TECHNICAL FEASIBILITY ASSESSMENT OF INTEGRATED SOLAR COMBINED CYCLE POWER PLANTS IN CIUDAD REAL (SPAIN) AND LAS VEGAS (USA)

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Abstract

The increase of natural gas prices and the higher ecological conscience of our society demand energetically efficient policies in electricity generation. The efficiency of combined cycle power plants diminishes with higher air temperatures. However, when this occurs, there is usually higher direct solar irradiation and, therefore, solar thermal generation increases. The goal of this study is to develop a sensitivity analysis of direct solar irradiation and air temperatures in the performance of integrated solar combined cycles, using parabolic trough collectors. The study is performed in two different locations, one in Ciudad Real (Spain) and the other in Las Vegas (USA). Based on the typical meteorological years of both sites, it has been developed a production model built on the SAM program by the NREL. With the help of this model, solar contribution, solar fraction and solar dumping have been studied to boost electricity production when decaying because of high temperatures. It has been proved that up to 0,2-0,3% of solar fraction, solar integration is technically feasible and it provides an efficient solution in both places without any modification in the operation.

Keywords: ISCC; Integrated Solar Combined Cycle; Solar Thermal Generation

Resumen

El aumento del precio del gas natural y la mayor conciencia ecológica de nuestra sociedad demandan políticas de eficiencia energética para la generación eléctrica. La eficiencia de los ciclos combinados se ve mermada con el aumento de la temperatura del aire exterior. Estas condiciones coinciden con los momentos de mayor irradiación solar directa y cuando la generación solar térmica sería mayor. El objetivo de este estudio ha sido el desarrollo de un análisis de sensibilidad de la irradiación solar directa y de la temperatura del aire en el rendimiento de ciclos combinados con hibridación solar compuesta por colectores cilindro parabólicos. El estudio se ha realizado en dos ubicaciones diferentes, una en Ciudad Real (España) y la otra en Las Vegas (USA). A partir de los años meteorológicos típicos de ambos lugares, se ha desarrollado un modelo de producción basado en el programa SAM del NREL. Aplicando el modelo, la contribución solar, la fracción solar y el dumping se estudian para aumentar la producción cuando decae por altas temperaturas. Se prueba cómo para un 0,2-0,3% de fracción solar, la hibridación solar es técnicamente viable y supone una solución eficiente en ambos lugares.

Palabras clave: ISCC; hibridación solar; generación solar térmica

1. Introduction

The rise on fossil fuel prices, the external energetic dependency on instable countries and the higher ecological conscience of some societies have made solar energy a very attractive source of thermal and electric energy.

Luz Solar International, linked to the nine Solar Energy Generating Systems (SEGS) of the USA, was the first developer of Concentrating Solar Power (CSP) plants from 1982-1991. The success of these projects fostered this technology and introduced the concept of the Parabolic-Trough and Heat Transfer Fluid (PT-HTF) CSP plants, which nowadays still remains the market leader with a global installed capacity of 1274MW (CSP Today, 2011). After a fifteen-year gap since the IX^{th} SEGS plant in 1991, in which no CSP plant was developed, a worldwide expansion of the CSP technologies is registered in the last five years. This expansion has allowed a significant price reduction on PT-HTF technology, from about 5euro/W_e in 2008 in some plants of Spain without thermal storage, to below 2euro/W_e in 2011 in India, caused by a major price reduction on the solar field components.

