

Performance prediction of solarized CC power plants operating in a load-following strategy

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Abstract

The paper reports on simulations and performance prediction of an Integrated Solar Combined Cycle (ISCC) plant operating in a load-following strategy. The ISCC plant was assumed to operate in an isolated or weakly interconnected grid, matching the electricity demand profile of a mid-size community in South Africa (Uppington area). Two different profiles, with the same peak level, have been taken as reference for Industrial and Domestic demand, respectively, in a typical winter/summer day.

The power block is based on Siemens SGT-800 gas turbine (rated 50.5 MW at ISO conditions) coupled to a dual pressure HRSG producing steam for the bottoming Rankine cycle. Additional steam is produced by a solar loop, sized for about 20% annual solar fraction, according to solar radiation availability. Performance of two different Concentrated Solar Power technologies was evaluated: i) Parabolic Trough Collectors (PTC) with thermal oil and ii) heliostats and Central Receiver System (CRS) with molten salt as heat transfer fluid (HTF). In the PTC case, steam is produced at slightly superheated condition, due to the maximum oil temperature of 392°C imposed by thermal oil degradation. The solar tower configuration ensures higher steam temperatures thanks to the usage of molten salt.

The load following strategy prescribed that the GT load is adjusted hour-by-hour to match the instantaneous power demand, including both the solar contribution to the total amount of energy generated and the influence of ambient temperature and relative humidity on ISCC power output. A computing procedure was developed by integrating commercial codes (Thermoflex for the power block and TRNSYS for the solar field) to predict thermodynamic performance at nominal and part load conditions, including the off-design behavior of all main components (GT, HRSG, steam turbine, air condenser). Simulation results demonstrated that both the investigated ISCC configurations are suitable for load following operation, with a significant fossil-free electricity production positively affecting the power plant efficiency. In addition, features of PTC vs. CRS were included in the discussion.

1. Introduction

Nowadays Combined Cycle plants are being forced to increase their operating flexibility to adapt to liberalized electricity market and to accommodate the variability of renewable power generation. Operational flexibility includes not only fast startup and shutdown, fast load changes and load ramps,

but also lower and lower technical minimum environmental load and good efficiency at partial load operation [1]. Ideally, CC plants should operate at high peak capacity during high demand periods, while maintaining high efficiency during turndown and load following. In practice, built as base load plants, CC efficiency at partial load is lower than the base-load point. A significant load reduction is responsible for an efficiency penalty of a few percentage points, with respect to base load operation [2].

Furthermore, stringent environmental requirements introduce additional constraints on part load CC operation. For example, the technical minimum environmental load is defined as the minimum condition at which the gas turbine can operate, still meeting the environmental limits for nitrous oxides (NO_x) and carbon monoxide (CO) emissions. As stated in [3], the minimum environmental load for most gas turbines is about 50% of full output because operation at lower loads can result in reduced combustion temperature, less conversion of CO to CO₂ and potential exceedances of emission limit. To facilitate a wider range of gas turbine output, manufacturers have introduced control systems designed to extend emissions-compliant turndown while minimizing efficiency impacts at part load. The control systems use variable inlet guide vanes to decrease air inflow and sequential firing to enhance combustion temperatures at part load. Higher combustion temperatures not only enhance the conversion of CO to CO₂ but also boost the steam turbine output, thus improving part-load overall efficiency. As a result, quite a few gas turbine models can achieve turndown to about 40% of baseload power, maintaining guaranteed emission profile, with a few cases of turndown as low as 25% of gas turbine baseload [4].

Low load turndown flexibility is extremely desirable to gas turbine operators in light of an improved load follow capability. This is especially true assuming a future expansion of renewables such as wind and solar energy. CC plants, previously designed for base load operation, will have to be run at part load during peak wind and sun periods, with complete shutdown necessary to avoid significant overcapacities. These plants will need to be started up from the shutdown condition as rapidly as possible to cover demand in the event of short term loss of wind and solar power. From a comparison between nuclear and fossil fired power plants [5], it can be concluded that CC plants allow faster load changes within wider load range, and also shorter startup times in the cold, warm and hot conditions. Stated that CC plants are able to meet fluctuating energy demand, the load following capability of an ISCC is investigated in the present study, for two different CSP technologies, i.e. PTC and CRS. The additional steam produced through concentrated solar energy is integrated into the HSRG and expanded in the steam turbine. Actually, ISCC plants using PTC technology are already in operation. Conversely, ISCC with CRS is a recent development [6]. In an ISCC, intermittency of solar energy can be compensated by fossil generation; otherwise, fossil fuel consumption can be reduced when the solar input is available. Bohtz et al. [7] defined two operation modes (Fig. 1): at times of high demand, the solar steam (yellow region) can boost the ISCC electricity output. Alternatively, the GT load can be reduced so that the fossil power is replaced by the solar power. In this case, the solar contribution does not increase the ISCC output but the gross efficiency, due to fuel savings.

The profiles of electricity demand for evaluation of the ISCC load follow capability are shown in Fig. 2.

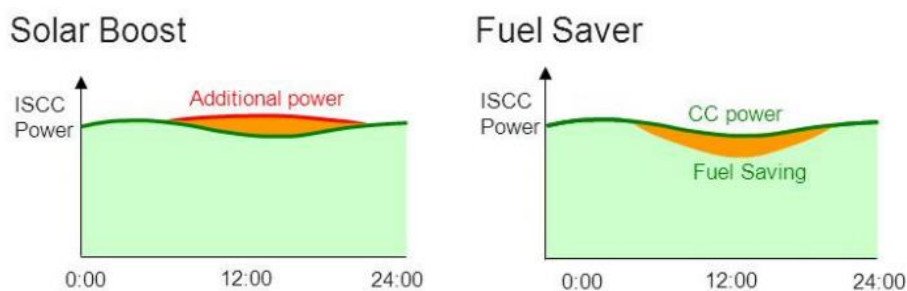


Fig. 1: ISCC operation modes [7].

