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SOLAR THERMAL ELECTRIC HYBRIDIZATION ISSUES

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Solar thermal electric systems have an advantage over many other renewable energy technologies because the former use heat as an intermediate energy carrier. This is an advantage as it allows for a relatively simple method of hybridization by using heat from fossil-fuel. Hybridization of solar thermal electric systems is a topic that has recently generated significant interest and controversy and has led to many diverse opinions. This paper discusses many of the issues associated with hybridization of solar thermal electric systems such as what role hybridization should play; how it should be implemented; what are the efficiency, environmental, and cost implications; what solar fraction is appropriate; how hybrid systems compete with solar-only systems; and how hybridization can impact commercialization efforts for solar thermal electric systems.

Our experience is that many in the renewable energy community consider hybrid systems an evolutionary dead end. Their argument essentially is that, in the long run, solar will be less expensive than fossil fuels, and substantial energy contributions to the U.S. economy can be made using solar-only plants. In this view, hybrid plants are an anomaly that at best would quickly fade away as solar plants become more cost effective, and at worst would cannibalize a market for solar power that would otherwise go to solar-only plants. Our goal in this paper is to advance an alternative view: hybrid systems may be an important strategy in further commercialization of solar thermal power.

Hybridization can bring many benefits to the value of solar thermal power for current markets. One of these benefits is providing a low-risk pathway to substitute for technology that has not been developed commercially. For example, energy storage technologies for dish/Stirling systems currently are not cost effective. Developing a combustor for the Stirling receiver is straightforward compared to developing new thermal or electric energy storage technologies, and the combustor provides the same benefit of allowing operation when the sun is not shining.

Another benefit of hybridization is that it can reduce the financial risk of commercial deployment of new technology. Consider the first commercial power tower plant, which, in the solar-only configuration, is expected to cost about $330 million (1990 dollars) for a 100-MWe plant (APS, 1988). If the plant is designed as a solar-only plant, the financial risk exposure is the total cost of the plant. If a parallel source of fossil heat is added to the plant, the plant costs would increase somewhat, but the financial risk from the new technology would now be limited to the capital cost of the original plant less that of the electric power generating system, or about $250 million.

Reduction in the delivered cost of energy can also be achieved through proper hybrid design. In today's environment of low-cost fossil fuels, hybridization decreases the delivered energy cost of the system as fossil energy displaces solar. A less obvious design option is the use of the fossil energy source to increase the temperature of the solar heat, allowing a more efficient conversion of the solar energy into electricity by allowing the use of higher-temperature, more-efficient thermodynamic cycles.

ESSENTIALS OF HYBRIDIZATION

For the purposes of this paper, a hybrid system is one in which a combination of solar and fossil energy are used to generate electricity. This definition could be generalized to other renewable energy sources and other energy carriers besides electricity, but the technology-specific description helps to simplify the subsequent discussions. Under this definition there are many different ways to develop a hybrid design, each with advantages and disadvantages. Some fundamental issues are independent of the design, however, and these issues are the topic of this section.

Under the definition above, any type of hybridization system must have at a minimum the following components: a heat engine subsystem for converting thermal energy into electricity, a solar energy subsystem for converting solar energy to thermal energy and transferring it to the working fluid of the heat engine, and a fossil subsystem for converting fossil fuel chemical energy into thermal energy and transferring it to the working fluid of the heat engine.

Depending on the choices of subsystems and how they are integrated, a number of different hybrid systems can be configured. The specifics of the hybrid system design determines whether the subsystem characteristics are highly linked or are independent, and this can affect overall system performance. For example, if a natural-gas-fired combined cycle is hybridized by providing solar steam to the steam turbine, this will affect the design and efficiency of both the steam turbine and possibly the fossil subsystem by requiring an oversized steam turbine. Alternatively, if a solar energy system is hybridized by adding a fossil-fired heater for the solar heat transfer fluid, the use of the fossil heater has no impact on the efficiency of either the solar field or the heat engine.

An important but potentially confusing hybrid issue is the efficiency of converting the solar and fossil heat into electricity. Efficiency is an important issue because the cost of solar heat is high, and we need to ensure that it is converted to electricity at the highest possible efficiency. A fundamental concept is that both the fossil heat and solar heat are converted to work at the overall cycle efficiency. Confusion often arises when considering heat engine cycles with multiple heat input points. Consider a heat cycle with two heat inputs, one of which appears to convert heat to work at a significantly higher efficiency than the other. Replacing the fossil heat at the high-efficiency input point with solar heat affects neither total heat input or total cycle work, so overall efficiency has not been affected. An argument based on higher conversion of solar energy at a specific point in the cycle ignores the concomitant reduction in efficiency of conversion of the fossil fuel in the lower-conversion part of the cycle.

