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Results and Comparison from the SAM Linear Fresnel Technology Performance Model

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WREF 2012: RESULTS AND COMPARISON FROM THE SAM LINEAR FRESNEL TECHNOLOGY PERFORMANCE MODEL

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ABSTRACT

This paper presents the new Linear Fresnel technology performance model in NREL's System Advisor Model. The model predicts the financial and technical performance of direct-steam-generation Linear Fresnel power plants, and can be used to analyze a range of system configurations. This paper presents a brief discussion of the model formulation and motivation, and provides extensive discussion of the model performance and financial results. The Linear Fresnel technology is also compared to other concentrating solar power technologies in both qualitative and quantitative measures.

The Linear Fresnel model - developed in conjunction with the Electric Power Research Institute - provides users with the ability to model a variety of solar field layouts, fossil backup configurations, thermal receiver designs, and steam generation conditions. This flexibility aims to encompass current market solutions for the DSG Linear Fresnel technology, which is seeing increasing exposure in fossil plant augmentation and stand-alone power generation applications.

Keywords: System Advisor Model; SAM; Linear Fresnel; CLFR; Annual Simulation; CSP; NREL; EPRI; Direct Steam Generation

1 INTRODUCTION

The Linear Fresnel Reflector (LFR) technology is of growing interest to US utilities as a candidate for combined-cycle integration through direct steam generation (DSG) [1]. The LFR concept uses a set of long mirror facets that reflect light to a linear receiver where it can be directly absorbed by the receiver [2] or concentrated a second time with a compound parabolic reflector [3]. The optical performance of the LFR system is limited by the angle at which the sunlight strikes the reflectors, and because the mirrors must be oriented to reflect the irradiation to the receiver, they most often do not directly face the sun. This non-normal orientation towards the incoming sunlight is the primary optical loss for LFR, and the loss is incurred both with respect to the transversal plane (perpendicular to the axis of the collector) and longitudinal plane (parallel with the axis of the collector). This concept is illustrated in Figure 1.

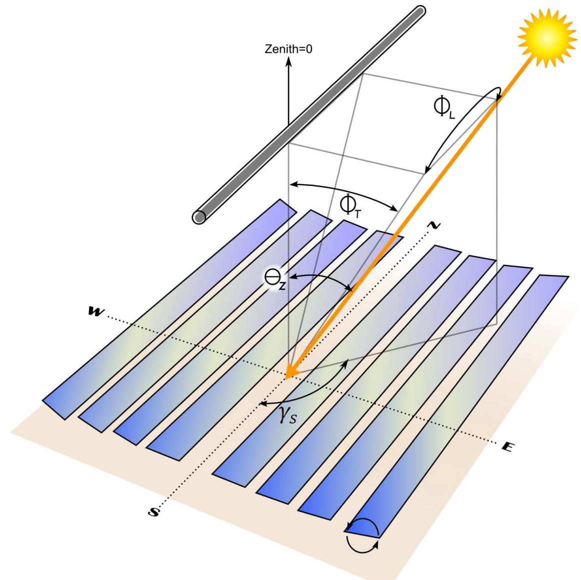

Fig. 1: Angles associated with the optical performance of the LFR technology, including transversal incidence ϕ_T, longitudinal incidence ϕ_L, solar zenith θ_z, and solar azimuth γ_s.

Optical performance for the LFR system varies significantly throughout the year, with peak performance in the summer months. Figure 2 shows the variation in total optical efficiency for a sample LFR field over the course of the year.

This annual productivity variation has several important implications in terms of plant integration, and it is consequently important to have performance modeling capability for the technology. Several models have been developed previously for various applications [4] [5] [6] [7] [8] [2], but no detailed annual-hourly performance model has yet been made public. Recently,

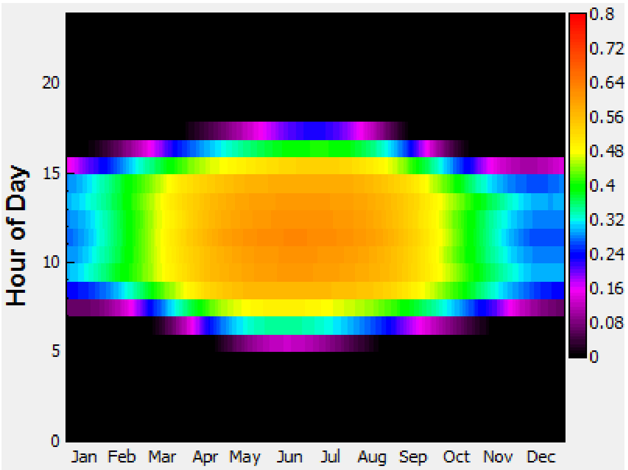

Fig. 2: LFR optical efficiency as a function of the time of day (vertical axis) and day of the year (horizontal axis) for a sample geometry. Peak optical efficiency at solar noon varies from 30% in the winter months to above 60% in the summer.