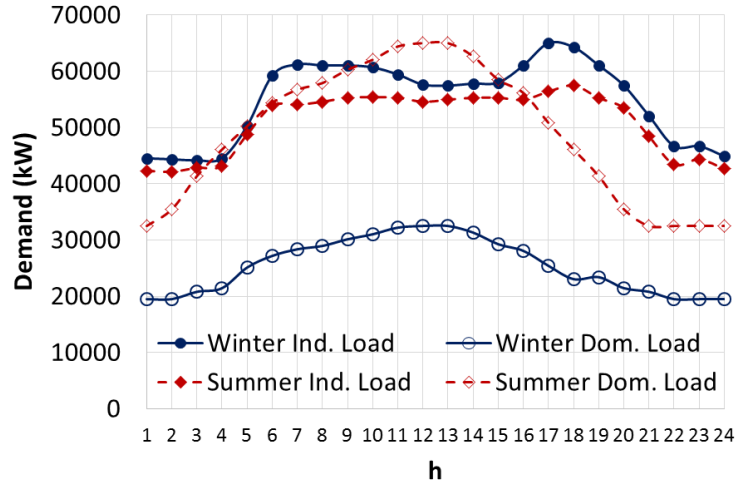


Fig. 2: Industrial and Domestic electricity demand profile, for representative summer/winter day.

Daily patterns of electric demand were defined for a typical summer and winter day, according with two types of load. Filled markers resemble an industrial load, estimated from South Africa global demand load [8]. A peak of about 65 MW occurs during the winter day, with a slightly lower summer electric request having a flatter shape. The same peak demand of 65 MW characterizes the domestic load, but in the central hour of the summer day. In this case, there is a big variation in the power request between day and night, to account for air conditioning consumption. The peak power in winter is approximately half of that in summer, consistently with [9].

2. Description of the ISCC plant

An ISCC combines a solar field and a gas fired CC power plant (Fig. 3). The steam generated by the solar section is joined to the one produced in the HRSG and is expanded in the steam turbine. A large part of the steam cycle is shared with the solar section and remains almost unchanged. Steam turbine and condenser over sizing is anywhere needed to accommodate the additional solar steam.

CC design parameters in fossil fuel operation are shown in Table 1. The CC plant includes the middle version of Siemens SGT-800 gas turbine rated 50.5 MW_e at ISO conditions. The steam section is based on a dual pressure HRSG generating steam at 69 and 7.7 bar. Steam is then expanded in a steam turbine producing 22.2 MW_e. HP and LP evaporator were sized assuming pinch point temperature difference values of 9°C and 8°C, respectively. Turbine efficiency values of 83% and 87.5% were set for HP and LP steam turbine sections. An air-cooled condenser with a design pressure of 0.06 bar at ISO conditions was considered.

In the ISCC plant, a 100800 m² solar field was included for both PTC and CRS technologies, corresponding to 21 trough loops and 840 heliostats, respectively. In the former, Synthetic oil (Therminol VP-1) was assumed as heat transfer fluid (HTF), with constant temperature values of 292°C and 392°C at the solar field inlet and outlet. In the latter, constant molten salt temperature values of 300°C and 550°C were set at the solar field inlet and outlet. Consequently, the solar steam is produced at 360°C/520°C in the PTC/CRS case. The thermal energy from the solar field is transferred to the bottoming cycle by means of a heat exchanger HX including an economizer, an evaporator and a superheater. HX receives preheated feedwater drawn from the HRSG, downstream of the first stage economizer (ECOHP1) and returns superheated steam. This mixes with the steam exiting the HP evaporator (see black circle in Fig.3)/HP superheater (see black diamond) for PTC/CRS solution, respectively. Concerning the HP steam turbine control, sliding pressure condition was assumed. GT operation was considered depending on ambient temperature and humidity. GT part load is achieved by combining progressive closure of inlet guide vanes and turbine firing temperature reduction.