As an example, consider a steam-Rankine cycle with superheat and reheat. For fixed reheat conditions, it can be shown that heat input to the superheater is converted to work at the isentropic efficiency of the high-pressure turbine, which can be as high as 90% for large steam turbines. It is therefore tempting to put the solar heat into the superheater and claim that it is converted at this high efficiency. However, in most cases, the superheating can also be accomplished with fossil fuel combustion. So displacing the fossil fuel in the superheater has the same effect as displacing fossil fuel elsewhere in the cycle (e.g., the evaporator or preheater)—that is, no net improvement in cycle efficiency.

A final essential of hybridization is related to economics. A question often asked about hybridization is, "For a given plant configuration, what solar fraction achieves the lowest levelized energy cost (LEC)?" With today's low fossil-fuel cost, the lowest LEC results from zero solar input. However, we believe the question is largely irrelevant to the issue of implementing hybrids in the marketplace. The LEC is a convenient figure of merit that is widely used by utilities and the solar thermal community for screening alternative sources of electric power. The LEC works well for screening technologies that provide the same service and are equivalent in risk and other important decision criteria. These requirements do not apply to comparisons of hybrid and solar-only designs. Solar-only systems are free from rising fuel price risk, whereas hybrid systems are not. Hybrid systems can be designed for dispatchability equivalent to fossil plants, whereas solar-only systems cannot. Hybrid systems and solar-only systems can differ substantially whether the LEC is driven by fixed costs (capital investment) or operating costs (fuel). These and other differences mean that implementation decisions for hybrid systems and solar-only systems will be made based on more than a simple comparison of the LEC.

HYBRID OPTIONS

Using the simple system description developed in the previous section, we developed five hybrid system configurations. Because the solar heat and the fossil heat may be carried by different working fluids at different temperatures and pressures, implementation of these hybrid systems requires significant process-engineering complexity involving heat exchangers, valving, etc. The hybrid variations described in this section deal with the first-order aspects of hybridization: two heat sources at two different temperatures that must be used in some way in a heat engine. We recognize that the complexities of heat exchangers and valving must be engineered properly, but these are of second order to the thermodynamic issues we explore here.

The first approach is shown in Figure 1 and is hybridization through a completely redundant system. In this case, two independent power plants are constructed—one fossil-fired and one solar-heated. This approach has the obvious disadvantage of having redundancy in the electric power generation subsystem. The approach has an advantage in being able to tailor the heat engine to be optimal for the temperature range of each energy source and has the greatest operating flexibility of any of the approaches. This is the case where a utility considers adding a solar-only plant to the grid. The solar plant is evaluated as a separate expansion of the resource base, while existing plants provide backup for periods when insolation is not available.

FIG. 1. REDUNDANT SYSTEM HYBRIDIZATION

A second hybridization approach is shown in Figure 2, where a fossil energy source is used in parallel with solar heat to provide a common heat input to the heat engine. This type of hybridization scheme was employed in the design of the parallel HTF (heat transfer fluid) heater used in the SEGS VIII and IX plants built by Luz (Kearney, 1991), which represent 160 MWe of installed capacity. It also represents most dish/Stirling hybridization schemes. In this approach, the system could be designed to work using only solar heat, only fossil heat, or a combination of both. A requirement for this flexibility is that the delivery temperatures of the fossil heat is the same as that of the solar heat. Compared to the redundant system approach, the parallel fossil heater approach has lower capital costs because of sharing a single heat engine and related equipment. The efficiency of the heat engine would be the same as for a similar fossil-only design, because the average delivery temperature of the heat has not been changed.