Figure 1 Ain Beni Mathar ISCC (Abeinsa, 2011)

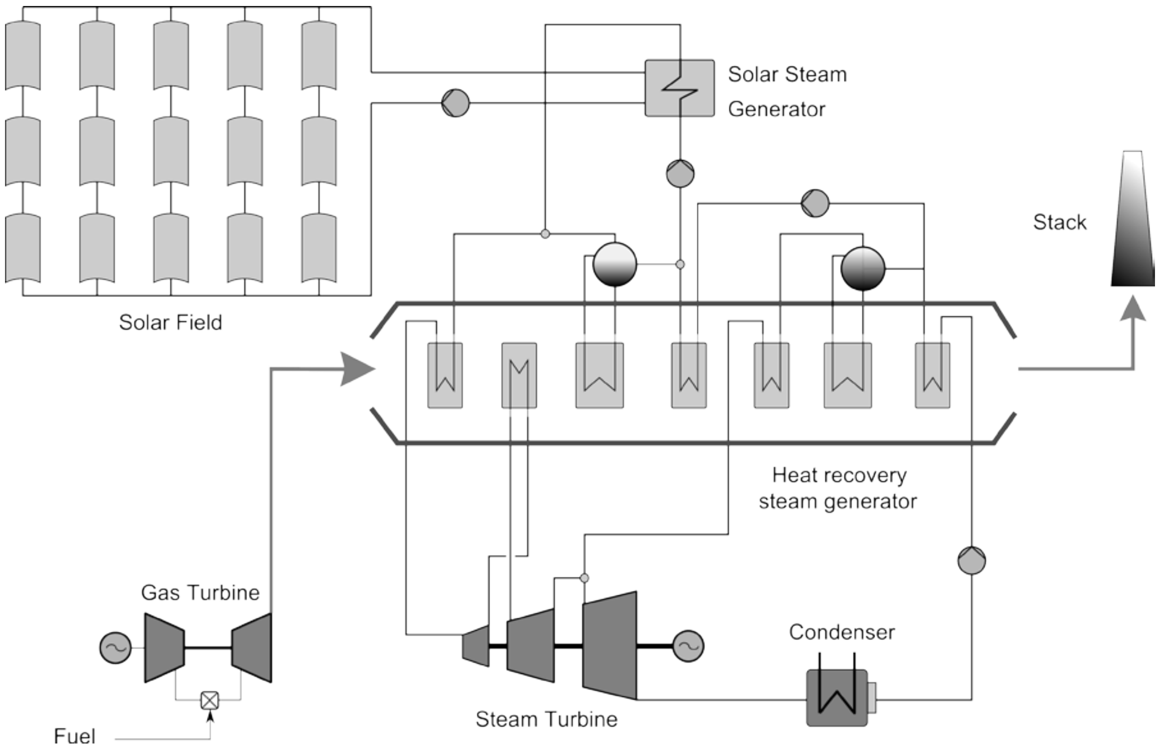
The concept of an Integrated Solar Combined Cycle (ISCC) derives from a Combined Cycle Gas Turbine (CCGT), in which the exhausted gases are boosted with solar thermal energy in the Heat Recovery Steam Generator (HRSG). An ISCC only requires the solar field as per a CSP plant, since the other components of the plant are provided by the CCGT. There are some technical advantages of the ISCCs versus the CCGTs and the CSP plants.

- The solar integration in a CCGT improves the thermo-dynamical efficiency (fossil fuel consumed versus electricity generated) when compared with a convectional CCGT (Derbal-Mokrane et al., 2012).
- The ISCCs does not suffer from the thermal inefficiencies associated with the daily start-up and shutdown of the steam turbine of a CSP plant (Dersch et al., 2004).

- The economic cost of implementing a solar field in the CCGT represents a significant lower quantity than developing an entire CSP plant. Operation and maintenance of an ISCC does not imply a significant incremental cost, being possible to program maintenance shutdowns of the GT during the summer, and doing the same with the solar field in the winter.

There may be different ISCC configurations according to the solar field technology: Linear Fresnel, Power Tower, Parabolic Trough with Direct Steam Generation and PT-HTF (Palenzuela et al., 2011 & Giostri et al., 2012), and also according to how the solar steam is injected in the CCGT (HRSG or directly in turbine). Figure 2 represents an ISCC with PT-HTF technology with solar steam injected in the HRSG.