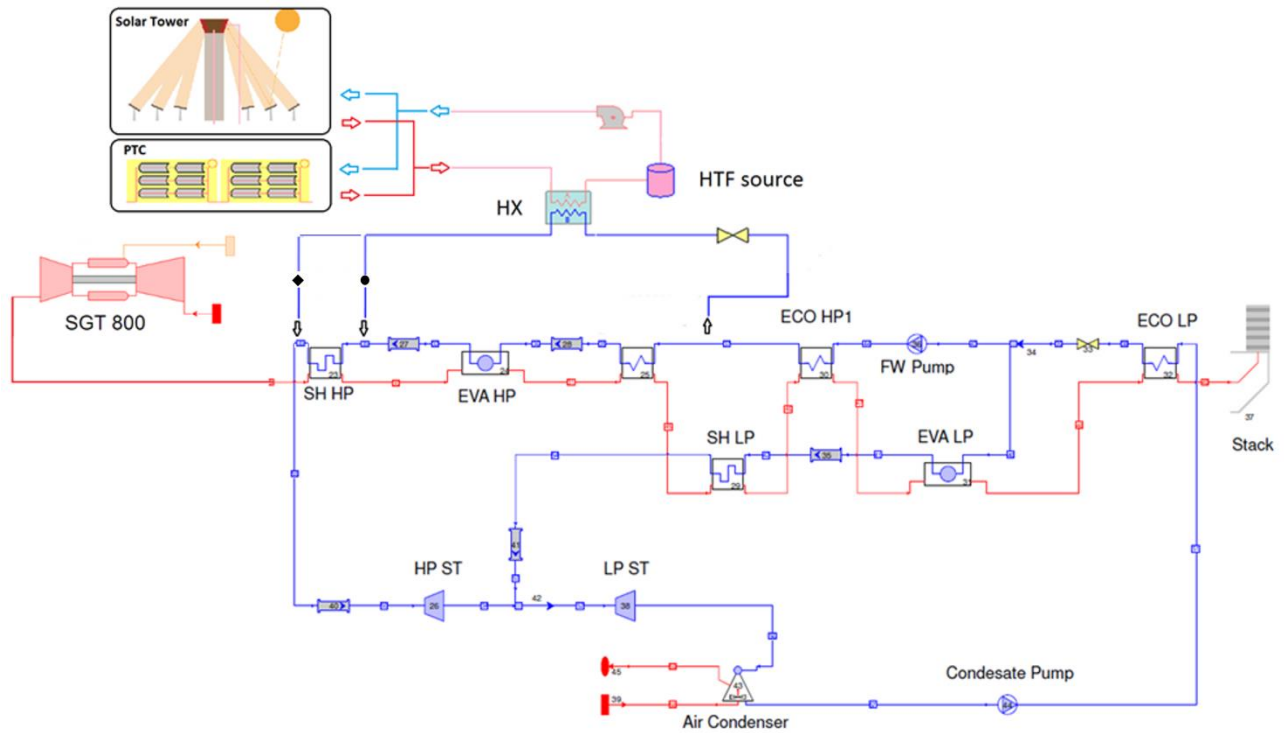


Fig. 3: ISCC layout (screenshot of Thermoflex®).

Design Parameter	Value
GT Power Output (MW _e)	50.5
GT Gross efficiency (%)	37.7
GT Pressure ratio	21.1
GT exhaust gas flow (kg/s)	132.9
GT exhaust gas T (°C)	559.5
HP - LP pressures (bar)	69-7.7
HP - LP SH temperatures (°C)	522– 218
HP - LP steam flow (kg/s)	17.8 – 20.9
Condenser pressure (bar)	0.06
ST Power (MW _e)	22.2
CC net Power Output (MW _e)	70.9
Fuel Consumption (MW _{th})	131.2
CC net efficiency (%)	54.1

Table 1. Design parameters of the CC in fossil fuel operation (ISO conditions).

3. Model setup

Trnsys® with the libraries STEC (developed by DLR) and TESS was used to model the solar field, whereas simulations of the power block were performed by Thermoflex®. Geometrical details of PTCs are summarized in Table 2. The PTC overall efficiency η_{PTC} under actual operating conditions was evaluated as follows:

$$\eta_{PTC} = \eta_{opt} \cdot K - (A + C \cdot V_{wind}) \cdot \frac{(T_{av} - T_{amb})}{I_{beam}} - \varepsilon \cdot B \cdot \frac{(T_{av}^4 - T_{sky}^4)}{I_{beam}}$$

The η_{PTC} formula (where T_{av} , T_{amb} and T_{sky} are the Synthetic oil average temperature, the dry bulb ambient temperature and the effective sky temperature for long wave radiation calculations, respectively, V_{wind} is the wind speed, ε is the absorber emissivity and I_{beam} is the direct solar irradiance) was derived from [10]. The coefficients A, B and C were computed to fit the thermal efficiency curve of Schott PTR70 receivers under standard conditions [11]. The optical efficiency η_{opt} (0.77) is related to the mirror reflectivity, glass transmissivity and receiver tube absorptivity. The incident angle modifier K takes into account the effect of the non-perpendicularity of solar radiation and it is a function of the incidence angle.

Trnsys[®] was also used to model the heliostat solar field (120 m² heliostat surface) and the tower receiver. The heliostat field performance was computed by means of an “efficiency matrix” whose consistency was checked against experimental data by DLR (Fig. 4). The solar tower was modeled in Trnsys[®] by using a typical performance map of a single North-facing cavity receiver. The receiver was simulated as a simple black body absorber including radiative losses. An average mirror reflectivity of 90% was assumed.

The location selected for the present analysis was assumed to have climatic conditions and latitude corresponding to those of Upington, in the Northern Cape province of South Africa. Meteorom database from the Trnsys[®] weather library provided the meteorological data for the daily simulations. Meteorological conditions in terms of ambient temperature (Fig. 5-left) and direct normal irradiation profiles (Fig. 5-right) are reported for the two selected days, chosen as representative of a typical summer and winter day.

Design Parameter	Value
Alignment	North-South
Total collector area (m ²)	100800
Length of single loop (m)	800
Aperture width of single collector assembly (m)	6
Number of loops	21

Table 2. Geometrical and optical parameters of PTCs.

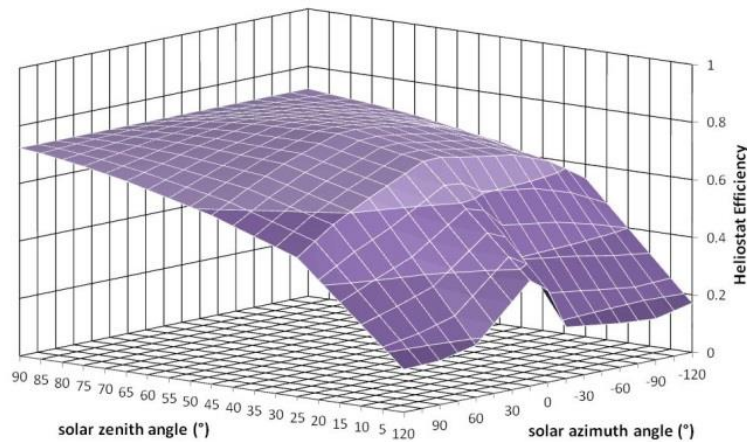


Fig. 4: Heliostat efficiency map.