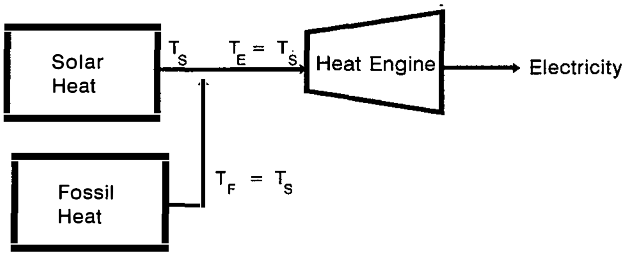


FIG. 2. PARALLEL FOSSIL HEATER HYBRIDIZATION, WHERE FOSSIL HEAT TEMPERATURE (T_F) = SOLAR HEAT TEMPERATURE (T_S). T_E IS THE TEMPERATURE REQUIRED BY HEAT ENGINE

A variation on the parallel hybridization approach is shown in Figure 3, where the parallel fossil energy and solar heat sources are at different temperatures and are mixed prior to entering the front end of the heat engine. The parallel solar- and natural-gas-fired boilers at the Luz SEGS VI and VII plants, which represent 60 MWe of installed capacity, are examples of this type of hybridization scheme. These plants can also be operated using only solar heat, only fossil heat, or a combination of both. However, the solar and fossil boilers generate steam at different temperatures. The steam generated from solar and fossil are mixed in a common steam header prior to its introduction into a Rankine cycle steam turbine. In this case, the overall conversion efficiency of the Rankine cycle changes as the relative mix and make-up of the solar- and natural-gas-generated steam change.

Solar can be used as an augmentation of the fossil fuel source, as seen in Figure 4. In this case, the solar heat is input through only a portion of the thermodynamic cycle. The Luz SEGS II–V plants, which represent 120 MWe of installed capacity, are examples of this type of hybridization. Although similar to the parallel boilers in the prior example, these plants generate steam at different temperatures and pressures. The fossil-generated steam is at the highest temperature and pressure and passes through the entire Rankine cycle steam turbine. The solar steam enters the steam turbine at an intermediate point after the highest-pressure turbine stages. A second example of a system that uses this approach is the Integrated Solar Combined-Cycle System (ISCCS) (Willrich et al., 1994). In the ISCCS, a combined-cycle power plant is powered by natural gas, and solar heat from a trough system is used to produce steam, which supplements the steam produced by the Brayton cycle heat-recovery steam generator. The steam then passes through the steam turbine part of the combined cycle. An advantage of this approach is that the temperature of the solar heat and the fossil heat no longer need to match. 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. Several alternative impacts on the heat engine efficiency are possible with this approach. If T_S is equal to T_F, then the overall heat engine efficiency is unchanged from a fossil-only case. If T_S is less than T_F, then the overall cycle efficiency will be reduced compared to a fossil-only design.

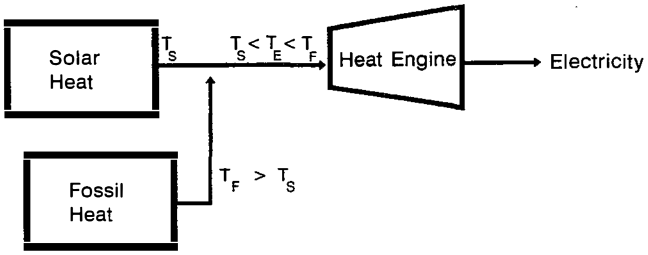


FIG. 3. PARALLEL FOSSIL HEATER HYBRIDIZATION, WHERE FOSSIL HEAT TEMPERATURE (T_F) > SOLAR HEAT TEMPERATURE (T_S)

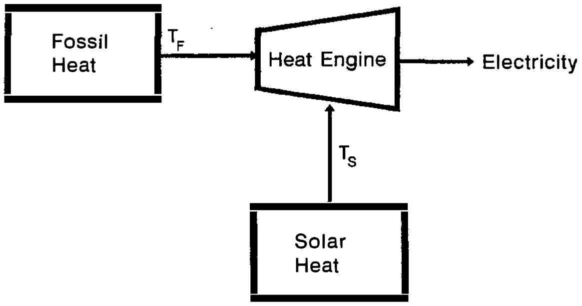


FIG. 4. SOLAR-AUGMENTED HYBRIDIZATION

The final basic hybridization approach is solar preheat in which fossil heat provides temperature topping, as shown in Figure 5. In the temperature topping approach, energy from fossil fuel combustion is used to raise the temperature to T_E prior to the heat engine. The Luz SEGS I plant used a combination of this approach and the parallel fossil heater approach for hybridization. A new concept for power towers using this approach with a combined cycle is discussed in a companion paper (Bohn et al., 1995). 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 combined cycle or aeroderivative turbines based on their attractive features, without having to suffer the research and development issues and efficiency drawbacks of producing solar heat at a very high temperature. A disadvantage of the approach is that the system cannot operate without fossil energy.

