Gas Turbine/Solar Parabolic Trough Hybrid Design Using Molten Salt Heat Transfer Fluid

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Craig S. Turchi and Zhiwen Ma

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GAS TURBINE/SOLAR PARABOLIC TROUGH HYBRID DESIGN USING MOLTEN SALT HEAT TRANSFER FLUID

Craig S. Turchi[1], Zhiwen Ma[2]

[1] Senior Engineer, National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, Colorado, USA, +1-303-384-7565, craig.turchi@nrel.gov

[2] Senior Engineer, National Renewable Energy Laboratory, 1617 Cole Blvd, Golden, Colorado, USA

Abstract

Parabolic trough power plants can provide reliable power by incorporating either thermal energy storage (TES) or backup heat from fossil fuels. These benefits have not been fully utilized in the United States because TES slightly increases the cost of power from trough plants and gas usage in a trough plant is less efficient than in dedicated gas combined-cycle plants. For example, while a modern combined-cycle plant can achieve an overall efficiency in excess of 55%, auxiliary heaters in a parabolic trough plant convert gas to electricity at less than 40%. Integrated solar combined-cycle (ISCC) systems avoid this pitfall by injecting solar steam into the fossil power cycle; however, these designs are limited to less than about 10% total solar enhancement. This paper describes a gas turbine / parabolic trough hybrid design that combines a solar contribution greater than 50% with gas heat rates that rival those of natural gas combined-cycle plants. Previous work illustrated benefits of integrating gas turbines with conventional oil heat-transfer-fluid (HTF) troughs running at 390°C. This work extends that analysis to examine the integration of gas turbines with salt-HTF troughs running at 450°C and including TES. Using gas turbine waste heat to supplement the TES system provides greater operating flexibility while enhancing the efficiency of gas utilization. The analysis indicates that the hybrid plant design produces solar-derived electricity and gas-derived electricity at lower cost than either system operating alone.

Keywords: parabolic trough, aeroderivative turbine, hybrid, molten salt

1. Introduction & Background

Parabolic trough, linear Fresnel, and power tower systems can readily integrate thermal energy storage (TES) by storing hot heat transfer fluids (HTF) or by using the HTF to heat a storage media. These technologies can also utilize natural gas to aid system startup and provide backup power. Both features serve to convert the intermittent solar energy into a reliable, dispatchable resource. As shown in Table 1, TES and fossil backup provide the same benefits with differing cost drivers.

Attribute	TES	Fossil Backup (hybridization)
Generation during clouds and after sunset	Yes	Yes
Ability to provide ancillary services to grid	Yes	Yes
Renewable energy source	Yes	Solar fraction only
Technical risk	Moderate	Low
Capital cost	High	Low
Operating cost	Low	Function of gas price

Table 1. Thermal energy storage and fossil backup both serve to increase reliability and dispatchability from the CSP power plant.

Although TES and fossil backup provide similar benefits, there are important distinctions between the two approaches. TES systems maintain a full solar fuel source but require the installation of substantial hardware, especially for parabolic troughs and linear Fresnel systems. (Molten salt power towers use storage more efficiently because of their higher temperatures and the ability to increase storage by simply increasing tank size and salt inventory.) The cost of tanks and storage media is not trivial, but the greatest increase to capital cost is the increase in solar field size required to provide the energy used to charge storage. In short, adding TES will substantially increase the installed cost of the solar plant. The levelized cost of electricity (LCOE) may increase or decrease with the inclusion of storage, depending on technology and cost factors. At present, storage systems increase the LCOE for trough power plants [12]. In addition, although conceptually simple, the TES technology is relatively new and entails an added risk for the project.