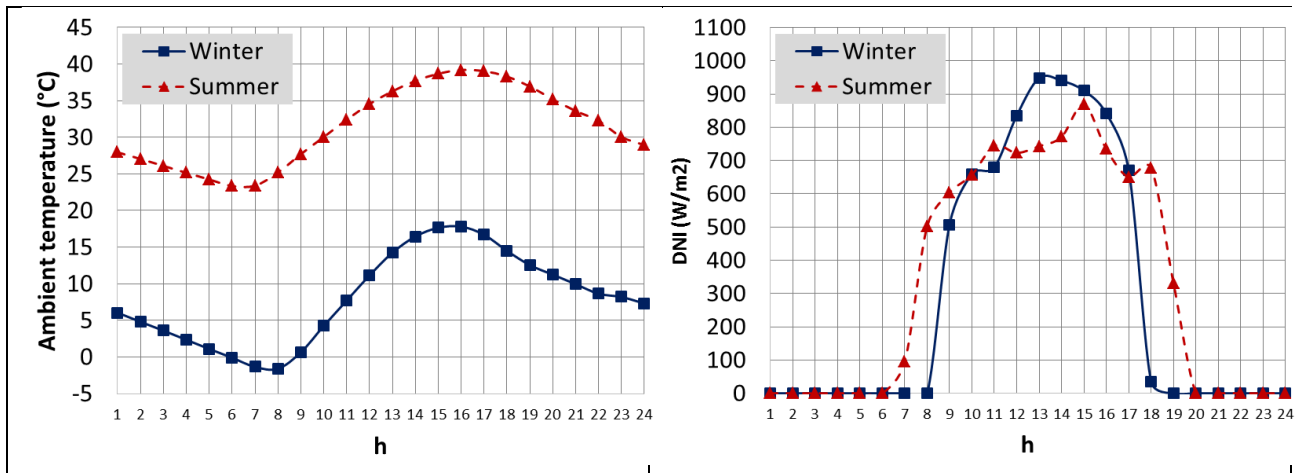


Fig. 5: Ambient temperature (left) and solar irradiation (right) profiles on a summer/winter day.

Hour by hour, the Trnsys[®] model of the solar field provides exit HTF flow rate based on climate conditions. These values are transferred to Thermoflex[®] as an input for the HTF source (see Fig. 3). The modeling of the ISCC plant was carried out according to the following logic:

1. The solar power is given dispatch priority, so the GT load is computed to match the electric demand, including the whole available solar contribution to the total power output.
2. If the resulting GT load is lower than the threshold of 25%, defocusing is admitted to diminish the solar steam entering the HRSG.
3. The new value of the solar steam is computed to match the electric demand, with the GT load imposed at the minimum level of 25%.

4. Results and discussion

As previously mentioned, both solar fields (PTC and CRS) have been sized with the same total aperture area, so they can be compared on an equal basis. Fig. 6 shows the daily profiles of the solar radiation (Q_{sol}) and the effective collected heat (Q_{coll}) transferred to the HTF, during summer and winter days. Fig. 7 reports the hourly solar to thermal efficiency for both CSP technologies. In the summer day, PTCs exhibit a very high solar to thermal efficiency as they intercept a significant amount of the incident solar radiation. Conversely, the heliostat field has to reflect the incident radiation toward the top of the tower: so a reduction of the collected solar energy takes place in the central hours of the day, when sun is approaching the zenith.

In winter, the fraction of solar radiation collected by the CRS significantly increases, whereas the efficiency of PTC dramatically decays, due to cosine effect and low ambient temperature.

Fig. 8 shows, hour by hour, the power production of the ISCC with PTC and CRS solar field, for comparison against the electric demand imposed by the Industrial load profile. Whatever CSP technology and ambient conditions are considered, the ISCC is able to match the electric request. The yellow region highlights the solar contribution to the power output, which is more significant in summer for the PTC case, and winter for the CRS case, in agreement with the aforementioned performance of the two solar technologies.