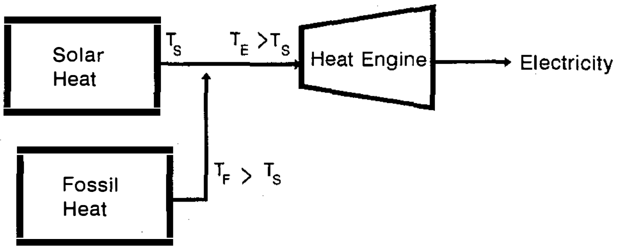


FIG. 5. SOLAR PREHEAT HYBRIDIZATION

From the perspective of the second law of thermodynamics, the best hybrid design approach will result from appropriate matching between the temperature of the solar heat and the temperature required by the heat engine. The lower the maximum available temperature of the solar heat, the fewer opportunities there are for hybridization. This is the reason that a molten-salt solar-only power tower plant must use a steam turbine. A less obvious meaning is that, all other things being equal, we should match the heat-source temperature as closely as possible with the heat-load temperature to minimize losses of thermodynamic availability. This would mean using solar heat in the lower-temperature heat exchangers and fossil heat at the higher-temperature heat exchangers.

For state-of-the-art and near-term solar thermal electric technologies, some general comments can be made regarding hybridization opportunities. At the present time, four options for heat engine cycles are either in use or under consideration for near-term applications of solar thermal power production: Stirling engines for parabolic dish applications, steam Rankine engines for parabolic trough or power tower applications, the Brayton gas turbine for dish and power tower applications, and combined cycles for trough and power towers.

In a Stirling engine, the working fluid operates in a closed cycle and is contained internal to the engine at all times. There is only one heat input point—at the engine heater head. The best option for dish/Stirling hybridization appears to be using a parallel fossil heater as shown in Figure 2. This is the approach being pursued in collaborations between the National Renewable Energy Laboratory, Cummins Power Generation (Hartenstine and Dussinger, 1994), and Stirling Technology Company (Noble et al., 1995). In this approach, both the fossil fuel heat and the solar heat are converted at the overall efficiency of the Stirling cycle (after accounting for thermal efficiencies of each heat input). Receivers for dish/Stirling applications have been optimized to interface the solar flux distribution from the dish to the engine working fluid. This is mainly a historical artifact—solarization of the engines took precedence and hybridization of the resulting receiver designs have only recently received attention. Fossil fuel input must be arranged around these specialized solar receivers to add the heat in parallel. Further optimization considering solar and fossil fuel heat sources simultaneously could result in more-refined and efficient hybrid receiver designs.

The Rankine cycle offers multiple heat input opportunities including feedwater heaters, preheaters, evaporators, superheaters, and reheaters. In the Rankine cycle, heat added at higher temperature is converted more efficiently, so superheaters and reheaters appear to be good candidates for efficient solar heat input. However, as discussed previously, this high-temperature heat could also be added by a fossil fuel, so the solar heat is converted at the overall cycle efficiency even if added at these locations in the cycle. Several concepts for hybridizing solar/Rankine plants have been proposed, including fossil-fired salt heaters in parallel with a salt receiver, solar heat supplied to superheaters or reheaters, and others. Unless these concepts can be shown to add solar heat where fossil heat addition is not possible, the conversion efficiency of the solar heat is equal to the overall cycle efficiency—currently about 40%.

Hybrid combined-cycle plants have recently seen emerging interest because of the potential for high conversion efficiency, competitive economics, and commercialization in new market sectors. Using combined cycles with solar-augmented hybridization is low risk and currently being considered by several organizations pursuing parabolic trough power plants. Combined cycles hybridized with a solar-preheat approach for power towers, as discussed earlier, are applicable to a smaller number of commercially available turbines, but offer substantial economic and commercialization benefits (Bohn et al., 1995).

BENEFITS AND ISSUES WITH HYBRID OPTIONS

The ultimate evaluation of hybrid solar power plants comes from the plant owner, who must decide whether the value of the service provided by the plant is worth what it will cost. From a technology standpoint, it is easy to gravitate toward considering factors such as conversion efficiency, solar fraction, optimal fossil/solar mix, and others. These factors are all important, but only to the extent that they affect the real decision criteria of end-users: value of service, economic attractiveness, technology risk, and external factors.