Figure 2 ISCC with a PT-HTF solar field



The net electrical efficiency of a CCGT basically depends on the altitude and the external air temperature. This fact implies important efficiency losses in places with high temperatures during long periods (Dersch et al., 2004). Locations with elevated solar irradiation, usually present high temperatures and therefore an ISCC provides the opportunity to compensate efficiency losses with solar thermal energy (Hosseini, Soltani & Valizadeh, 2005). In order to evaluate the possibilities of the solar integration for a CCGT, it is necessary to attend the Typical Meteorological Year (TMY) of the site to reduce efficiency losses and to maximize the electric generation with the optimum solar field (Ordorica, Vidal & Fernandez, 2011).

The ISCC commercial operation has been proved since 2010 in the MNGSEC (USA) and in the Archimede (Italy) power plants. Table 1 compiles the current commercial ISCC projects.

Table 1 ISCC projects. Source: National and Renewable Energy Laboratory, (NREL2012)

Project	Country	Full Capacity	CSP Capacity	Status
Martin Next Generation Solar Energy Center (MNGSEC)	USA	1125MWe	75MWe	Operational since 2010
Archimede	Italy	750MWe	5MWe	Operational since 2010
Hassi R'mel	Algeria	150MWe	25MWe	Operational since 2011
Ain Beni Mathar	Morocco	470MWe	20MWe	Operational since 2011
Kuraymat	Egypt	140MWe	20MWe	In construction
Victorville 2 Hybrid Power Plant	USA	573MWe	50MWe	Under development
Palmdale Hybrid Power Plant (PHPP)	USA	570MWe	50MWe	Under development

Previous studies have analysed ISCCs considering the solar-dispatching mode, in which the ISCC absorbs the entire solar thermal production, with the intention of assessing how much fuel can be saved with the solar integration by increasing the steam turbine capacity (Baghernejad & Yaghoubi, 2011).

Nevertheless, the objective of the present study is to analyse how much electricity production can be raised with the solar-boosting mode. This means that the CCGT will operate full-loaded along the year without any modification in the steam turbine. The assessment is carried out in two different scenarios, to analyse the potential integration of solar thermal energy under two different climatological conditions. These two locations are about the same altitude above the sea level, but they present significant differences in their TMYs, which would potentially affect the performance of the ISCCs.

2. System analysis

The assessment is performed considering two equal CCGTs of 400MW_e, composed by a 270MW_e gas turbine and a 130MW_e steam turbine. The CCGTs are located in Las Vegas (USA) and Ciudad Real (Spain). The solar field sizes with PT-HTF technology are analysed to evaluate the potential solar integration and to convert the CCGTs into ISCCs without modifications on the original turbines. Inlet steam in the steam turbine is 500ºC and 100bar, which implies a higher temperature than the degradation point of the HTF, 393ºC (Dersch et al., 2004). For this reason, solar thermal energy will be used to displace latent vaporization heat at the highest possible temperature and also to preheat in the HRSG of the ISCC.

The meteorological conditions of each site are defined by their TMYs by Meteonorm (Meteonorm V.6.1., 2011), which provides a year of hourly values of Direct Normal Irradiation (DNI), Wind Speed (WS) and Air Temperature (T_a).

Table 2. Site conditions of tested locations

	Las Vegas (USA)	Ciudad Real (Spain)
Latitude	36,17º N	38,9254º N
Longitude	115,17º W	3,9275º W
Altitude	680m	632m
DNI (annual)	2593,1kWh/m^2	1837,5kWh/m^2
Mean Ta	19,47ºC	14,26ºC
Mean WS	4,6m/s	3,99m/s