In contrast, backup via fossil burners has a relatively low investment cost and is a mature, low-risk technology. While it does not provide renewable power, the solar fraction of the total plant can still be quite high. The greatest downside to the use of natural gas in this fashion is the argument that it would be better burned in a dedicated combined-cycle power plant. A modern natural gas combined-cycle (NGCC) plant can achieve thermal cycle efficiencies greater than 55% (heat rate less than 6200 BTU/kWh), whereas a parabolic trough plant has a thermal cycle efficiency of less than 40%. The use of small amounts of gas backup may be justified by the investment in the solar plant infrastructure, but the economics of burning natural gas in auxiliary boilers falls rapidly as gas consumption increases.

This paper continues the analysis of gas turbine / parabolic trough hybrid designs that overcome the limitations listed above. A previous analysis examined the integration with an oil-HTF parabolic trough running at 390°C [13]. That study illustrated how a hybrid gas turbine / parabolic trough design provided a lower installed cost and lower LCOE while utilizing proven commercial technologies. The plant did not include TES. The focus of the present work is the integration of a gas turbine with a parabolic trough plant using direct TES. It is assumed that the trough plant uses a molten salt HTF that is stored directly in a two-tank system. For analysis purposes the salt is assumed to be Hitec XL, a ternary blend of approximately 7% $NaNO_3$, 45% KNO_3, and 48% $Ca(NO_3)_2$ with a melting point near 120°C.

1.1 Overview of Prior Integrated Solar/Fossil Designs

Various types of integrated solar/fossil plants designs have been described and ISCC systems have been built: for example, the Martin Next Generation Solar Energy Center in Florida. In the 1990s, Luz, the builders of the SEGS trough plants in California, proposed hybrid plant designs where solar steam would be used to supplement a combined-cycle power plant. Under contract to NREL, Kelly et al. [2,3] examined the potential of such designs through a detailed analysis of power cycle performance using GateCycle. The studies focused on sizing equipment for extracting water from feedwater heaters to produce solar steam that was fed to the superheater along with the fossil-produced steam. Overall conclusions held that such a hybrid plant offered three advantages:

- Solar energy was converted to electric energy with an efficiency of about 39%; in contrast, the efficiency of the Rankine-cycle plants was estimated at about 37%;
- The incremental unit cost for the larger steam turbine in the integrated plant was less than the overall unit cost in a solar-only plant; and
- A hybrid plant did not suffer the thermal inefficiencies associated with the daily startup and shutdown of the steam turbine.

Nonetheless, the integrated concept did suffer from two distinct disadvantages. First, in the absence of the solar contribution the steam turbine operated at partial loads during cloudy weather and at night. Operation at partial loads caused an increase in the fossil fuel heat rate, which effectively subtracted from the annual thermal contribution of the solar field. Second, the annual solar contribution for plants was in the range of only 2–8% because higher contributions led to lower overall efficiency.

Recent work by the Electric Power Research Institute (EPRI) examined the optimum means for augmenting coal and NGCC plants with solar thermal energy [4]. While the EPRI study also examined feedwater extraction for solar steam production, the study highlighted the advantages of integrating solar steam into NGCC plants that are designed with gas-fired duct heaters between the gas turbine and heat recovery steam generator. Plants with duct firing are designed with slightly oversized steam systems. During high demand periods, natural gas is fired directly in the steam generator train to boost the energy flow to the steam turbine and increase power output.

The use of natural gas for duct firing is inherently less efficient than gas used in the upstream gas turbine. In addition, most duct-firing occurs during hot afternoons that correspond to peak demand in the U.S. and lower gas turbine performance. Thus, replacing gas-fired duct heating with solar thermal energy is a natural match.

EPRI's analysis examined a host of different extraction and injection strategies for solar augmentation. The best cases led to improved solar use efficiency (versus a solar-only plant) and improvements in gas heat rate. In general, solar use efficiency drops and heat rate improves as the amount of injected solar thermal energy increases, and the optimum combination for maximum solar contribution and efficiency occurred in the range of about 10% solar contribution. This is consistent with the design proposed for most ISCC projects.