Value of Service

Owners of solar thermal power plants are investing money to gain an energy service. The value of the energy depends on the application and is driven largely by the predictability and flexibility of the energy delivery. In some applications (e.g., utilities that need firm capacity), large premiums in value are associated with being able to provide highly reliable power. Flexibility may be needed to dispatch the plant according to schedules that may be unpredictable or may change in the future.

Hybrid system designs can generally be used to enhance the value of the energy service by providing flexible operating times (beyond solar periods) and reliability (accounting for extended weather outages).

Not all hybridization options will be equivalent in impacting the value of service. The best hybridization schemes in this regard will be essentially "transparent" to the plant operator. When solar is available, fossil fuel consumption is reduced, and when solar is not available, the plant operates exactly as a fossil-only plant would. A hybrid scheme that allows the plant to operate steadily through solar transients is very desirable, especially if this can be accomplished with minimal control or emission problems for the fossil combustor.

Thermal storage can also be used to increase the value of service; the choice between hybridization and thermal storage will be driven by the relative economics for the application, which are not necessarily easy to assess. Although thermal storage may be relatively inexpensive, charging storage requires adding collection capacity which will substantially increase the plant cost. In addition, increasing reliability with storage becomes more costly as the probability of operating is increased. For example, in a given site, a solar-only plant might be designed to operate on 90% of the winter afternoon periods using 2 hours storage. If the plant were designed to operate on 95% of the same time periods, the storage would have to be increased to account for the infrequent periods with extended poor insolation. The added storage for the 95% reliability case would not be as cost effective as the 90% case because it would be used only a small portion of the year.

We believe that because of the high value associated with predictable and dispatchable power in most applications, the majority of commercial solar thermal electric plants will be designed with either energy storage or hybrid operations. In the near-term, hybridization would seem to have strong advantages for providing the highest degree of reliability and ability to provide significant operating time extensions. Storage will have the best opportunities in remote applications and in situations where only very modest operating time extensions are needed.

Economic Attractiveness

Designing a solar thermal plant as a hybrid can have a positive effect on the economics of the application in a number of ways. Without accounting for externalities and tax equalization, early solar thermal power plants are expected to have energy costs that are somewhat higher than fossil fuel. For these plants, introducing low-cost fossil fuels to supplement the solar cost will obviously lower the overall energy cost from the plant. An additional significant benefit from hybridization, though, is the ability to extend the operating hours of the plant to help amortize the fixed capital investment. If hybrid operations double the operating hours of the power plant, the impact of non-solar fixed costs (turbine, generator, buildings) in the energy cost is immediately cut in half. In essence, the solar plant would no longer need to amortize the cost of these items in the energy cost, but would only need to amortize half of the cost. Hybrid operations can also increase plant revenues by allowing higher capacity credits or providing energy during periods when it is very valuable.

Other economic benefits of hybridization are equally important but are far less obvious and design-specific. The energy conversion system of choice for many applications is rapidly becoming the combined cycle. Not only are the efficiencies of combined cycles very high, but the unit costs (in $/kW) are lower than steam turbines. Solar-only combined cycles are not attractive for commercialization today because the high temperature/pressure requirements into the gas turbine are beyond current capabilities of solar systems. However, if the system is designed as a solar-preheat hybrid, then a combined cycle can be selected as the energy conversion source and used with lower-temperature solar heat.

Our belief is that the most cost-effective hybrid options will all be designed by first selecting the most efficient and cost-effective energy conversion cycle, and then ensuring that the solar energy achieves the full conversion-cycle efficiency. This belief is based on recognizing that obtaining solar heat is costly, and the heat must be converted into electricity efficiently. Examining the options for hybridization, parallel fossil heaters could meet these criteria if the solar heat can be provided at the proper temperature. If temperature limitations exist for supplying heat from the solar field to the heat engine, then options using the solar-preheat approach would seem the most promising.

Economic attractiveness does not correlate with the fraction of the annual thermal energy requirements supplied by solar (solar fraction). In some cases, small solar fractions may provide cost-effective entry into applications that would not happen otherwise. In other cases, large solar fractions will be economically preferred. In any event, the solar fraction cannot be simply optimized by a LEC comparison between solar heat and fossil heat. Such a comparison ignores differences in the value of energy sources, risk, and other important drivers for installing solar plants such as environmental benefits and fuel diversity.