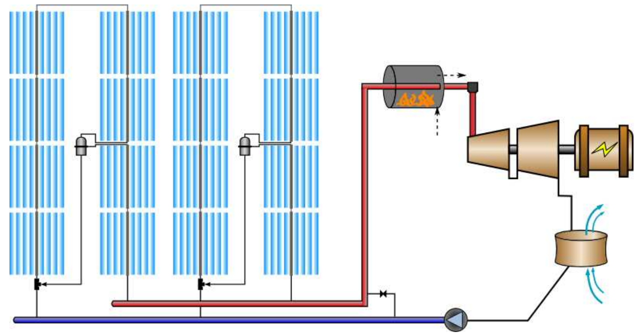

Fig. 3: A simplified example LFR plant layout with two loops in parallel and an auxiliary fossil heater in series after the field outlet.

a new hourly-annual techno-economic model was implemented to address this gap in System Advisor Model (SAM) developed by the National Renewable Energy Laboratory, Sandia National Laboratory, and supported by the US Department of Energy. This model is presented in detail in [9] where a more thorough review of previous work is also discussed.

The current document provides a review of the main features and capabilities of the LFR model in System Advisor and provides the results of a study comparing the performance of the LFR technology with other CSP systems.

2 MODEL DESCRIPTION

This section discusses the main features of the System Advisor LFR model in light of the variety of technology options that are currently available. The current technology solutions available in the market use water/steam as the heat transfer fluid, as represented by [3] and others, and are thus referred to as "Direct Steam Generation" (DSG) systems. The solar field is arranged into a number of parallel loops, where each loop is composed of a series of collector modules, as shown in Figure 3.

Once steam is generated, it can be used to drive a stand-alone power cycle, to displace fuel usage by integration with an existing fossil fuel plant [10], or to provide industrial process heat. Because of the modular nature of the technology, a relatively wide range of steam outlet conditions are achievable, with the current upper limit of superheated steam at 500°C [3]. The System Advisor LFR model is capable of modeling direct-steam systems with various geometry arrangements and outlet temperature requirements.

2.1 Loop Configurations

Two loop configurations are considered in System Advisor. The first option uses a recirculated boiler, as shown in Figure 4. The recirculated boiler is similar in concept to traditional pulverized coal boilers. Water enters the boiler section as a high-pressure subcooled liquid and absorbs energy as it converts from liquid to steam. The partially evaporated mixture exits the boiler section and passes through a separator device that removes the liquid phase from the mixture. The liquid is recirculated back to the inlet of the boiler and the saturated vapor is sent to the superheater section for additional heating.

The recirculated arrangement has several advantages, including the ability to maintain stable heat transfer between the hot pipe wall and the liquid/steam mixture. Good heat transfer prevents overheating of the tube walls, which can reduce the lifetime of the tubing and lead to material failure. However, recirculation increases the flow requirement in the boiler section, requiring additional pumping power and increased annual parasitics. The steam temperature at the outlet of the superheater is also constrained since the mass flow rate through the superheater is determined by the boiling rate and cannot be controlled with pumping. This

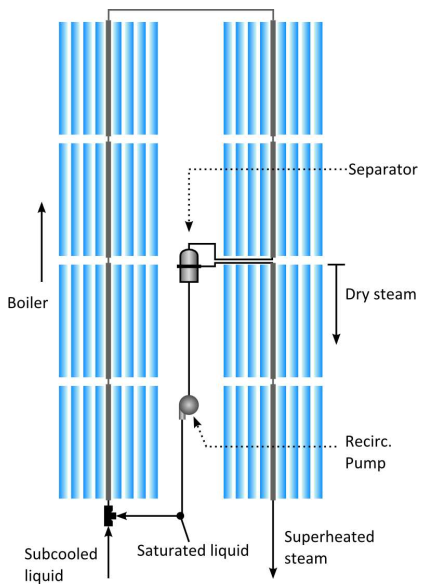

Fig. 4: The recirculated boiler arrangement. In a recirculation system, partially boiled steam passes through a separator where the liquid portion is returned to the loop inlet and the vapor portion is sent to the superheater section.