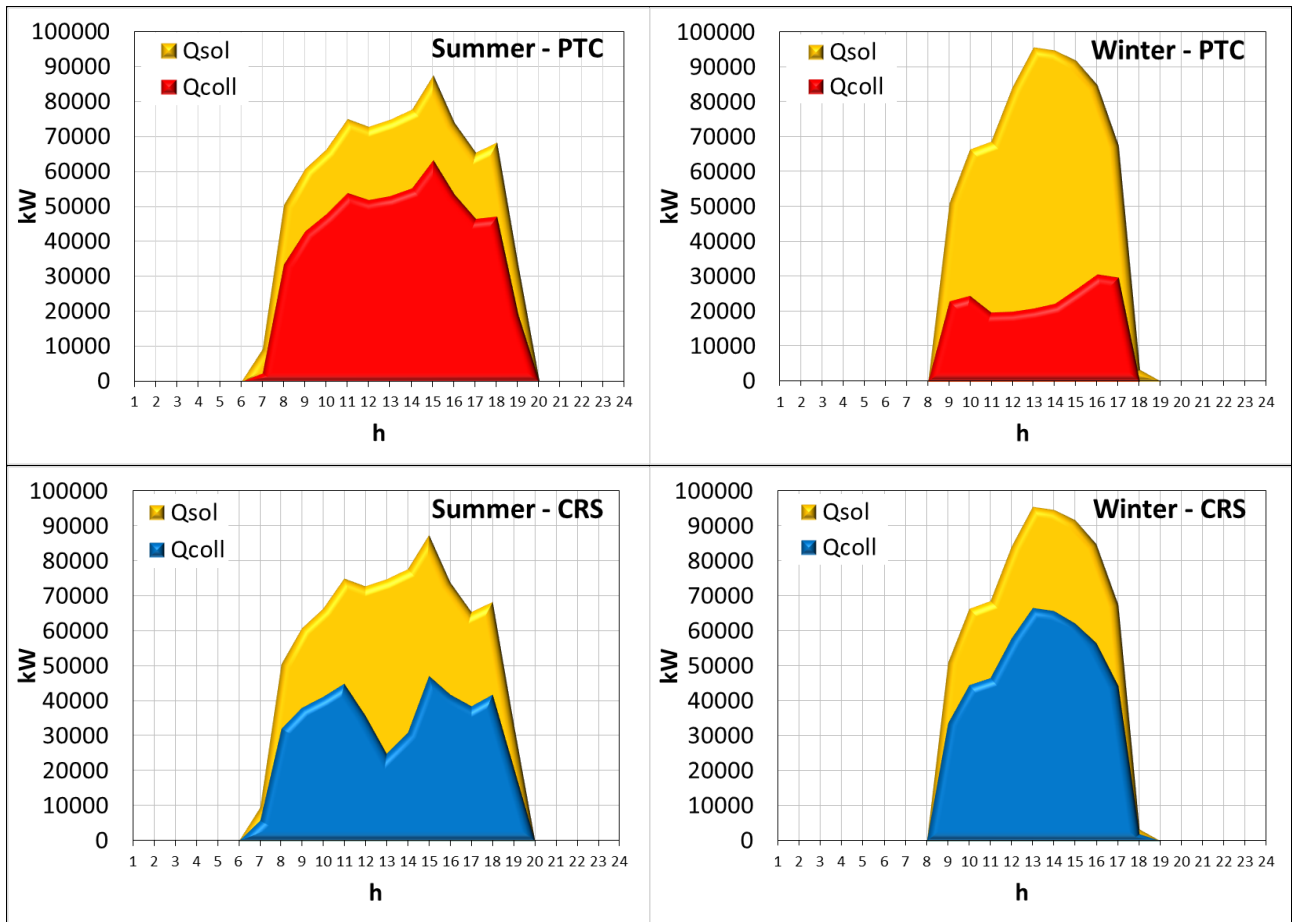


Fig. 6: Hourly solar radiation and collected heat.

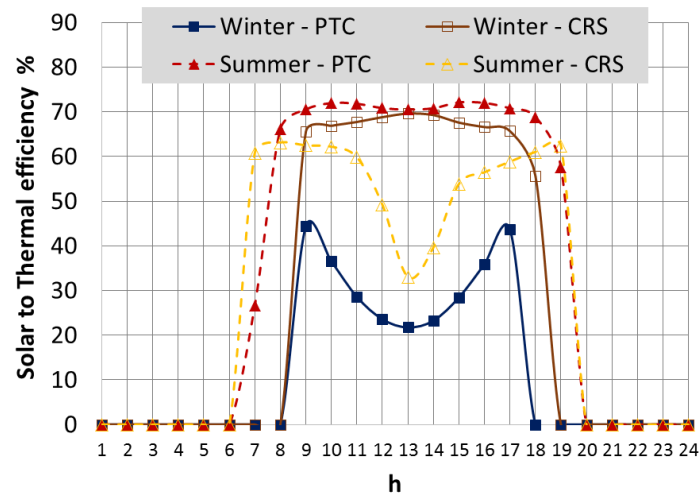


Fig. 7: Solar-to-thermal efficiency for PTC and CRS.

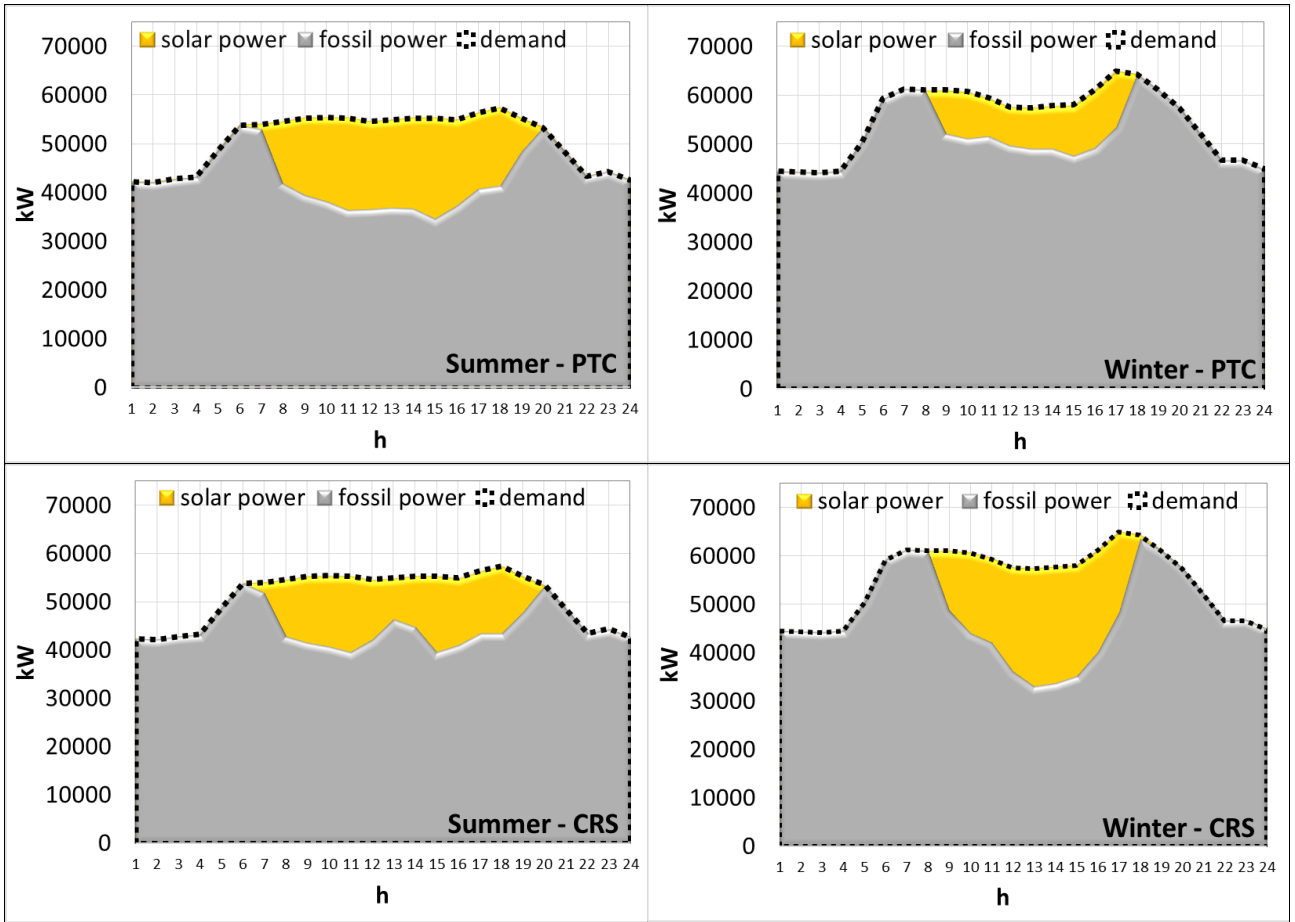


Fig. 8: Fossil and solar contribution to the electricity demand - Industrial load profile.