Technology

Our definition of technology risk is uncertainties in the operating characteristics of a new technology leading to possibilities of a lower return on investment than anticipated. Prominent factors that will affect the perceived technology risk are the uncertainty of the performance, life, and long-term operation and maintenance for the solar plant. The technology risk for a solar thermal power plant is similar to many new energy technologies; the important operating characteristics can be predicted much more confidently after several commercial plants have been built and operated over a period of time. This generally leads to a desire to minimize the capital investment in new technologies during the early commercial period. Minimizing risks also leads to lower return-on-investment requirements by owners and lenders.

Hybrid systems can help minimize financial risk by breaking the linkage in economies of scale between the heat engine and the solar field. The heat engine can be sized large enough to provide for good project economics, while the solar field can be sized independently based on requirements to demonstrate commercial viability and the desire to generate significant production levels of solar hardware. For example, the minimum commercially viable size for a solar-only molten-salt power tower is generally considered 100 MWe, with a capital cost of about $330 million for the first commercial plant. By designing the plant as a hybrid with a smaller solar field and more cost-effective heat engine, the amount of money at risk from new technology could be reduced substantially. This risk reduction can be accomplished while actually improving the economics of the plant, for reasons articulated in the previous section.

One important aspect of risk is the degree to which the plant can efficiently operate without solar input. The best hybridization scheme, from the standpoint of risk, is one in which complete loss of the solar plant will not affect the operation of the plant, either in terms of capacity, dispatchability, operating cost, or efficiency. If the plant is unaffected by the loss of the solar capabilities, this greatly reduces the plant owner's risk of using the new technology. If the plant operates at lower efficiency when solar is not available, the operational risk would be greater.

External Factors

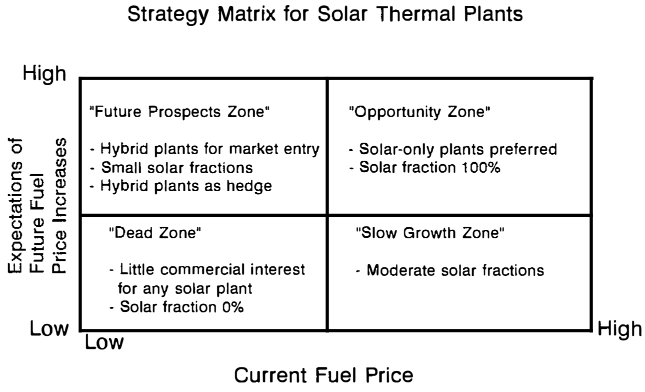
By external factors, we mean the constraints and issues that exist outside the plant boundary but which have a significant impact on the value of the hybrid system. Environmental emissions must be considered and may not be trivial for hybrid plants. Hybrid emissions can be minimized by using state-of-the-art combustors including those, for example, that incorporate recent advances such as low-NO_x designs. Although hybrid plants will have more emissions than a solar-only plant, they will reduce emissions relative to fossil plants. In the case of fossil plants that are already quite clean (e.g., natural gas plants with low-NO_x burners), the reduction in emissions to be gained by adding solar heat can be very significant. For well-designed plants, hybridization would more generally lead to lower emissions than for fossil-only plants, but higher emissions than for solar-only plants. In any event, the emissions impacts need to be carefully considered.

Regulatory treatment for any solar incentives will be very important for hybrid systems. Arbitrary cutoffs of incentives based on the fraction of solar energy used by the plant could discourage many promising applications. Regulatory treatment of hybrid plants is likely to be an area of continued debate if significant market interest in the technology emerges.

Hybrid Systems and Solar Power Commercialization

Do hybrid systems help in the commercialization of solar thermal power plants? Historically, the answer is a resounding yes, because the 354 MWe of trough capacity installed by Luz (Kearney, 1991) was all hybrid. The future is difficult to predict, but we believe the benefits articulated in this paper of well-designed hybrid systems can play a strong role in accelerating the market penetration of solar thermal technologies. The difficulty in predicting the future is in fact one of the reasons we believe that hybrid systems will continue to play a role in the commercial deployment of solar thermal technology.