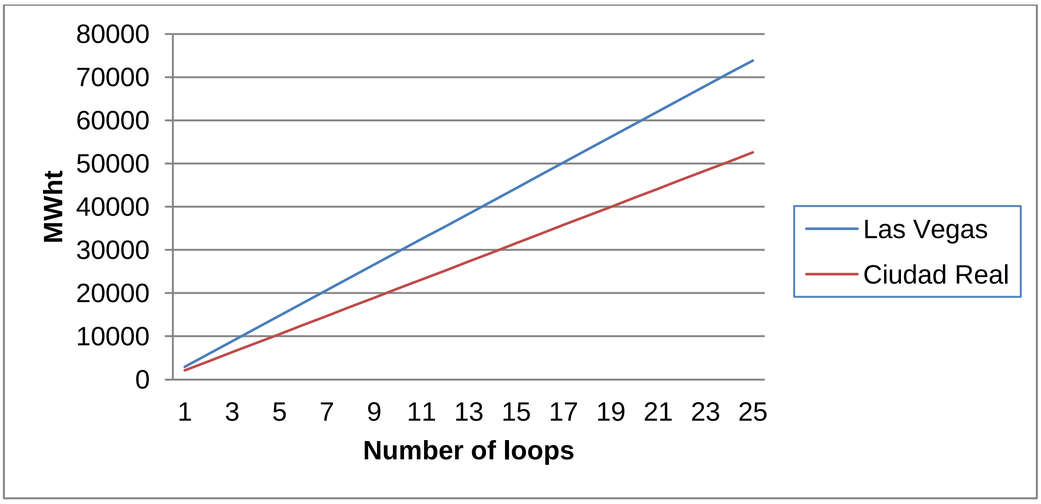
In a first step, the potential solar thermal energy is analysed based on our own production model based on the SAM program by the National Renewable Energy Laboratory of EEUU (NREL, 2012). In order to calculate the hourly thermal production, the model is fed with the TMY and the technical specifications of the solar field. Table 3 compiles the technical specifications considered in the solar field.

Table 3. Technical specifications of the solar field

Type of collector	LS-3
Length of SCA	99m
SCAs per loop	4
Collector orientation	South
Mirror cleanliness	97%
Transmissivity	95,5%
Reflectivity	94%
Interception factor	99,7%
Absorptivity	95,5%
Emittance	9,5%
Efficiency peak	85,5%
Width	5,76m
Focal Distance	1,71m
Opening area	545m^2
Parallel distance between collectors	15m
HTF	Therminol VP1
HTF_{inlet} nominal temperature	293ºC
HTF_{oulet} nominal temperature	393ºC

Figure 3 represents the solar thermal energy transmitted to the HTF in the SCAs. This heat is firstly transferred to produce steam in the solar steam generator so that it will be posteriorly addressed to the HRSG.

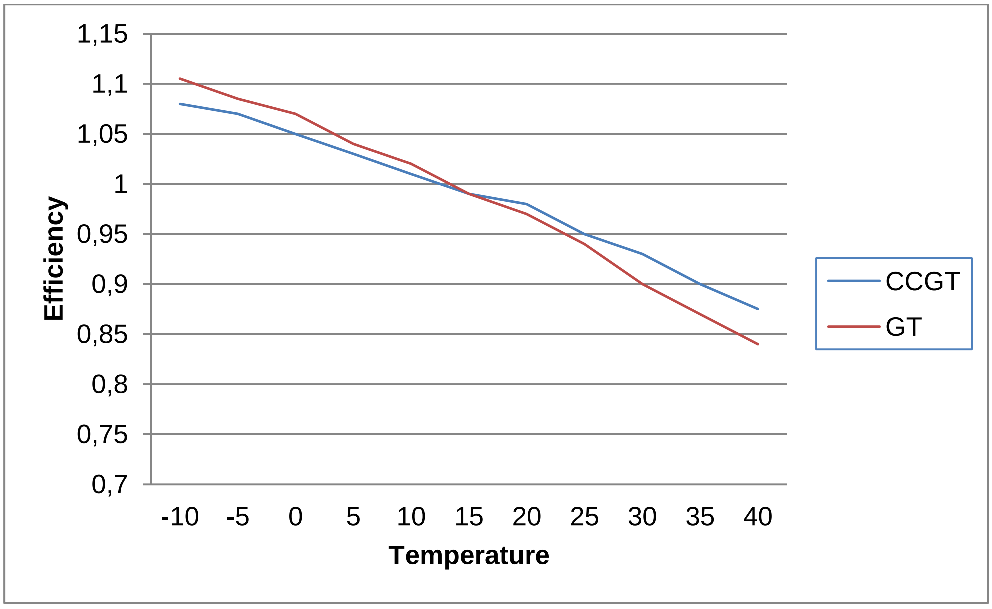
Figure 3. Potential annual thermal yield of the solar field vs. number of loops