Bohn and Williams [5,6] evaluated a molten salt power tower hybrid design that provides preheated combustion air to a conventional NGCC power plant. Three plants of varying capacities (30, 100, and 300 MWe) were examined and compared with a solar-only 100 MWe plant and with a NGCC plant of similar capacity. The work studied hybrid plant solar fraction, capacity factor, material cost, and fuel cost effects on economic competitiveness. The study concluded that the hybrid design was more cost effective than any of the solar-only configurations. Because of the higher temperatures required, this concept applies to power towers only.

The Solar Hybrid Gas Turbine Electric Power System (SOLGATE) uses a high-temperature power tower for direct air heating to drive a gas turbine [7]. SOLGATE uses solar energy to raise air temperature close to gas combustion temperature in a gas turbine combustor and then uses a booster burner to bring the gas temperature to the desired level for maximum efficiency. SOLGATE achieved 47.5% efficiency in a combined-cycle configuration, or 37.3% in simple cycle with turbine exhaust heat recuperation. The solar contributions in both cases are high too, with 56.8% in combined cycle and 35.04% in simple cycle. The concept is only applicable to power tower systems and has significant material challenges to handle the high solar fluxes; however, the combination of efficiency and solar contribution is promising. In general, the higher temperatures possible with power tower configurations grant them a greater potential for efficient hybridization.

1.2 Integrating Aeroderivative Turbines with Parabolic Troughs

The relevant characteristics of aeroderivative turbines have been described elsewhere [8,13]. Briefly, aeroderivative turbines feature rapid startup and load-following capabilities. The units have a modest capital cost and run at high efficiency. Their exhaust gas temperatures range from about 420°C to 520°C, which is an essential feature for integration with parabolic troughs. Representative GE aeroderivative turbine properties are given in Table 2; other turbine suppliers include Rolls Royce and Pratt & Whitney. The concept described here is equally applicable the linear Fresnel systems, but this discussion will focus on the trough design.

Model	Rated Power (MW)	Heat Rate (BTU/kWh) LHV	Exhaust Temp (°C)	Efficiency
LMS100DLE	100	7600	415	44.5%
LM6000PC	42.6	8323	451	41.1%
LM2500PK	30.7	8815	515	38.7%

Table 2. Selected GE Aeroderivative Gas Turbine Specifications [9,10].

The flexibility of the aeroderivative turbine allows for multiple hybrid configurations with parabolic troughs. A prior analysis [13] examined the integration of gas turbines with oil-HTF parabolic troughs having no storage as shown in Figure 1. That analysis showed that a hybrid gas turbine / trough design had the following advantages versus a solar-only plant: lower installed cost, lower solar LCOE, greater annual generation, higher solar efficiency, and lower heat rate (versus combustion turbine only). While each of these benefits was relatively modest, combined they indicated a clear advantage for the hybrid design. In addition to these quantitative advantages, the hybrid system utilizes commercially proven technologies and provides greater dispatch reliability. We follow that prior analysis by examining the advantages of using gas turbine integration on a trough plant that incorporates direct TES.