Since the solar power is given dispatch priority, the GT load is determined so to match hour-by-hour the residual demand, i.e. the grey area labeled “fossil power” (Fig. 8). Consequently, the GT load depends not only on ambient temperature but also on the solar steam production. It can be observed (Fig. 9) that the GT load has a decreasing trend in daylight hours due to solar power, with the exception of the CRS case in summer, when the GT has to compensate for the drastic performance penalty of the solar tower system in the central hours of the day. A reduction in the GT load corresponds to an increase in the ST power output (as a percentage of the ST design rate, 22.2 MW). During the night hours, the ISCC output equals that of a conventional CC, anyway requiring GT turndown as low as 50% of base load. Actually, the pure fossil CC would be able to follow the Industrial load both in summer and winter: this means that the ISCC operation mode is “fuel saver”, according to the definition provided in [7]. Therefore the ISCC gross efficiency increases due to fuel savings when the solar power is available: the peak of 81% gross efficiency occurs around noon time for the CRS case in winter, thanks to a favorable combination of high available DNI (948 W/m²) and high solar to thermal efficiency for the solar tower (70%). In summer, the solar power provided by the PTC technology makes the gross efficiency increase to about 70% in the central hours of the day, whereas, in the same time of the winter day, the gross efficiency stays around 60%. Conversely, during night hours, the ISCC gross efficiency is lower than 55% because of GT efficiency penalty under part load conditions.

The degree of plant hybridization was evaluated by using the solar fraction SF :

$$SF = \frac{Q_{th,sol}}{Q_{th,sol} + Q_{th,fuel}}$$

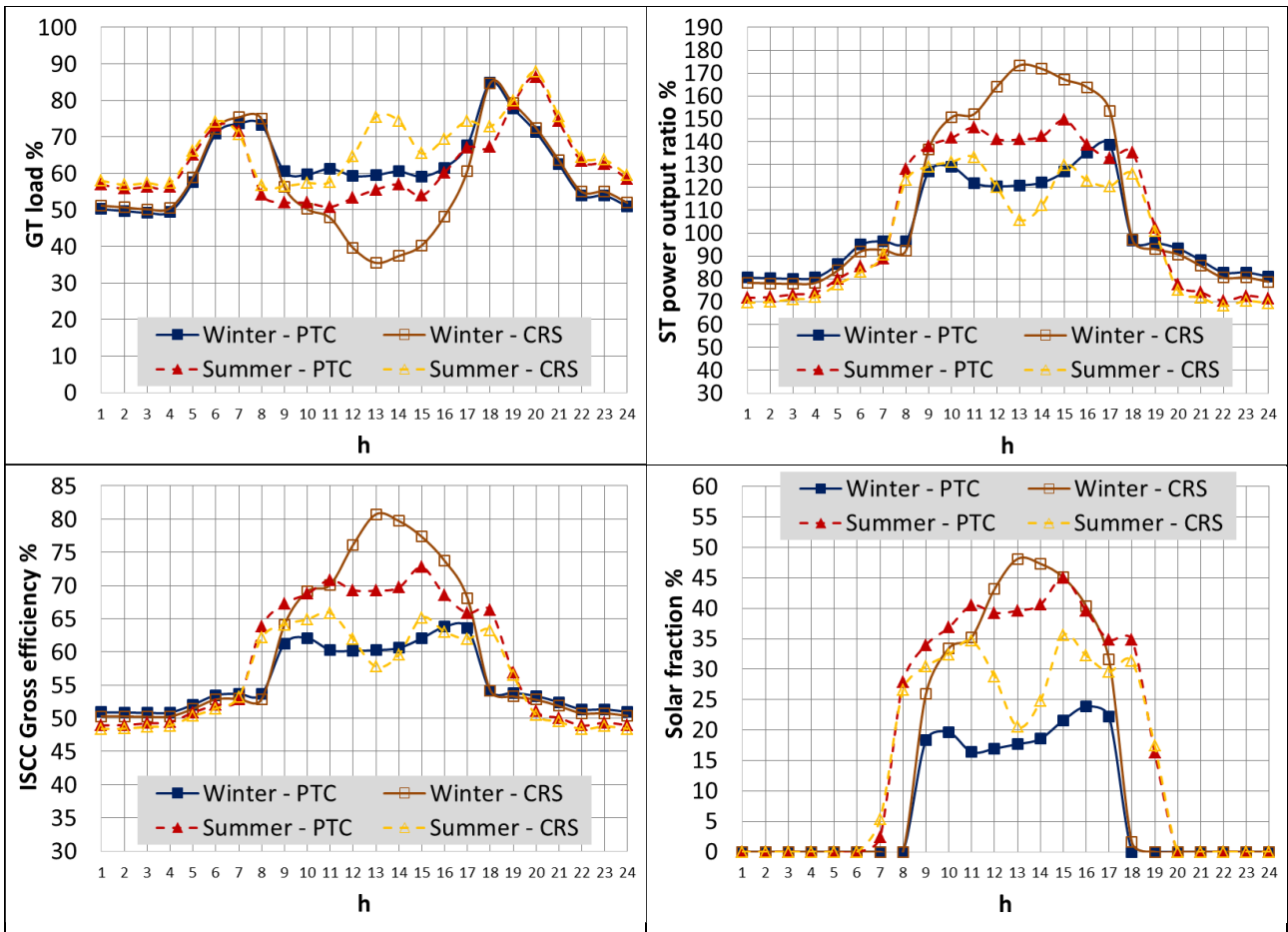


Fig. 9: ISCC performance in load following mode - Industrial profile.

The amount of thermal energy provided by the solar technology ($Q_{th,sol}$) was divided by the total thermal input. During winter daylight hours, the CRS achieves the highest SF of 48% whereas the PTC provides the lowest level of hybridization, with SF even lower than 20%.

