Scaling up Solar Hybrid Gas Turbine Electric Power System: Simulation and Results

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Abstract *Scaling up Concentrating Solar Power (CSP) to larger power block sizes is an essential step to reduce unit investment cost, O&M costs, and increases performance. In the present paper a larger solar hybrid gas turbine of 50 MW is investigated whereby annual performances of different parts are estimated using a mathematical program implanted in Visual Fortran 6.0. The selected location for the study is Hassi R'mel where the first solar power plant in Algeria has been built.*

The simulation results show that the solar hybrid gas turbine efficiency of up to 32% is possible, amongst the highest conversion efficiencies for the hybrid system. However, solar electricity ratio up to 85% are feasible; this leads to significant reductions in fuel consumption of 2000 T/ year. This is the key motivation to follow this concept, although the technical integration of the receiver into the gas turbine is rather complex.

Keywords: solar hybrid gas turbine; pressurized air receiver, solar power tower.

NOMENCLATURE

A_s	total mirror area of heliostats field
C_p	specific heat of the air
D	natural gas mass flow
D_f	fuel required for powering a turbine in pure fossil
D_h	fuel required for work a turbine in hybrid mode
DNI	direct insolation
E	the solar constant,
D_s	fuel saving in hybrid mode
fcv	natural gas calorific value.
m,	compressor mass flow
Q_s	net power intercepted by the receiver
Rs	net solar electricity ratio
T_{2s}	volumetric receiver outlet temperature
W_{GT}	output of the gas turbine in fossil mode
W_K	compressor energy consumption
W_{HSGT}	output of the solar gas turbine in hybrid mode
W_T	gas turbine section output
W_s	net solar electricity in fossil mode

Greek Symbols

η_g	heliostat field optical efficiency
η_{SHGT}	efficiency of the solar gas turbine in hybrid mode
τ	atmospheric transmittance
θ_z	zenith angle

1. INTRODUCTION

Recognising both the environmental and climatic hazards to be faced in the coming decades and the continued depletion of the world's most valuable fossil energy resources, hybrid solar thermal power plants can provide critical solutions to global energy problems within a relatively short time frame and is capable of contributing substantially to carbon dioxide reduction efforts. Among all the solar hybrid plants available today and for the next few decades, hybrid solar gas turbine is one with the potential to make major contributions of clean energy because of its relatively conventional technology and ease of scale up.

The solar hybrid gas turbine has been developed within the European SOLGATE project and was successfully demonstrated that the combination of pressurized volumetric solar receivers and a gas turbine really feasible. This project has included experimental investigations of a REFOS receiver at the Plataforma Solar at Almeria, Spain as well as theoretical studies concerning the up scaling of the plant to medium size of 16 MW [1].

Scaling to larger power plants is an essential step for all technologies to reduce unit investment cost, unit operation and maintenance costs, and increases performance. The integration into larger gas turbines specifically for solar tower power technology means a significant challenge due to the less modular design [2]. Here the development of low risk scale up concepts is still lacking.

In the present paper a modified large solar hybrid gas turbine is investigated whereby the performance of each part is evaluated. The selected location in this study is Hassi R'mel where the first solar thermal power plant in Algeria has been built [3, 4]. This concept is a central receiver solar hybrid plant with REFOS receiver type. Different than in all other hybrid solar thermal power plants, solar energy is introduced into a gas turbine and additional fuel is used to increase the temperature to turbine inlet conditions.

The proposed configuration offers many advantages such as:

- High power conversion efficiencies for both solar and fossil input are achievable.
- Able to deliver the design electrical output in pure fossil operation mode.
- Hybrid operation would yield a constant and well defined capacity factor.
- Specific investment costs are generally lower than for Rankine cycles and relatively low LEC compared to solar only operation.
- Development a solar only operation at higher receiver outlet temperatures and the use of thermal energy storage is promising.

Some disadvantages of this concept are:

- The plant actually needs additional fuel to increase the temperature above the level of solar system.
- Limitation of the power output is caused by the strong dependency on ambient temperature which is common for gas turbine cycles.