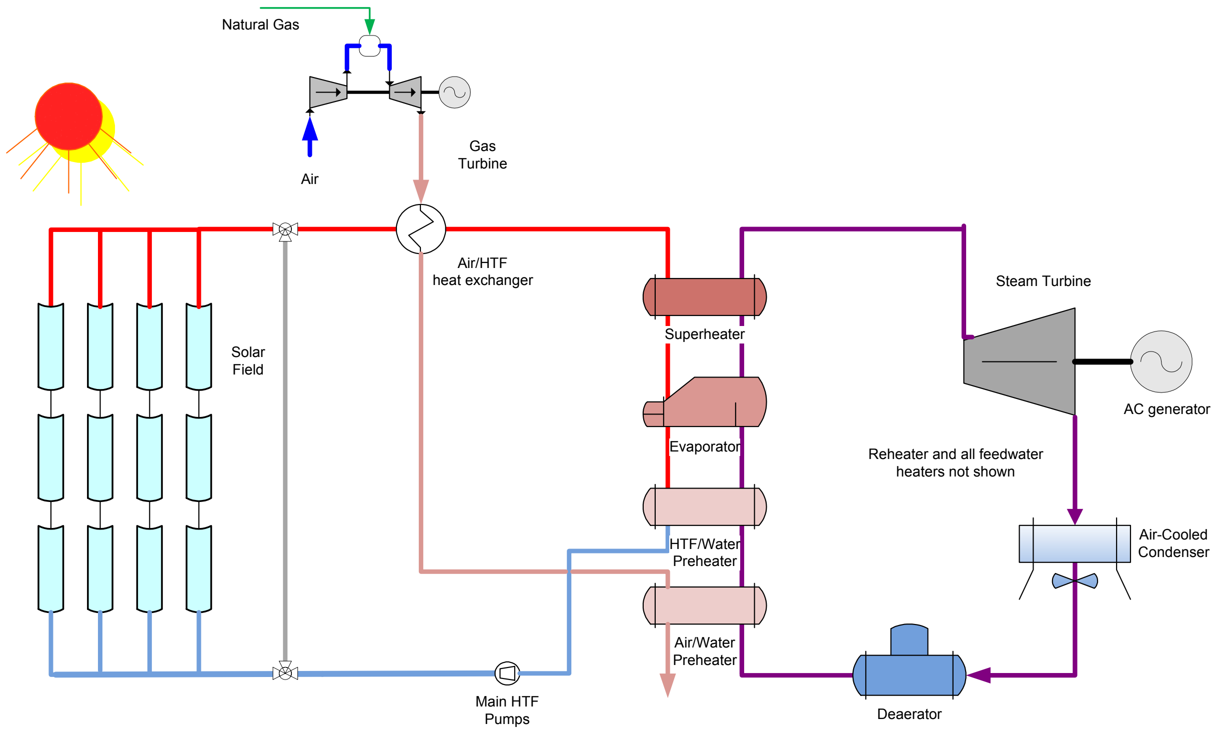

Figure 1. Simplified schematic of gas turbine / trough hybrid with turbine exhaust used to heat the solar HTF. Adapted from [13].

2. Results

2.1 Hybrid Plant Design with TES

Whereas the prior work used the gas turbine exhaust to heat the HTF and feedwater (see Figure 1), in the current paper we examine a case were the gas turbine exhaust heat is used in a dedicated flow path to supplement the TES system as shown in Figure 2. As previously, the thermal energy balance for the integration of aeroderivative turbines into a trough plant was undertaken using IPSEpro simulation software. The analysis assumed a single GE LM6000 turbine combined with a 100-MW or 50-MW parabolic trough plant. The integration included the following assumptions:

- A parabolic trough plant using Hitec XL as HTF running at 450°C. The HTF is stored directly in a two-tank TES system. Such a design is similar to that selected as a possible next-generation trough technology in reference [12].
- A gas/salt heat exchanger sized to produce 440°C salt for the hot storage tank. This represents an approximately 10°C approach temperature for the turbine exhaust gases.
- Back pressure on the gas turbine is increased by 4 inches of water (10 mbar) to account for the downstream heat exchangers.
- Gas turbine electric output is derated based on ambient temperature for the site using the same weather file that supplied the hourly solar input. IPSEpro was used to determine the gas turbine performance curve as a function of temperature.
- When dispatched, the gas turbine runs at full load, except when the TES system nears full capacity. In order to avoid dumping turbine exhaust heat, the gas turbine will not run when storage capacity exceeds 90% of full. The 90% constraint was imposed to prevent the gas turbine from cycling on and off when solar input to storage is cycling.
- The total installed cost for the solar hardware was based on values provided in [12] for the 2015 salt-trough scenario. These costs include combined solar field, site preparation and HTF System at \$315/m^2, TES at

$50/kWh-t, and dry-cooled power block at $1140/kWe. A 10% contingency and 24.7% indirect cost multiplier were applied to the direct costs. For the fossil system, the gas turbine, heat exchanger, and associated direct costs were assumed to be $900/kWe (based on gas turbine net output) and the same contingency and indirect cost multipliers were used to arrive at an installed cost. The total direct costs for the gas turbine system ($900/kWe) were slightly higher than reported values for conventional combustion turbines ($812/kWe [14]) to account for the added air/salt heat exchanger.