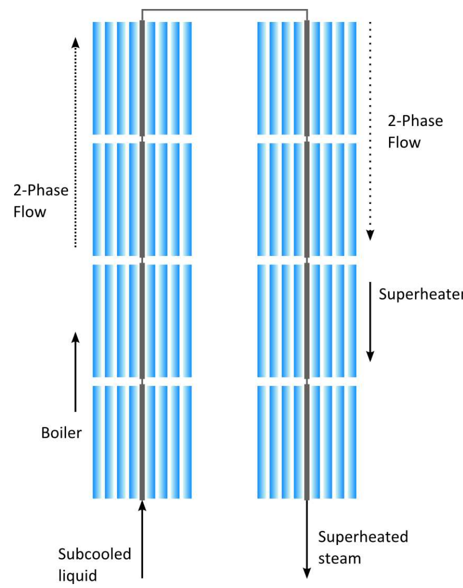

Fig. 5: The once-through boiler arrangement. Liquid water enters the loop and is heated through to superheated steam in a single pass without recirculation.

introduces additional complexity in maintaining suitable steam temperatures that accommodate both solar field and high-pressure turbine material limitations. Previous work in [9] presents modeled behavior of a recirculated system in more detail.

The second loop configuration is the once-through system as shown in Figure 5, where liquid water is heated up to superheated steam in a single pass without recirculation. This option has been proposed for both LFR and Parabolic Trough technologies [11] [12], but has not yet been demonstrated because of control complexity. Nonetheless, System Advisor includes this option for purposes of comparison and analysis of future technology options. Potential advantages of the once-through design are reduced pumping parasitics, reduced equipment and piping cost (from removing the separator and return piping), and improved steam outlet temperature control. However, boiling stability remains a concern and must be addressed before commercial implementation.

One model limitation given the mixed applications available in the LFR market is System Advisor's inability to model low-temperature saturated steam systems. In industrial heat and fossil plant integration applications, steam leaves the solar field in a saturated rather than superheated state. The CSP technology suite in System Advisor assumes stand-alone power generation, and some of the models (including LFR) share common algorithms for power cycle performance calculations. The power cycle formulation uses the most common steam conditions - namely, superheated subcritical steam. Saturated steam can therefore not be modeled directly.

2.2 The Optical Model

Optical modeling of an LFR system can be complex, requiring detailed information on the reflector geometry, error distributions, and receiver dimensions. The most practical method for analyzing optical performance of a given geometry is with computational methods such as ray tracing. In balancing complexity of user-supplied input with ease of use, System Advisor does not include detailed specifications for collector and receiver geometry, so the model defines optical performance using a table of efficiency values that are defined by the user. This input can be generated externally in a ray tracing package such as SolTrace [13] for a variety of solar positions.

While optical performance can be specified in terms of solar position, it is more common with the LFR and technology to express it in terms of the transversal and

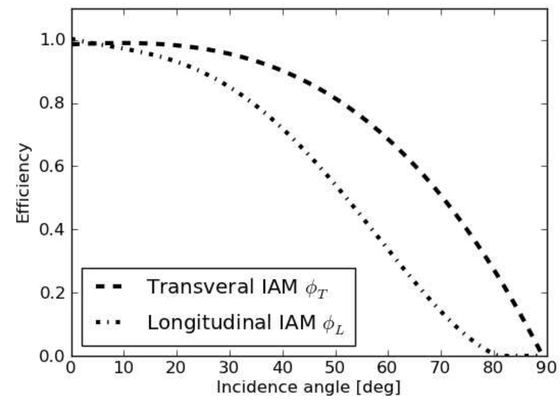

Fig. 6: Incidence angle modifier curves for both the longitudinal (ϕ_L) and transversal (ϕ_T) plane effects.

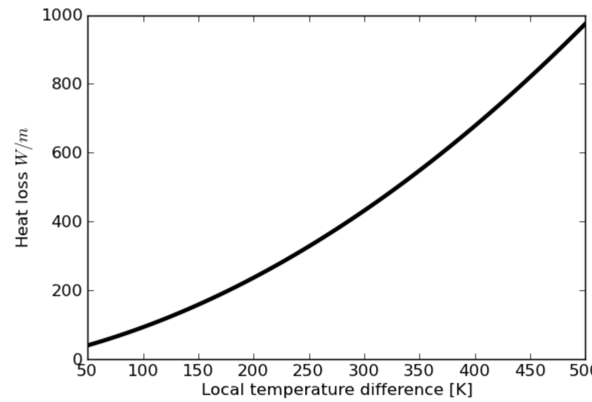

Fig. 7: Default behavior of the receiver thermal losses in the System Advisor LFR model as a function of local temperature difference (steam temperature minus ambient temperature).