In a second step, the ISCC performance is analysed with different sizes of solar fields to calculate the potential solar thermal integration according to a solar-boosting operational mode. This approach consists on operating the ISCC as a CCGT; then, when power losses due to high temperature affect the CCGT performance and there is solar resource available, the Steam Turbine (ST) will be boosted with solar thermal energy.

The productivities of the CCGTs are modelled on an hourly basis regarding the T_a (Sabugal & Gomez, 2006). Figure 4 represents the efficiency of both the Gas Turbine (GT) and the CCGT regarding the T_a. Based on this curves and the T_a of the TMYs, the available capacity of the steam turbine is analysed to evaluate the potential solar thermal integration on an hourly basis.

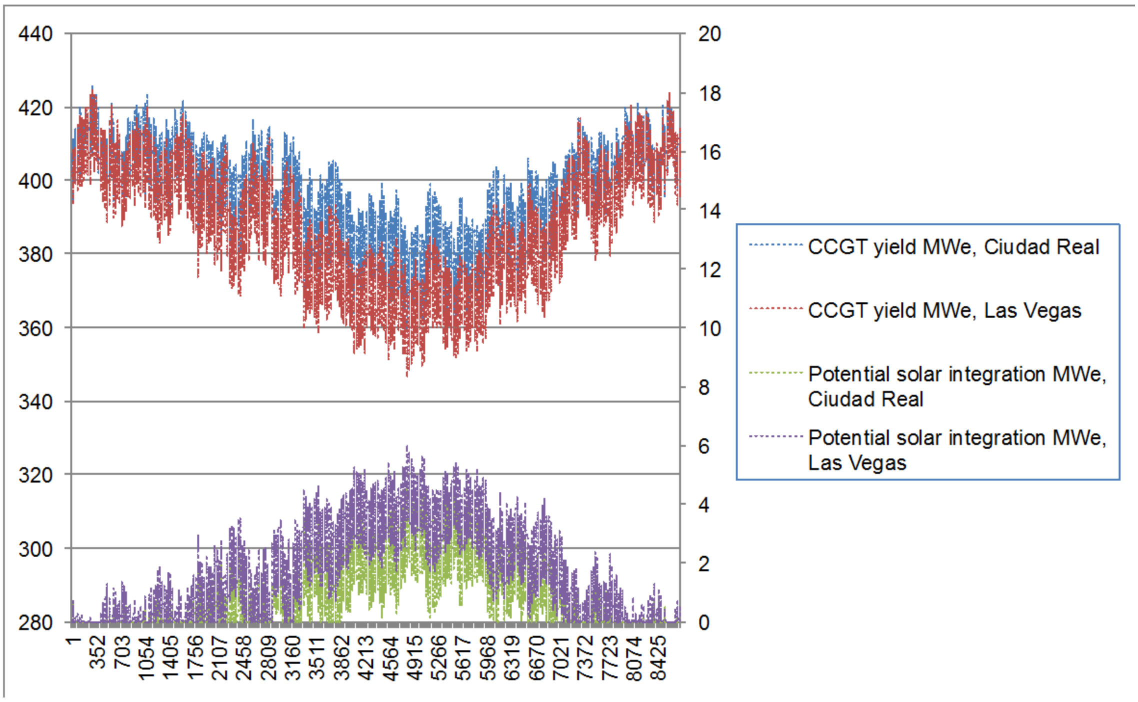
Figure 4. Efficiency of the GT and CCGT



The influence of the number of loops of the solar field is analysed according to the performance of the two CCGTs and to the potential solar power that would be integrated in the ST. The potential solar integration (P_{int}) (1) is computed through the difference of the nominal and real ST capacities.