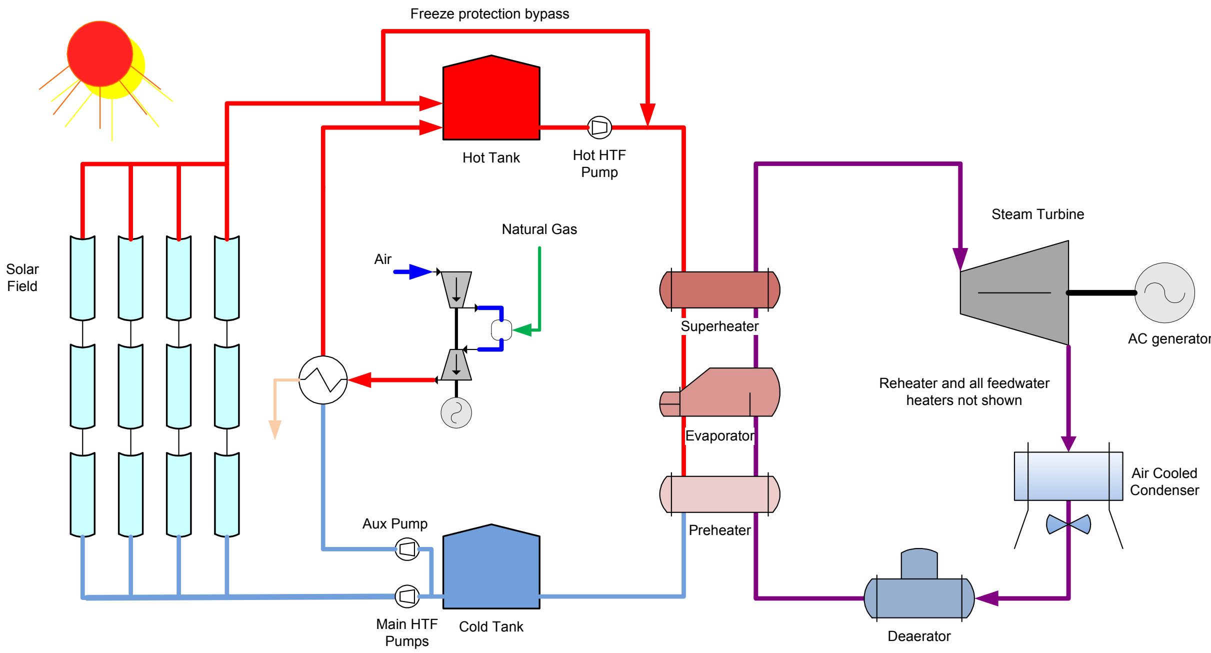

Figure 2. Simplified schematic of gas turbine / trough hybrid with turbine exhaust used to supplement TES.

2.2 Hybrid Plant Simulation

The simulations were undertaken using a modified version of NREL's System Advisor Model (SAM), available at https://www.nrel.gov/analysis/sam/. The Physical Trough code in SAM 2011-06-30 was modified to provide the fossil backup configuration shown in Figure 2. In the modified version of SAM, the existing fossil dispatch control structure was used to dispatch gas turbine exhaust energy to charge storage, provided storage capacity was available. This operation depended only on the availability of storage capacity and was independent of the solar plant's operation. Thus, the gas turbine could be run at any time of day and its waste heat captured for later use in the steam cycle.

