plants, particularly carbon dioxide. These applications would have premium solar energy payments that reflect avoided emissions, and would likely include subsidies for initial plants to reduce economic risk. The decision influences and project attributes would be similar to commercial demonstrations, with the exception that environmental benefits would become the most important attribute.

Green markets are applications in which the solar energy is sold to clients at a premium, and the fossil energy of the plant would be sold on the open market. Green markets may be created by legislative mandate (such as solar portfolio standards for power sales) or by consumer preference. Green market applications have different priorities than the applications above because they are purely market driven. The interests of the plant owners and financial organizations dominate the decisions for these applications. Public interests also play a role, because public acceptance of the solar output will be essential to a viable market. The most important factor is the plant LEC, because the sale of energy on the open market has the most significant impact on plant economics. Risk and solar investment costs are likely to be the next most important issues, followed by operating characteristics and solar LEC. A solar fraction that is "acceptable" in the public's view would be a prerequisite for projects of this type.

Niche markets are applications in which solar energy is economically competitive with competing fossil fuels. When niche markets emerge the decision influences likely will be the same as for green markets. Compared to the green markets, though, the solar LEC would be the most important criteria because the project depends on solar being less expensive than fossil. Other project attributes are likely to be similar to those of green markets.

Although all of the application scenarios above have been proposed and discussed within the solar community, they are not all equally likely to happen in the near future. With support from the Global Environmental Facility (GEF), opportunities for commercial demonstrations exist today, and utility restructuring within the United States has created significant promise for green markets there. Development applications and environmental markets could emerge within the next few years, but the timing and probability are difficult to predict. Niche markets appear to be somewhere in the future for molten-salt power towers, with the timing uncertain.

4. HYBRID CONFIGURATION OPTIONS

Several attractive designs have been proposed for hybrid molten-salt power towers. This section provides a brief overview of these approaches and a discussion of how they vary from one another on the key attributes that will drive project selection.

The simplest hybrid approach is to install a parallel source of fossil heat to supplement the solar heat. This could be a simple salt heater, but more likely would be a separate fossil-fired boiler. This is commonly referred to as a *fuel-saver* design, although it may be applied for purposes other than saving fuel. This type of design can allow operation of the plant entirely on solar energy. High capacity factors could be achieved using energy storage along with a high solar fraction. A fuel-saver design is a logical next step for Solar Two, because it requires the least amount of new technology or design modifications and thus it has a low technology risk. The approach can be applied to any type of fossil-fueled Rankine cycle plant, allowing the displacement of coal usage to reduce greenhouse gases [3,4].

Other design options become possible if the system augments, rather than supplements, fossil energy use by the plant [5]. For example, the solar heat can be added to the bottoming cycle in a combined cycle plant [3, 4]. In this case the solar heat is input through only a portion of the thermodynamic cycle. An advantage of this approach is that the temperature of the solar heat and the fossil heat do not need to match, as they do in the parallel approach. This provides flexibility in selecting the heat engine/fossil source to provide the best overall economics, and in selecting the solar heat source based on the most cost-effective production of heat without a temperature constraint. Two generic design approaches will be considered here. The *combined cycle fuel-saver* would provide a small fraction of solar steam to augment the energy production in the steam turbine of the combined cycle. The plant typically would be designed so that during hot weather (when the efficiency of the Brayton cycle decreases) the solar-supplied steam would allow continued operation at nameplate capacity. An alternative approach would provide more steam to the bottoming cycle, with an increase in plant capacity (up to about 12%) when solar is available. This *power-booster* approach has the advantage of providing additional capacity at a low capital cost, which may have significant economic benefits with the proper structure of capacity payments. The additional increases to the steam turbine capacity mean that the power-booster plant will operate in off-design conditions most of the time. Careful attention to the system design is needed to avoid degradation to the plant efficiency. While the combined cycle fuel saver and power-booster are not significantly different in conceptual design, the additional design concerns associated with a large degree of oversizing of the steam turbine make the power-booster approach somewhat more risky. Another difference between the concepts is that the power-booster approach would operate below nameplate rating when solar energy is not available.