Different considerations can be drawn moving to the Domestic load profile (Fig. 10). The peak-load demand occurs in summer, when high ambient temperature negatively affects the GT efficiency and solar radiation is higher. In this case, the ISCC plant can meet the electric demand only thanks to the solar contribution (yellow area). The red line shows the maximum power generation for the GT at full-load, without solarization: for 5 hours in the summer day, the fossil-fired CC could not cover the peak demand. Whatever the solar technology (PTC or CRS), the summer Domestic load profile emphasizes that the solar power can boost the ISCC power output.

In winter, when the daily peak is only 42 MW_e , the solar contribution becomes redundant, mainly for the CRS case, which exhibits a higher solar to thermal efficiency, as documented in Fig. 7. For 7 hours per day, the power production exceeds the electric demand although the GT is operating at minimum load (25%), so some heliostats must be defocused to reduce the steam production (purple area). The PTCs require a very limited defocusing, due to lower efficiency in winter.

The influence of the defocusing strategy on the ISCC performance can be inferred looking at Fig. 11. For the CRS case, the GT load is set at the minimum value of 25% in the central hours of the winter day, when defocusing takes place. This translates into ISCC gross efficiency as high as 71% and hybridization of about 43%, in terms of solar fraction. On the opposite, the GT operation at near full load is required at hour #13 in the summer day, if the CRS is chosen as CSP technology.

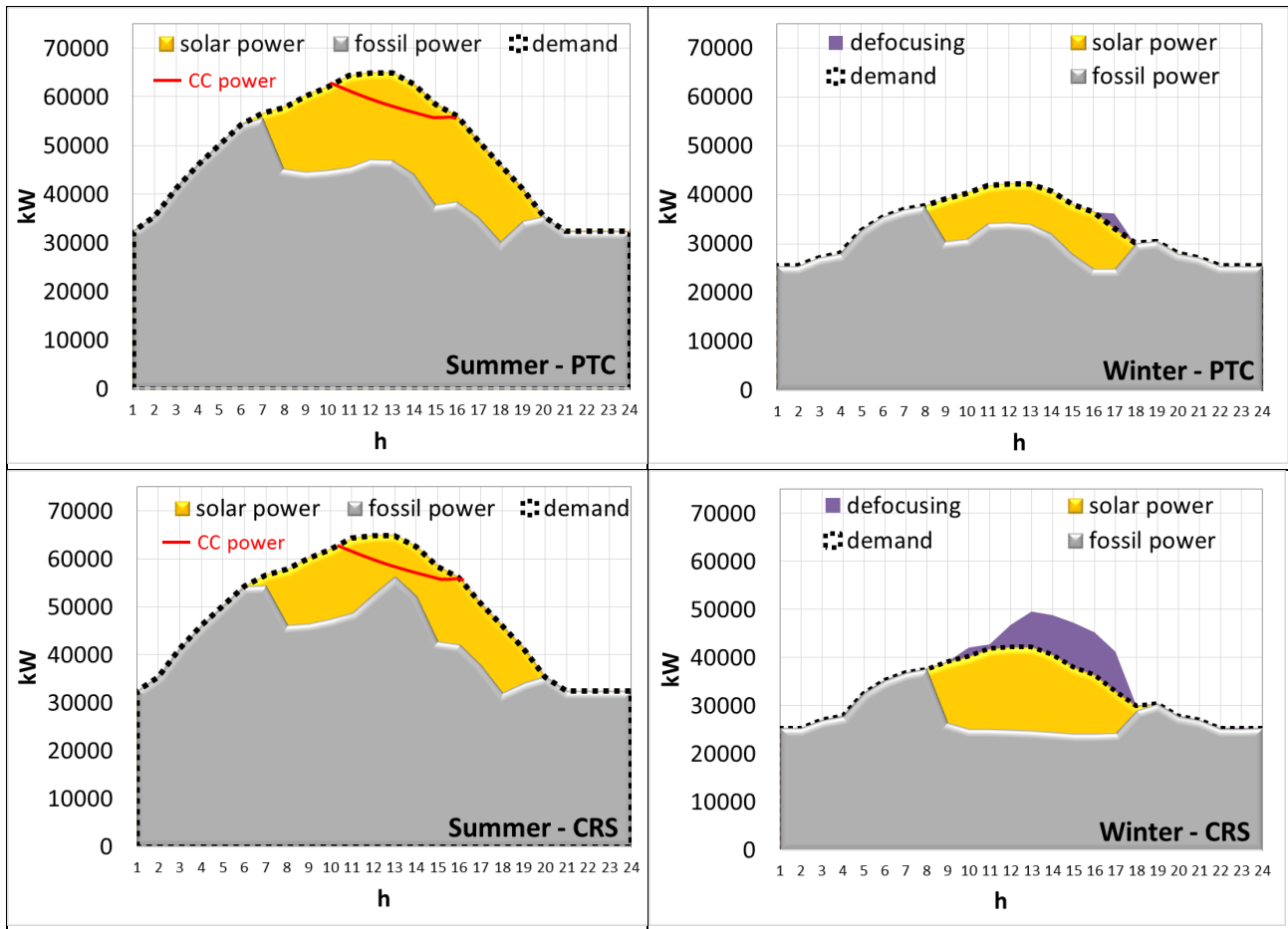


Fig. 10: Fossil and solar contribution to the electricity demand - Domestic load profile.

At that time, the very high electric demand is combined with poor performance of the solar tower so the fossil power is needed at almost full load. As a result, both ISCC gross efficiency and solar fraction show a minimum at 59% and 18%, respectively.

In summer, the solar power provided by the PTC solar field makes the gross efficiency increase to about 70% in the central hours of the day, whereas, in the same time of the winter day, the gross efficiency stays around 60%.

During night hours, GT turndown even lower than 50% of base load is needed to match the demand, with more severe load reduction in winter, due to lower electric request than in summer. As a result, the gross efficiency goes down to the lowest value of about 42%, in winter night hours.