SAM simulated the solar plant operation and tracked TES charging from both solar and gas sources on an hourly basis. The weatherfile used for these simulations was Daggett, CA. Discharged thermal energy was used in the steam power cycle per SAM's normal solar plant control. However, SAM did not track electricity produced by the gas turbine. Hourly SAM data were exported to a spreadsheet where gas turbine generation was estimated and integrated into the total plant output. Because SAM did not track all power generation, the LCOE calculation was performed external to SAM.

The simple LCOE analysis included an 8% real discount rate and a 20-year analysis period giving a uniform capital cost recovery factor (UCRF) of 0.1018. Total 20-year life cycle costs were multiplied by the UCRF and divided by annual energy production to yield total LCOE [11]. Solar hardware O&M cost was calculated using a value of $60/kW-yr. Natural gas price was set at $5/MMBTU and, like other O&M costs, was escalated with inflation. (Note: gas price is quoted based on higher heating value, whereas turbine efficiency is commonly reported in lower heating value. Within the simulation, gas price was increased by 10% to account for this difference.) The solar LCOE for the hybrid plant was calculated by solving:

$$(LCOE)_{total} = x_{gas} * (LCOE)_{gas} + x_{solar} * (LCOE)_{solar}$$

where x_{gas} and x_{solar} are the fractional contributions to total generation. Neither investment tax credits nor accelerated depreciation was included in the simple LCOE calculations. This was reasonable for this study because the objective was to determine the relative advantage of the hybrid plant versus the stand-alone designs.

2.3 Simulation Results

The baseline design for the analysis was the 2015 salt-HTF parabolic trough plant from reference [12]. This design assumed a trough plant running at 450°C using a molten salt HTF. The 450°C temperature was selected as a compromise temperature that minimized stability and corrosion concerns for the salt HTF and minimized heat loss concerns from the receivers, yet provided a substantial boost to power cycle and storage efficiency. The baseline plant had a solar multiple of 2.0 and 6 hours of full-load TES. The specifications and performance of this baseline design are outlined in Table 3.

The primary objective of the hybrid designs was to demonstrate that the hybrid plant could have a lower installed cost and lower solar LCOE compared to the solar-only baseline (S2), while producing a comparable energy output. Secondary metrics included maintaining a solar fraction greater than 50%, increasing annual solar efficiency, and producing a more uniform plant output, i.e., reducing ramp rates. Two basic sizing options were explored. Hybrid plant H1 used the same 100 MWe steam power block from the baseline plant. Hybrid plant H2 used a smaller 50 MWe steam power block and dispatched the gas turbine to produce a relatively uniform, baseload output.

Case	S2	AGT-1	H1	H2
	Solar Only	AGT Only	Hybrid	Hybrid
Solar Multiple	2.0	-	1.5	1.5
Thermal Storage (hrs)	6.0	-	3.0	4.0
Steam Turbine Capacity (MW, net)	100	-	100	50
AGT Capacity (MW)	-	39.0	37.8	37.8
Steam Turbine ops (hr/yr)	4,142	-	3,672	3771
AGT ops (hr/yr)	-	3,939	3,939	4498
Steam Turbine Annual Gen. (MWh)	378,700	-	315,500	172,700
AGT Annual Gen. (MWh)	-	140,500	136,300	164,900
Total Annual Gen. (MWh)	378,700	140,500	374,800	337,600
Solar Fraction	1.00	0	0.64	0.42
Annual Solar Efficiency (MWhe/MWh)	16.0%	-	16.2%	16.0%
Total Installed Cost ($M)	660	49	558	312
Effective Heat Rate (BTU/kWh)	-	8,250	7,060	7,150
Gas Consumption (MMBTU/yr)	-	1,158,500	1,129,000	1,401,000
Total LCOE ($/MWh)	208	91	165	135
Gas LCOE ($/MWh)	-	91	92	86
Solar LCOE ($/MWh)*	208		206	203

* levelized cost of electricity, no incentives included

Table 3. Solar-only, gas turbine, and hybrid configurations.