The life-cycle cost of fossil plants is determined primarily by two external factors: the current cost of fuel and the estimated increase in fuel cost over the plant lifetime. If we focus only on the cost considerations that drive hybrid versus solar-only plants, a decision matrix for all possible combinations of both of these variables is shown in Figure 6. The decision matrix illustrates how these fossil fuel factors can affect attitudes toward hybrid plants and solar thermal commercialization. The strongest driving force for commercializing solar power plants exists if current fuel prices are high and expectations of future price increases are high. This is the area of the strategy matrix we have labeled the "Opportunity Zone." In this case, the strategy is fairly obvious: develop solar-only plants quickly. This scenario fits with the market realities of the 1970s, where many companies were aggressively pursuing the development of solar-only power plants.


Strategy Matrix for Solar Thermal Plants

	Low	High
High	"Future Prospects Zone" - Hybrid plants for market entry - Small solar fractions - Hybrid plants as hedge	"Opportunity Zone" - Solar-only plants preferred - Solar fraction 100%
Low	"Dead Zone" - Little commercial interest for any solar plant - Solar fraction 0%	"Slow Growth Zone" - Moderate solar fractions

FIG. 6. STRATEGY MATRIX FOR SOLAR THERMAL PLANTS

The other zone of the strategy matrix where decisions are fairly obvious we have labeled the "Dead Zone." In this case, fossil prices are low and expected to stay low for a long time. This may be the current market reality that many perceive today. In this case, there is little economic driving force for developing solar thermal power systems of any type.

Decisions are less obvious in the two other sectors of the strategy matrix. Low current costs that may increase in the future could create opportunities ("Future Prospects Zone"). In this case, there is an incentive for companies to get solar thermal technology to the marketplace to establish a future competitive position. We believe the logical strategy in this quadrant is to use hybrid plants as a market-entry mechanism. We would expect to see solar technologies demonstrated and improved while using hybridization to minimize risks and improve the overall economics of the system. We would also expect that the solar fractions for the hybrid systems would be small. The small solar fractions would minimize investment costs (important in a hedging strategy) while allowing reductions of technology risk by gaining operating experience. Even the small solar fraction plants would reduce uncertainty in solar cost estimates and would help to slowly decrease costs through manufacturing experience.

In the "Slow Growth Zone," fuel prices are high but are not expected to increase in the future. In this quadrant, we would expect decisions between solar-only and hybrid plants to be very application-specific. Hybrids may be used to increase reliability and energy value, although there could also be significant use of energy storage to accomplish this. Solar fractions for initial hybrid plants might be higher than the "Future Prospects" zone because more of the economic driving force comes from current prices (which are less uncertain) rather than future increases.

It is beyond the scope of this paper to make definitive statements on which zone of the strategy matrix the United States is currently in. Some general observations can be made, however. It seems clear that the low fossil prices we see today would rule out being in the "Opportunity Zone" or the "Slow Growth Zone." The current level of commercial interest in solar argues that at least some portion of the industry and end users of the technology believe that we are in the "Future Prospects" zone, or at least have some other reasons for their involvement. We believe that hybrid systems will represent an attractive strategy for many of the groups in this zone.

As a final comment regarding commercialization, it is not obvious how much solar-only plants and hybrid plants will directly compete against each other in the marketplace. Some of the potential benefits of hybrid plants (risk reduction, lower capital costs, and lower energy costs) will appeal to users considering solar-only plants. In these cases, the concepts will compete against each other. In other cases, a hybrid plant may represent an alternative to a fossil source in a situation where the user would not consider a solar plant. In this situation, the concepts do not compete, but the hybrid acts to expand the market for solar thermal technology.

CONCLUSIONS AND RECOMMENDATIONS

We believe that well-designed hybrid plants can have significant advantages over solar-only plants, particularly for near-term markets. These advantages include the opportunity for higher energy-conversion efficiency, lower capital investment in new technology, higher-valued energy due to dispatchability, and lower energy costs.

One recommendation is that as an industry (including developers, users, national laboratories, and stakeholders) we should evaluate how hybrids could facilitate commercialization of solar thermal technologies. Many of our current commercialization strategies evolved during a time when most people believed we were in the "Opportunity Zone" of the strategy matrix in Figure 6. These strategies are unlikely to be effective today. Instead, we should be developing new strategies that are responsive to today's markets and use low fossil prices rather than waiting for the low prices to disappear. We believe that a focus on hybrid systems will lead to solar thermal systems with higher value, lower energy costs, and less commercialization risk.

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