Starting from the hourly simulation results, the average performance of the investigated ISCC configurations have been computed. Table 3 reports the average GT load, the ISCC gross efficiency based on the fossil energy input, the solar fraction and the percentage of defocused solar energy for both load profiles and both solar technologies (PTC vs. CRS). The reference CC without solarization is reported as well. Looking at the Industrial load case, the solar contribution allows for increasing the CC gross efficiency from 51.7% up to over 57%, with a solar fraction of 14.7% and 17.1% for PTC and CRS, respectively. Concurrently, the average GT load decreases from 72.6% down to 61.7%.

For the Domestic load case, it has to be reminded that the non-solarized CC plant is not able to meet the electricity demand for some hours in summer. With respect to the Industrial load case, ISCC gross efficiency is slightly lower (less than 54%), due to the significantly lower GT load. The solar fraction is higher than 17% for both the solar fields, but the ISCC plant with CRS requires 14.7% defocusing of the available solar energy.

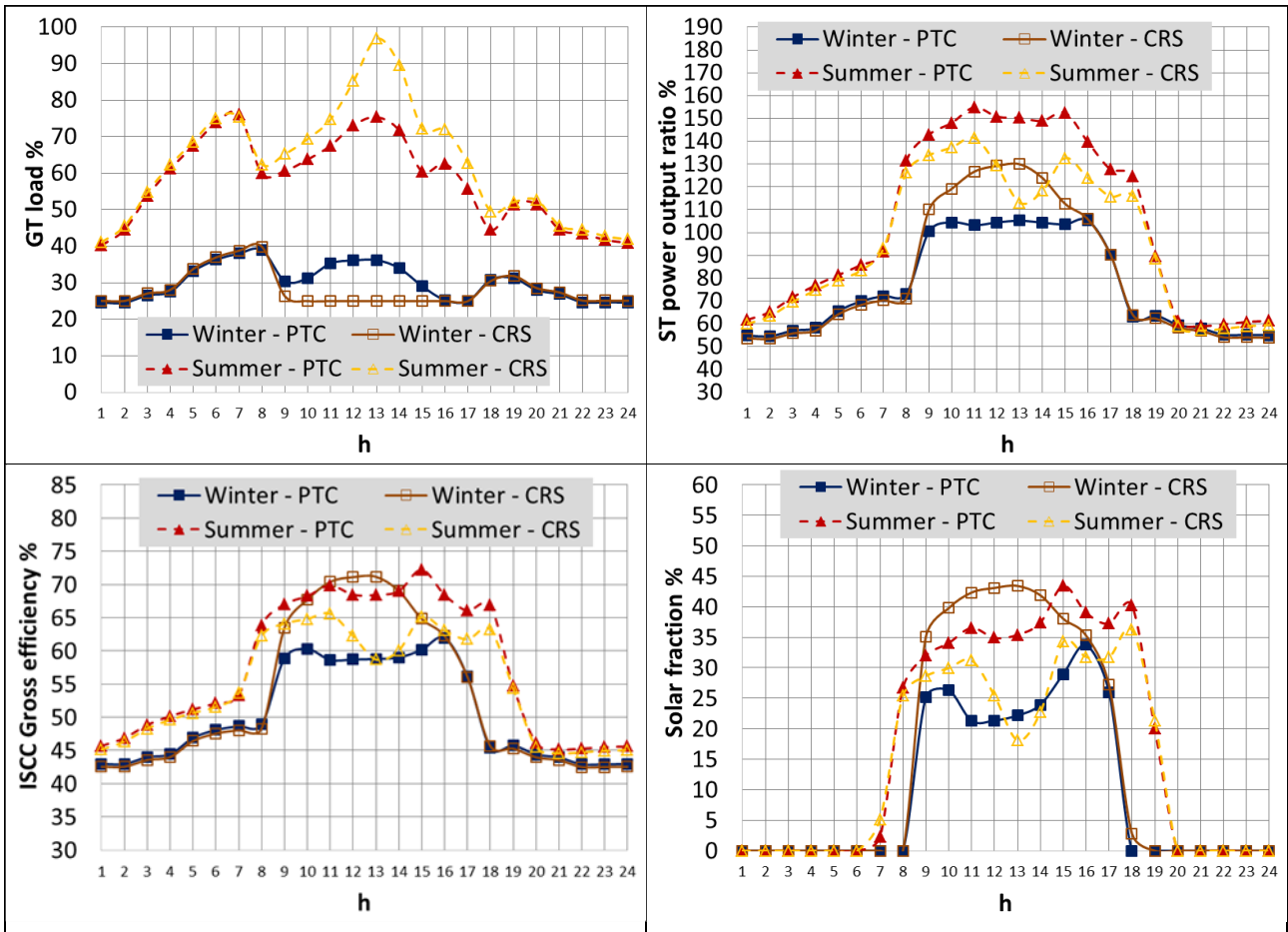


Fig. 11: ISCC performance in load following mode - Domestic profile.

	Industrial load			Domestic load		
	PTC	CRS	CC	PTC	CRS	CC*
GT load %	61.7	61.7	72.6	43.9	45.4	53.4
ISCC Gross efficiency %	57.2	57.8	51.7	53.9	53.8	48.0
Solar fraction %	14.7	17.1	--	17.5	17.7	--
Defocusing %	--	--	--	1.1	14.7	--

* electric power imbalance

Table 3. ISCC average performance.

5. Conclusions

The load following capability of an ISCC, coupled with PTC or CRS, has been assessed under daily patterns of electric demand resembling two different profiles, i.e. Industrial vs Domestic profile. Simulations of the ISCC configurations were carried out for climate and latitude corresponding to Uppington, in a typical winter/summer day. The solar power was given dispatch priority. Defocusing was admitted in case of overcapacity, with the minimum GT load imposed at 25% of rated power. Simulation results demonstrated that both the investigated ISCC configurations are suitable for load

following operation, with a significant fossil-free electricity production positively affecting the gross efficiency. The price paid for the load following mode is the GT partial load operation. To sum up, the Industrial demand was matched thanks to a “fuel saver” ISCC operation mode, meaning that the fossil power is replaced by the solar power, during day light hours. On the other hand, the solar power was necessary to boost the ISCC electricity output, in addition to the fossil power, in order to match the high demand of the Domestic profile, in summer.

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