$$P_{int} = P_{ST,nom} - \left(P_{CCGT,nom} \cdot \eta_{CCGT} - P_{GT,nominal} \cdot \eta_{GT}\right) \quad (1)$$

Figure 5. Power output along the year and solar potential integration



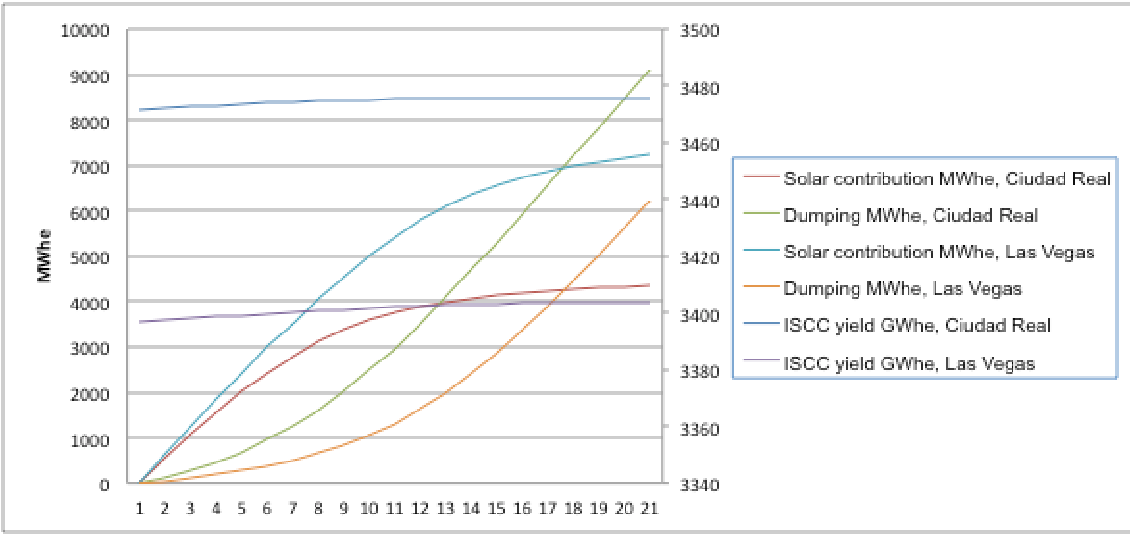
The CCGT located in Las Vegas gives a lower performance than the one in Ciudad Real, primarily because of the higher temperatures of Las Vegas. As a result, the ISCC potential with solar-boosting mode is higher in Las Vegas than in Ciudad Real. Additionally, the ISCC of Las Vegas is able to generate more solar thermal energy per loop than the one in Ciudad Real, because of the higher DNI and the better distribution of irradiation through the year.

The excess of solar thermal energy is denoted by solar dumping (D_{exc}) (2). This indicator depends on the difference of the potential solar power of a given solar field (P_{CSP}) and P_{int}, and it characterizes the optimization of the ISCC.