Gas turbine dispatch was selected with an effort to minimize solar LCOE while retaining the desire to keep total generation similar to the baseline S2 plant. While multiple dispatch maps were tested, a systematic optimization was not undertaken. A multitude of possible configurations and dispatch options were possible with the proposed design, and in future, the ability to incorporate the full power generation (from steam and gas turbines) within SAM will allow use of SAM's statistical routines to optimize sizing and dispatch options.

The gas turbine dispatch profile for hybrid plants H1 and H2 are conceptually mirror images of each other (see Figure 3). The H1 dispatch is consistent with a desire to maximize generation during daylight hours corresponding to the typical load peaks in the United States, while the H2 map seeks to operate the gas turbine when the solar plant is not producing power, thereby producing a uniform output over the entire day. The calculated capacity factor for H2 was 77% based on a 50 MWe nameplate rating. However, for most applications in the United States, a summer-peaking dispatch similar to the H1 map is more probable.

Hour ending

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Feb	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Mar	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Apr	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
May	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Jun	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Jul	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Aug	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
Sep	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Oct	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Nov	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Dec	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1

Hour Ending

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Feb	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Mar	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Apr	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
May	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Jun	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Jul	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Aug	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Sep	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Oct	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Nov	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Dec	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0

Figure 3. Dispatch control map used for the gas turbine. Bottom map is for hybrid plant H1, top map for H2. 1 = running; 0 = off.

A comparison of heat rates indicated the benefit of integrating the gas turbines with the steam cycle. The heat rate for the LM6000 was about 8250 BTU/kWh, based on values reported by GE [1]. Integration with the trough plant created a clear benefit to heat rate from the capture of the waste heat and subsequent use in the steam cycle. As shown in Table 3, heat rate dropped from 8250 BTU/kWh for gas turbine operating alone to 7060–7150 BTU/kWh for the hybrid plants; that is, the effective gas-use efficiency increased from 41% for the gas turbine operating alone to 48% in the hybrid plant. Further improvements are possible if the gas leaving the air/salt heat exchanger is utilized in the steam-cycle feed water heaters, but this requires simultaneous operation of both power cycles. Such a configuration was presented in [13].

A comparison of the hybrid H1 design and the solar-only S2 design reveals the following advantages of the hybrid system:

- 15% lower installed cost due to replacing part of the solar field with the gas turbine
- 15% lower heat rate (versus combustion turbine only) due to capture of gas turbine exhaust heat
- Solar LCOE and efficiency are marginally better in the hybrid design, primarily due to reduced solar dumping.

While each of these benefits is relatively modest, combined they indicate a clear advantage for the hybrid design. In addition to these quantitative advantages, the hybrid system provides greater operating flexibility by being able to access the gas turbine to maximize generation on peak and capacity value. The hybrid solar fraction of 64% far exceeds any ISCC design.

3. Conclusions

Solar/fossil hybrid designs reduce the impact of solar intermittency by either providing fossil backup to the solar plant or integrating solar output into a much larger fossil power installation. Hybrid designs utilize shared infrastructure that reduces the capital cost compared to separate stand-alone plants. However, previous solar/fossil hybrid designs have been hampered by poor gas utilization efficiency and/or limited solar contribution. Incorporation of aeroderivative gas turbines overcomes these limitations and expands the hybrid design options available to developers.

In the preliminary analysis provided here, it is shown that a single 40-MW aeroderivative gas turbine mated with a 100-MW parabolic trough plant can be more efficient than two separate power plants. The solar plant design assumed direct storage of a salt HTF and integrated the exhaust heat from the gas turbine to provide supplemental energy to the TES system. By incorporating a gas turbine, the size of the solar field and TES system was decreased, leading to capital cost savings of over $100M despite the inclusion of the gas turbine system. Total power generation was approximately equivalent, with 64% of the total coming from the solar power source. Numerous integration and dispatch options are possible with the proposed gas turbine / trough hybrids, and this initial analysis looked at only one configuration. Further examination is expected to yield alternatives that provide greater operating or efficiency benefits than those described here.

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