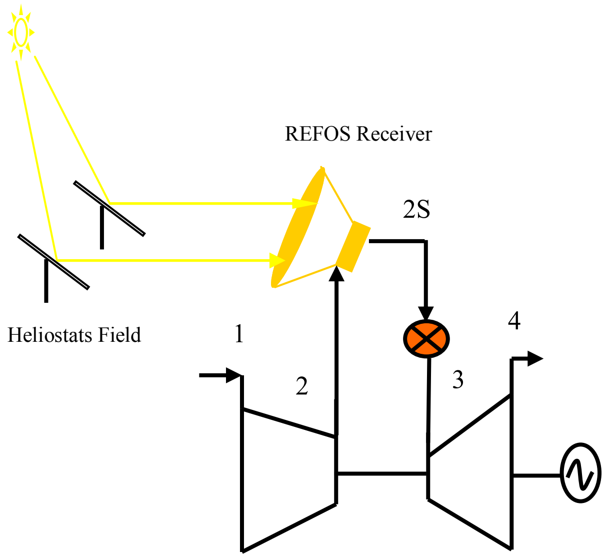

Figure1. Solar Hybrid Gas turbine

2. DESIGN AND CONFIGURATION

As shown in figure 1, the proposed solar hybrid gas turbine basically consists of:

- A modified Siemens Gas Turbine SGT800 of 47MW under Standard conditions.
- A solar tower with 127650 m^2 of heliostats that concentrate Direct Solar Irradiation into pressurized air receiver called Refos.

During sunny period pressurised air from the compressor of the gas turbine is fed into the Refos receiver where it is heated up and the remaining heat required to reach the turbine inlet temperature of 1200°C is provided by natural gas burned in a combustion chamber.

The Refos receiver technology that was used in Solgate project for air heating in gas turbines has been selected in this study. It consists of 3 modules: low temperature module, middle temperature module and high temperature module.

3. MATHIMATECAL ANALYSIS

To simulate the annual performance of each part of the hybrid plant, the solar radiation and then the performance are determined by evaluating the following parameters:

- Solar time: the sunrise and the sunset times.
- Each of the following angles: the solar declination, the sun elevation, the sun azimuth.

- The zenith angle and atmospheric transmittance.
- The instantaneous direct normal irradiation (DNI) is then predicted from sunrise to sunset.
- The solar thermal energy gained by the solar tower receiver.
- The receiver outlet temperature is calculated based on the DNI intensity and solar field design.
- The required natural gas to reach the turbine inlet temperature.
- The annual performance of hybrid gas turbine including the efficiency and the output.
- The solar electricity ratio.

In order to do so, *a mathematical program is developed using the visual FORTRON 6.0*. This powerful program is able to predict the performance of any part of the solar hybrid gas turbine in every second though a year.

A. The Solar Power Tower

The net power intercepted by the receiver Q_s is the product of the heliostat field optical efficiency η_g, the direct insolation (DNI) and the total mirror area of heliostats field A_s. The optical efficiency includes the cosine effect, shadowing, blocking, mirror reflectivity, atmospheric attenuation, and receiver spillage [5].

$$Q_s = DNI \,.\, As. \,\eta_g \qquad (1)$$

Because of the large area of land required, complex optimization algorithms are used to optimize the annual energy produced by unit of land however the heliostats are individual tracking reflective Fresnel segments subject to complex performance factors, which must be optimized over the hours of daylight in the year, by minimizing the cosine effect, shadowing and blocking, and receiver spillage. In the present study the global solar system efficiency is assumed to be equal to the average annual efficiency of 0.75.

The direct normal irradiation in the site where the power plant is located is predicted by using the Hottel method [6].

$$DNI = \tau \,.\, E_x \,.\, \cos(\theta_z) \qquad (2)$$

Where E_x is the solar constant, τ is the atmospheric transmittance and θ_z is the zenith angle. See reference [4] for more detail about solar radiation estimation.
The receiver outlet temperature varies according to solar energy and compressed air parameters.

$$T_{2s} = T_2 + [Q_s \,/\, m.C_p(T)] \qquad (3)$$

Where m, T_2 and C_p are the mass, the outlet temperature and the specific heat of the compressed air.