$$D_{exc} = P_{CSP} - P_{int} \quad (2)$$

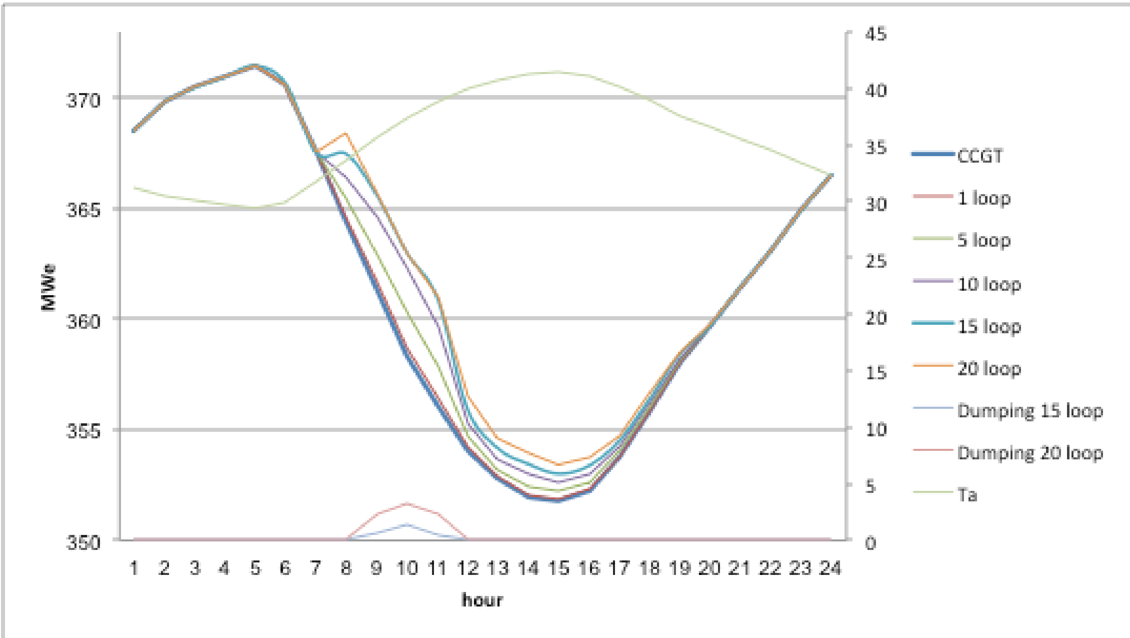
Figure 6 synthetizes the integration and performance of the two ISCCs during a TMY of operation related to the number of loops. While the ISCC yield and the CSP contribution curves grow like asymptotes, the solar dumping curve grows exponentially. As a result of the lower P_{int} and the distribution of the DNI, solar dumping is more significant in Ciudad Real than in Las Vegas,

Figure 6. ISCC analysis



The ISCC behaviour is studied in a day with high temperatures as shown in Figure 7. The solar integration has a higher potential during the mornings-afternoons of warm days.

Figure 7. ISCC performance for a day in August, Las Vegas



The annual solar fraction represents the proportion of the solar energy in the overall ISCC annual yield. In the case of ISCCs with 20 loops, the solar fraction is 0,13% and 0,21% for Ciudad Real and Las Vegas respectively.

3. Conclusions

CCGTs located in high-irradiated areas, such as the south of Europe or the southwest of the USA; present an interesting opportunity to improve the electric yield during the hottest months of the year. The efficiency of the CCGT operating full-loaded significantly depends on the temperature.

Operating the ISCC with the solar-dispatching mode implies a high dependency of the whole CCGT efficiency on weather transitories, such as clouds over the solar field (Niknia & Yaghoubi, 2012). Nevertheless, the solar-boosting mode lacks of that high dependency on weather transitories, because the CCGT is operated full-loaded and the solar integration is applied only to boost the ST when possible, but not to save as much fuel as possible as the solar-dispatching mode does.

The balance of plant, the start-ups and the shutdowns are more efficient in an ISCC than in a CSP plant, as the steam turbine is continuously working and irreversibility is lower.

In energy markets, such as the Spanish, the annual demand peak occurs during the summer months in the afternoon. The possibility of incrementing generation in this period can be perfectly assumed with solar thermal energy and it supposes an attractive reason to develop ISCCs.

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