longitudinal angles (as defined previously in Figure 1). System Advisor allows the user to define optical performance using either method by filling in the optical table accordingly. A third option is to specify the angularly-dependent performance with Incidence Angle Modifier (IAM) equations, which are simple polynomial relationships. IAM behavior depends strongly on the collector and receiver geometry and optical properties; however, the general trends are shown with a sample system based on the Novatec Solar design in Figure 6. The polynomial-based curves when multiplied together are equivalent to the two-dimensional optical efficiency table.

2.3 The Receiver Heat Loss Model

Several varied LFR receiver designs have been proposed and are currently used in marketed designs. The two most well-known design concepts are the "oven-box" concept that uses a set of small parallel absorber tubes nested within a trapezoidal insulated cavity [14], and the compound parabolic secondary concentrator tubular receiver presented by Morin [3]. Other receiver concepts have been proposed including those by Goswami [4] and Mills & Morrison [2].

Considering the diversity and geometric complexity of the available receiver options, developing an enveloping thermal performance model from heat transfer and fluid mechanics first-principles is not practical. Whereas the parabolic trough evacuated tube receiver is rotationally symmetric and can easily be modeled and validated using heat transfer first principles [15], thermal performance models for LFR receivers tend to use computationally intensive two or three-dimensional CFD analyses (see for example [14] [16] [17]) that are not feasible as part of an annual-hourly simulation tool.

The primary means for determining receiver thermal performance in the System Advisor LFR is a simplified set of polynomials curves that express heat loss as a function of the difference between local steam temperature and ambient temperature. The equation of the form shown in Eq. [1] returns a heat loss factor in units of W/m.

$$\dot{q}'_{hl} = C_0 \left[\frac{W}{m}\right] + C_1 \left[\frac{W}{m \cdot K}\right] \Delta T + C_2 \left[\frac{W}{m \cdot K^2}\right] \Delta T^2 + ... \tag{1}$$

$$\Delta T = T_{steam,local} - T_{ambient} \tag{2}$$

The heat loss in watts per meter of collector length ($\dot{q}'_{hl}$) is multiplied by the collector length that is described by the local temperature difference in Eq. [2] to determine the full receiver thermal loss. The default heat loss correlation in System Advisor is plotted in Figure 7. A second polynomial equation is provided to scale heat loss as a function of wind velocity, though the default behavior modeled in System Advisor does not include this sensitivity.

For purposes of comparison, and because high-performance receivers have been proposed for high-temperature applications, System Advisor also includes an evacuated tube receiver model as an alternative to the polynomial model. The model is the same as described in Forristall [15] and implemented in [18].

2.4 Power Cycle and Balance of Plant

In DSG systems where the solar field heat transfer fluid also serves as the working fluid in the power cycle, the behavior and response of the power cycle to various effects more directly impacts operating conditions in the solar field. This interdependency results in a highly coupled system, and model accuracy depends on capturing the power cycle behavior. Described elsewhere in detail [19] [20], the power cycle model contains relationships describing how heat input to the cycle and gross power output depend on three independent variables - namely, hot steam inlet temperature, steam mass flow rate from the solar field, and condenser pressure (affected by ambient temperature and heat rejection technology). The reader is referred to the above-cited material for a more detailed discussion of this model.

One interesting aspect of the DSG technology is the potential for integrating an auxiliary fossil backup boiler to assist in steam generation. System Advisor provides three configuration options for the auxiliary boiler:

Minimum Backup Level engages fossil backup when the solar field output falls below the user-specified fraction of design-point power cycle heat input.

Supplemental Operation adds fossil energy to bring the total thermal input to the power cycle up to the design-point level. The maximum amount of fossil energy supplied at any given time step is equal to the user-defined fraction times the design-point power cycle thermal energy.

Topping Mode puts the auxiliary heater in series after the solar field (unlike the previous two parallel options), and the boiler is used to boost the steam temperature during time periods where the solar field cannot supply steam at temperature.