B. The Hybrid gas turbine

The gas turbine mathematical analysis is taken from [7]. Note that the air cooling system and the energy losses are taken into account to make the simulation more significant. Some data for the gas turbine is presented in table 1.
The output from and the efficiency of the solar gas turbine is given by the following equations respectively.

$$W_{SHGT} = m.(W_T - W_K) \qquad (4)$$

$$\eta_{SHGT} = W_{SHGT} \,/\, (D.fcv) + (DNI.A_s)] \qquad (5)$$

D is natural gas mass flow in (Kg/s) and fcv is its calorific value of Hassi R'mel field, equals to 45.806 Mj/kg.
The fuel saving (D_s) is the difference between the quantities required for powering a turbine in pure fossil (D_f) and solar hybrid (D_h) modes.

$$D_s = D_f - D_h \qquad (6)$$

The net solar electricity ratio depends on solar radiation intensity and the required fuel mass to reach the turbine inlet temperature.

$$R_S = W_S \,/\, W_{GT} \qquad (7)$$

With W_s and W_{GT} are the net solar electricity production and the output of the gas turbine in fossil mode respectively.

4. SIMULATION AND RESULATS

The direct normal irradiation: In order to evaluate the solar tower power performance, it is necessary to estimate the DNI from sunrise to sunset. Figure 2 points up the variation of the DNI though a year. From first January (day number 1) to 31 December (day number 365) the solar energy that can be intercepted by the receiver varies according to the variation of time of the day and the day of a year .The direct solar irradiation is higher at midday and has the lowest value during sunrise and sunset for each day. From the day number 80 (in spring) to the day number 280 (in autumn), it is very important and can be more than 600 W/m^2 between 10am and 4pm of each day. Moreover in summer, it is higher than other season and can be reach the value of 900 W/m^2.

The useful energy gained by the receiver: The solar energy gained by the receiver varies according to the variation in solar radiation from sunrise till sunset, where the operation duration varies for each day (figures 3). The amount of solar field output during the summer is greater than for the other seasons due to the higher solar radiation intensity and longer solar radiation duration. The average amount in winter is about 25MW. In spring and autumn, this amount will be more than 60MW. However during sunny period in summer the intercepted solar energy by the Refos receiver can reach the limit of 90MW.

The Refos receiver outlet temperature: the receiver outlet temperature depends on the compressed air parameters, the amount of solar radiation intensity and the solar field performance. Figure 4 represent the instantaneous variation of the receiver outlet temperature through a year. The simulation result confirms the ability of pressurized air receiver to power the gas turbine cycle. As shown in figure 4 the outlet temperature is very high at summer and at midday because of solar radiation intensity and it can attain the value of 1100°C when DNI reach the limit of 900 W/m^2. In spring and autumn it varies from 600 to 900 °C depending on the climatic conditions of Hassi R'Mel location. However it is a relatively lower in winter due to lower solar radiation and shorter daylight duration.

The solar hybrid gas turbine performance: The efficiency of and output from the hybrid gas turbine are both vary according to the variation in receiver outlet temperature from sunrise till sunset, where the operation duration varies for each day (see figure 5 and 6). Both are decrease when the amount of solar radiation increase, this is due the lower solar system performance including heliostats field and the air receiver. In winter and during sunrise and sunset times the output from and the efficiency of the hybrid gas turbine is higher, vary from 42 to 43.8 and from 0.35 to 0.375 respectively.