A final hybrid option is solar preheating. In the solar preheating approach, fossil energy is used to boost the temperature of solar thermal energy prior to using it in the heat engine. An advantage of this approach is that the selection of the heat engine can be made for the most efficient and economic system, regardless of the capabilities of the solar technology. This allows the selection of various Brayton cycle engines (including aeroderivative turbines) or combined cycle systems, without the necessity of providing solar heat at a very high temperature. The system and solar conversion efficiency for this approach is very high, leading to the promise of low solar LEC values. The Kokhala design uses molten-salt to preheat compressed air to the combustion turbine in a combined cycle, with energy cost projections that are half that of a similar solar-only design [2]. Commensurate with the promise of high efficiency and low cost is the fact that technical risks for using this type of hybrid approach are higher than the previous approaches. Although design changes that simplify the integration are very feasible, the expense of these changes, coupled with the current small market, make it uncertain that a customized "solar gas turbine" will occur anytime soon. It is more likely that designers of these systems will need to utilize the best standard turbines available, even if the designs are not optimal for a solar hybrid plant. The Kokhala-type design is likely to require pilot-scale plant operations before proceeding to a commercial system.

5. DISCUSSION

All of the solar/fossil hybrid options described in this paper appear to be preferable for early commercial applications compared to solar-only designs. Several characteristics drive this conclusion. Hybrid plants offer lower project operating risks, can be built with much smaller solar investment costs (minimizing economic risk), and can produce solar energy less expensively than the solar-only system [2, 3, 4]. Although niche markets could conceivably allow commercial applications for solar-only plants, it seems likely that the lower risks and enhanced operating characteristics of hybrid plants make them preferable even in these applications.

Achieving the lowest solar LEC would be a priority for a development application type project, but is not likely to be a primary issue for most other projects. Minimizing technical and economic risk are among the most important criteria for designing projects in most of the scenarios described here. This leads to several general conclusions. Minimizing the solar investment cost reduces economic risk, but is generally possible only with low to moderate solar fraction plants. These plants will probably dominate most serious project proposals if the issue of solar fraction does not become a roadblock in the minds of any of the key decision makers. Minimizing solar investment costs also makes it very unlikely that storage would be employed at early commercial plants, even though molten-salt power towers offer excellent energy storage capabilities. For most of the application scenarios, the plants would likely be designed with modest solar fractions at design point, and short duration buffer storage to minimize thermal transients.

As has been discussed, the selection of the best hybrid plant design varies according to the decision makers, and the influence of various decision makers will vary with the type of project. This creates a complex objective function that would be very difficult to quantify in today's rapidly changing market environment. It thus appears very unlikely that there is a clear "optimal" or "best" hybrid approach for power towers that would fit all potential commercial applications. Perhaps the best that can be currently hoped for is to identify options that seem generally preferred for most project scenarios, or for the most likely scenarios. Considerations of how the individual technologies might mesh within each of the project scenarios are given below.

Kokhala-type designs would appear attractive in the *development applications* scenario because of the low solar LEC and the relatively high tolerance for risk. Kokhala type designs carry more technical risk than the other options described in this paper, and so would not be likely to be highly evaluated in any of the other project scenarios. It is unlikely that a true commercial plant would be constructed for the

Kokhala design prior to pilot plant operation and evaluation, which is a step that may not be necessary for the other hybrid approaches.

Fuel-saver designs would be good options for *commercial demonstrations* because of their minimal risk, low solar investment costs, and ability to achieve a low plant LEC. The choice between the Rankine system and the combined cycle system is not obvious for this application and would likely be based on the predominant approach used on the local power grid. Power-booster systems may be somewhat less attractive for these applications if they are perceived to have more technical risk in the design. However, a power-booster approach could easily be the preferred option in this case if there were a strong capacity need that was coincident with solar insolation.

Green market applications will have a high premium on the price of fossil energy and project risk that might drive a strong preference for fuel-saver combined cycle designs. Power-booster options could have economic advantages with the right demand profile, but for this market scenario the primary driver for installing the solar plant will be the payments for solar energy. In addition, the added technical risk and potential operating issues for power-booster systems will make them less attractive in these applications.

Niche applications are generally speculative today, and it is possible to imagine a specific application that might prefer any of the power-booster or fuel-saver approaches.

The fuel-saver Rankine design could be preferred in the *environmental markets* since it is the only plant that could easily displace coal, gaining benefits for avoiding large amounts of carbon dioxide emissions. The combined-cycle version of the fuel saver would also be attractive because of its low plant LEC. Power-booster options have the drawback of higher risk.

An issue that must be addressed for any of the hybrid plants is a pathway for reducing the costs on future plants. Early power tower projects will be necessarily expensive by being "first of a kind," but steady and substantial cost reduction is necessary. Having a credible plan for achieving this cost reduction will be a prerequisite for the industry to secure any subsidies for the early projects. Successfully implementing the plan will be a prerequisite to developing a real and sustainable market for the technology.

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