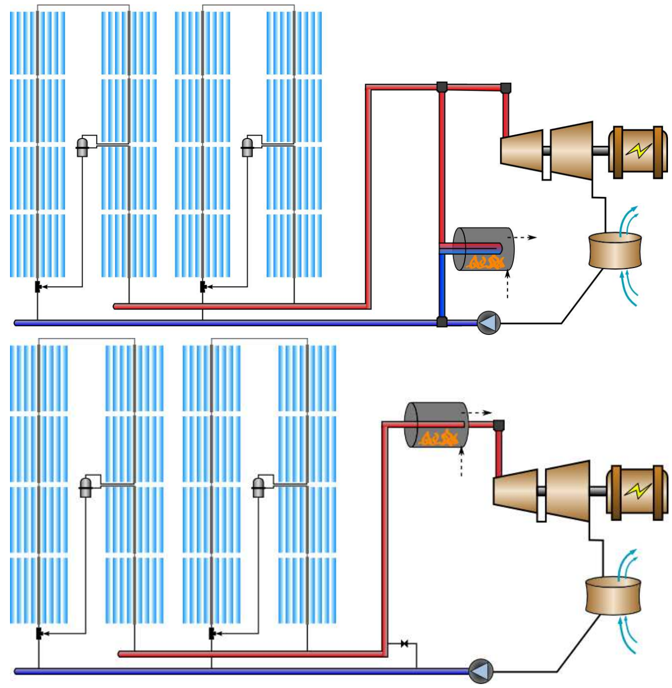

Fig. 8: Possible arrangements for the auxiliary fossil boiler: parallel (top) used in the Minimum Backup Level and Supplemental Operation mode, and series (bottom) used in Topping Mode.

3 TECHNOLOGY COMPARISON

One role of the System Advisor tool is to facilitate technology comparisons within a consistent framework. With the addition of the LFR model, an extensive CSP technology comparison can be made that investigates both performance and economic factors. Similar comparisons appear frequently in literature, including [16], [21], [22], [23], and [24]. The current analysis differs from previously published results in the extent of the included technologies and/or in the modeling of a DSG LFR system as opposed to a sensible-heat HTF. The four technologies included in this comparison are the DSG LFR, DSG Power Tower, Molten Salt Power Tower, and Parabolic Trough (Therminol with solar salt thermal storage).

3.1 Study Methodology

In comparative studies where the goal is to analyze different technologies on equal footing, the choice of design-point parameters can have a significant impact on the final conclusions, even leading to technology bias under certain conditions. For CSP technologies that can include thermal storage, design parameter definition is even more challenging. Several different system design features can be chosen to be held constant for each technology, such as design-point electrical output, solar field mirror area (or aperture area), plant cost, land

TABLE 1: FIXED DESIGN PARAMETERS

Item	Units	Value
Plant location	-	Phoenix, AZ
Federal ITC	%	0
Debt service coverage ratio	-	Optimized
Project IRR	%	15
Annual electricity production	GW-hr	300
Heat rejection	-	Dry cooling
Dispatch market	-	Flat rate
Fossil backup	-	None

area, etc. The most likely candidates for common comparison are power block rating and solar field aperture area, but - as shown in the work currently presented - unnecessarily constrains the technologies.

The current study uses total annual electricity production as the "design" metric, adjusting the other plant design parameters until the goal output is reached. Each system was optimized for the Phoenix, AZ, location to produce the minimum levelized cost of energy (LCOE). The process for defining the system design follows the general procedure:

1. Define the fixed design-point parameters as established in Table 1
2. Parametrically optimize the solar multiple (the ratio of design-point solar field thermal output to power cycle thermal input)
3. For systems with thermal storage, parametrically optimize the equivalent hours of thermal storage.
4. Adjust the power cycle design-point rating until the annual output matches the target production.

The other design-point values for the various technologies were left at their default System Advisor values. Some notable items are presented in Table 2. The LFR solar field is modeled as a recirculated boiler with a boiler outlet quality (vapor mass fraction) of 75%. The LFR case also uses the polynomial heat loss model and optical performance table based on published information from Novatec Solar [3]. All technologies define design-point cycle efficiency assuming a condenser pressure of 8,000 Pa, corresponding to an ambient dry bulb temperature of 20°C.

3.2 Analysis Results

This procedure allows for optimization within each unique CSP technology and frees systems with thermal

TABLE 2: TECHNOLOGY-SPECIFIC DESIGN PARAMETERS

Item	Units	LFR	PT-dsg	PT-ms	Tr
Outlet temp.	$^{\circ}C$	440	565	565	390
Cycle eff.	%	38.0	42.5	42.5	37.8
Boiler Pres.	bar	110	160	100	100

storage to reach a substantially different optimum than systems without. The results of the optimization exercise are shown in Table 3, with the design parameters for each optimized technology reported.