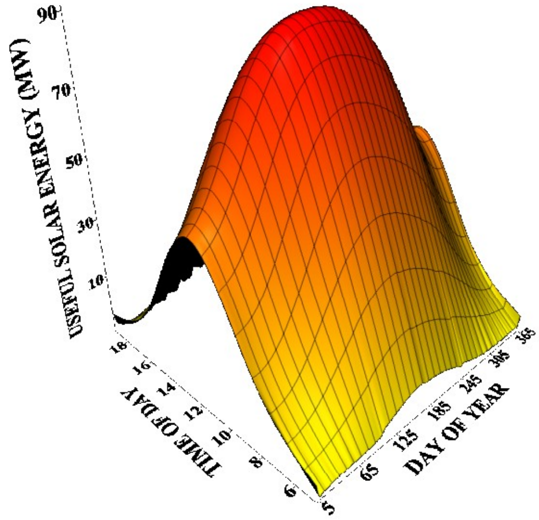

Figure3. Annual useful solar energy

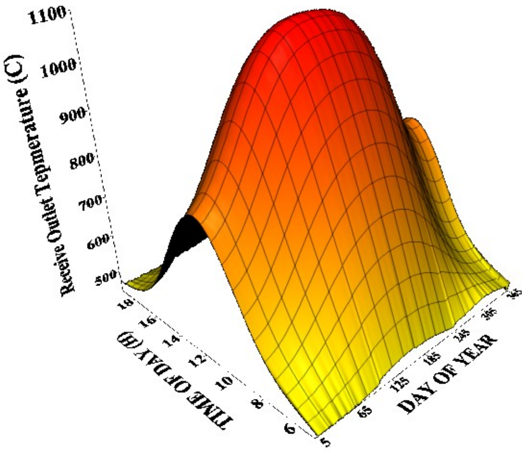

Figure4. Instantaneous receiver outlet temperature

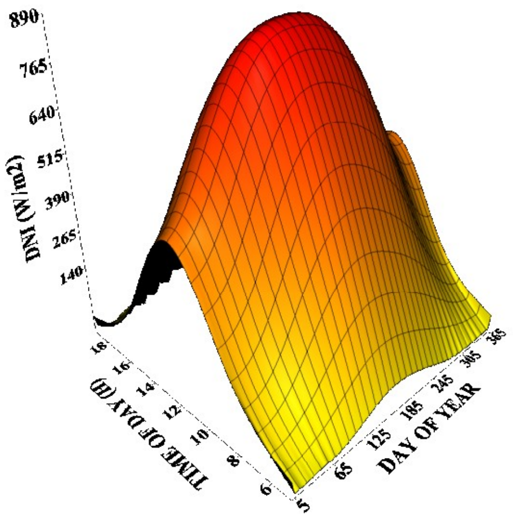

Figure2. Annual Solar Direct Irradiation

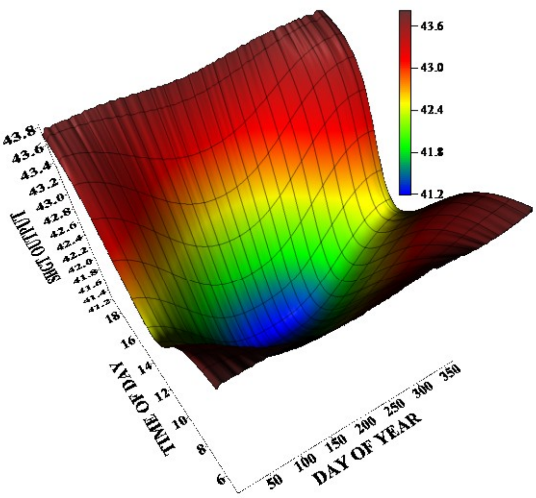

Figure5. Instantaneous electricity production though a year

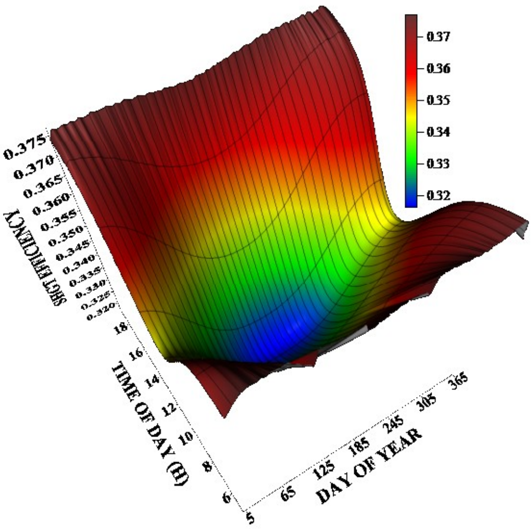

Figure6. Instantaneous hybrid turbine efficiency though a year

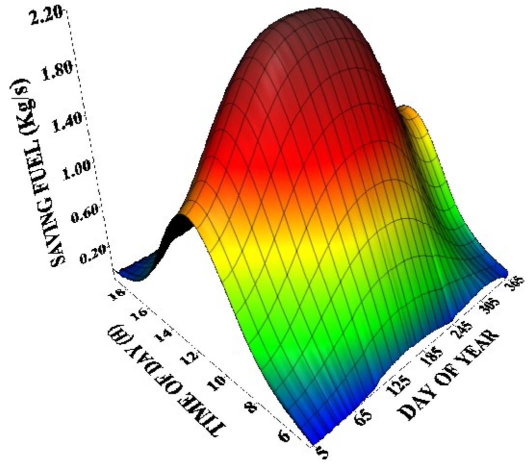

Figure7. The amount of fuel saving though a year

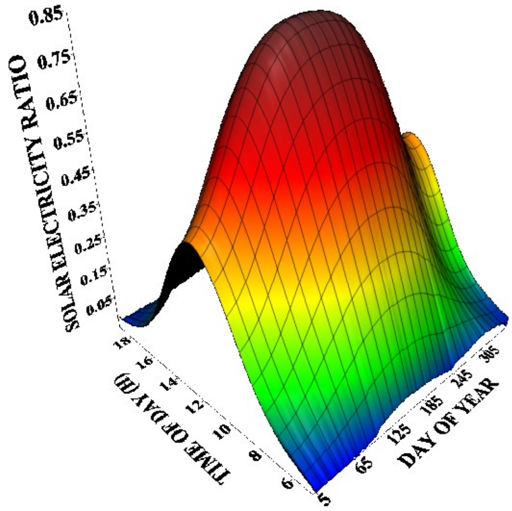

Figure8. Instantaneous solar electricity ratio during a year

TABLE I. Some data of solar hybrid gas turbine

	Hassi R'Mel geographical location		
	Latitude	***Longitude***	***Altitude***
	33.8°North	3°East	776 m
	Solar tower configuration		
	Solar Field area	***Number of heliostats***	***Land area***
Solgate	38000 m^2	313	432 m^2
Modified SGT800	127650 m^2	1052	1450 m^2
	Gas Turbine Data		
	Compr. Ratio	***Efficiency (SI)***	***Output (SI)***
	19.9	37%	47MW

For more information see reference [2, 8]

When the solar radiation is higher and thus the ambient temperature, the performance of the hybrid system including the electricity production, the efficiency and saving fuel are lower and the higher is the DNI the lower are the performance.

The amount of saving fuel during summer is greater than for the other seasons due to the higher solar radiation intensity and longer solar radiation duration (figure 7). The average amount in winter is about 0.7 Kg/s. In spring and autumn, this amount will be more than 1.2 Kg/s. The big saving quantity occurs between 10 am to 16 pm from March through September. In summer, the saving fuel reaches the amount of 2.2 Kg/s at midday. As a result, the solar electricity ratio achieves the value of 85%, at this time the Refos outlet temperature can attain 1100°C. The variation of solar electricity ratio during a year is shown in figure 8. The higher the intercepted solar energy the higher is the ratio.

5. CONCLUSION

Scaling up a solar hybrid gas turbine to 50 MW leads to benefits for both the solar and the fossil operation. The simulation study points out that pressurized air receiver outlet temperature can reach the limit of 1100°C under Hassi R'Mel climatic conditions during sunny periods. As results the solar electricity radio and the amount of saving fuel will expect 85% and 2.2 Kg/s respectively.

Therefore, the combination of high solar shares with high conversion efficiencies is one of the major advantages of solar gas turbine systems compared to other solar fossil hybrid power plants.

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