The most notable (but perhaps expected) result from the optimization exercise is the stark difference in rated power block size. While the LFR technology without storage finds an optimal power block size at 158 MWe gross, the thermal storage-heavy molten salt tower finds an optimal LCOE with a power block of 55 MWe. The high cost of thermal storage per unit energy for the Parabolic Trough leads to an LCOE optimum at very low storage capacity - one hour - to assist in riding through weather transients. Another interesting result from the plant design is that the total aperture area for the Parabolic Trough and Power Tower technologies is approximately the same near 850,000 square meters, while the LFR plant requires nearly 40% more aperture area to achieve the same annual output. However, the compact nature of LFR requires only approximately 1/2 of the land area compared to Parabolic Trough and 1/3 of the land area required for Power Towers.

If the primary goal of installing a CSP facility is to offset fossil fuel generation, then aside from practical implementation issues, the most important metric in assessing candidate technologies is the LCOE[1]. However, some market environments may value consistent output throughout the year, dispatchability, or other considerations. Figure 9 shows electric output by month for the various technologies.

Notably, the LFR and Parabolic Trough systems excel during summer months compared to Tower technologies but are optically inferior during winter months. The LFR system nearly coincides with the Trough plant over the year even considering the fact that it has 40% more aperture area. Thus we conclude (as have others [24] that with the significant optical penalty for LFR, collector cost must be significantly lower than for other

[1]Assuming a flat-rate market without peak production incentives, etc.

TABLE 3: SUMMARY OF OPTIMIZED INPUT PARAMETERS AND SIMULATION RESULTS

Description	Units	LFR	PT-DSG	PT-MS	Trough
Design gross power output	MWe	158	140.5	55	150
Solar multiple	-	1.7	1.35	3.36	1.46
Design solar field thermal power	MWt	706.4	446.3	434.8	580.3
Field aperture area	m^2	1,208,000	886,714	836,075	850,302
Land area	acres	478	1,326	1,360	883
Hours of thermal storage	hr	None	None	16	1
Total installed cost	M	592.3	550.1	474.6	624.3
Net annual energy	$GWe \cdot hr$	299.7	299.6	300	299.7
LCOE (real)	$/_{kW \cdot hr}$	20.80	19.22	15.34	21.54
Average parasitic loss	%	6	6	9	8
Capacity factor	%	23.0	25.9	68.4	24.8
Annual water usage	m^3	31,560	58,721	60,541	72,237

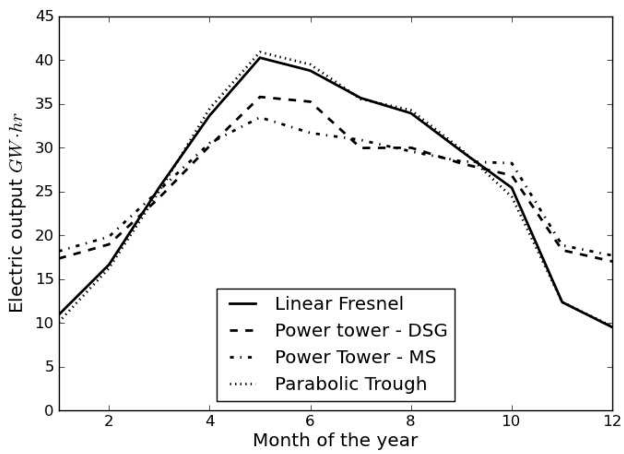

Fig. 9: Electric output by month for the systems described in Table 3.

CSP technologies in order for it to compete.

4 SUMMARY AND CONCLUSIONS

This paper presents an overview of the recently added LFR model in System Advisor and provides an LCOE-optimized plant comparison between various CSP technologies. The analysis results show that while LFR is cost-competitive with other CSP technologies - especially Parabolic Troughs, the leading low-LCOE candidate is the molten salt Power Tower. LFR offers a number of potential advantages, including low-cost collectors and simplified receiver piping that facilitate relatively high-temperature operation. Because of the low solar field cost, ability to generate steam directly, and low land usage, LFR lends itself to integrated solar combined cycle (ISCC) projects.

As grid penetration of renewables increases, thermal storage adds value to the electricity a plant generates [25]. This seems to encourage LFR to pursue solar fields that operate with molten salt or some other medium that is compatible with thermal storage. In this regard, the System Advisor model will continue development by adding a sensible-HTF solar field model in the near future.

ACKNOWLEDGEMENTS

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