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Integrated Solar Combined Cycle Using Particles as Heat Transfer Fluid and Thermal Energy Storage Medium for Flexible Electricity Dispatch

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Abstract. In this work, it is investigated about the application of an Integrated Solar Combined Cycle (ISCC) that uses particles as heat transfer fluid at the receiver and as the storage medium to provide flexible electricity dispatch without any supplementary gas burning. The paper investigates two cornerstones' of concentrating solar power technologies (CSP); i.e., the application of highly efficient power cycles and the ability to meet grid demand throughout flexible dispatch strategy. Using particles for the solar loop allows meeting both requirements at the same time. On the one hand, very high temperature can be achieved on the solar receiver which enables the use of highly-efficient power cycles according to thermodynamics second statement. On the other hand, particles ease for handling and storage makes them suitable for thermal storage at CSP applications which results into flexible electricity dispatch of the power block. Results shown in this paper prove the feasibility of flexible electricity dispatch of particles-based ISCC following real curve demand.

INTRODUCTION

It is widely known that technological, scientific and social progress together with the general improvement of the quality of life is tightly bounded to extensive energy consumption. In this context, primary energy demand keeps growing rapidly and the forecast from the World Bank is showing a drastic increase in the global demand for energy supply. Experts are warning that projections on electricity demand will increase by roughly 100% by 2050 compared to the levels of year 2000 [1,2].

Renewable energy becomes crucial to satisfy the ever-growing electricity demand and at the same time reducing the environmental impact and the dependency on fossil fuels. Despite commercial maturity of *non-dispatchable* renewable energy sources such as photovoltaics and wind technologies, their capacity is not always available and the electricity generation becomes highly dependent on the time of the day and the weather. These fluctuations in generation become a challenge for the grid management. For that reason, it becomes mandatory increasing the presence of renewable energy sources with flexible dispatch. In particular, *Concentrating Solar Power or CSP* is one of the most suitable candidates for flexible electricity dispatch since it allows for massive and non-expensive thermal energy storage (TES). Wise design of TES systems and plant operation strategies allow for decoupling the energy harvesting of the solar field from the electricity production on the power block. That issue improves grid stability and allows for power plant operation extension even after sunset or during cloudy events[3].

Lot of experience has been gained over the last few decades about the operation of commercial CSP plants, mainly using parabolic trough technology and more recently molten-salts towers. Despite good performance of both technologies, figures are showing that CSP technologies are still expensive in terms of levelized cost of electricity (LCOE) compared to photovoltaics and wind[4]. There are different ways to improve cost competitiveness of CSP technologies; one of the typical approaches is to improve the efficiency of each component of the solar plant.

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Based on thermal nature of CSP technology, increasing the working temperature of the power block would boost power cycle efficiency. Nevertheless, the main constraint on CSP plant efficiency is imposed by maximum operating temperature of the heat transfer fluid (HTF). For solar tower plants, molten salts are used as HTF and the working temperature is currently limited to approx. 565 ºC on the receiver and in turn imposes the steam Rankine cycle as the most efficient solution for the power block.

In Next-CSP concept, dense particle suspension (DPS) is used as HTF for the receiver and solid particles as storage medium instead of commercial molten salt. This enables to reach working temperatures above 800 ºC [5] which in turns will lead to higher energy density of the TES system and implement higher-efficiency thermodynamic cycles[6–8]. Apart from highly efficient energy conversion of the power block, particles use as storage medium facilitates flexible strategies for TES discharge which turns into flexible electricity dispatch. In particular, two electrical dispatch scenarios for particles-based ISCC are analyzed in this work; (i) 5 hours of nameplate capacity during the evening demand peak; (ii) 6 hours of flexible dispatch following real grid demand curve, this production is divided into 2 hours for the morning demand peak and 4 hours for the evening demand peak. ISCC plant performance is evaluated under both dispatch strategies in terms of annual production, amount of particles stored by the end of a day, operation hours of the power block or sun-to-electricity efficiency.

PLANT LAYOUT DESCRIPTION

Figure 1 shows the basic layout of Next-CSP plant that uses dense particles suspension (DPS) as heat transfer fluid (HTF) and solid particles as storage medium. The main sub-systems of the plant are (i) the heliostat field and particles receiver, (ii) the storage tanks and a series of heat exchangers that are connecting the solar-loop to the topping air Brayton cycle[9] and (iii) the power cycle itself. In addition, auxiliary subsystems involving particles elevation to the receiver and transportation from/to the receiver towards the storage tanks are considered.

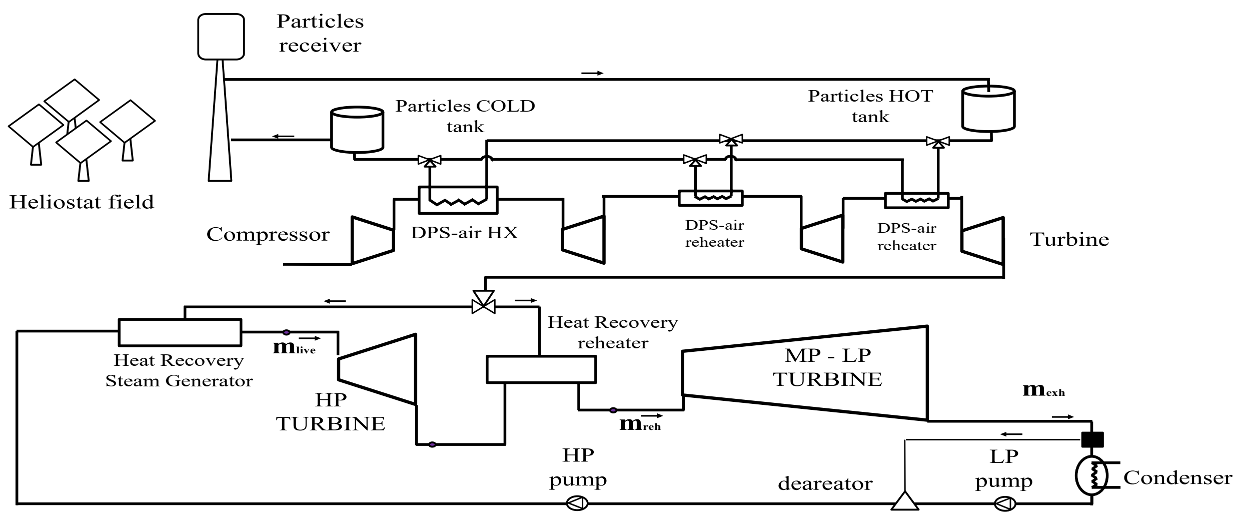


FIGURE 1. Next-CSP power plant layout

Integrated Solar Combined Cycle (ISCC) has been optimized based on particles working conditions predicted from experimental testing which determined that 825 ºC was the maximum temperature of particles leaving the receiver[10]. That resulted into relatively low temperature of the topping cycle (800 ºC) and the need for double reheating configuration for the Brayton cycle and single reheating for the Rankine in order to maximize conversion efficiency without supplementary firing. Most relevant design conditions of the ISCC can be found in Table 1.

TABLE 1. Power plant operating conditions at design point

Topping cycle		Bottoming cycle	
HP inlet pressure	14.3 bar	HP inlet pressure	160 bar
MP inlet pressure	6.1 bar	MP inlet pressure	20 bar
LP inlet pressure	2.5 bar	HP inlet temperature	585 ºC
HP – MP – LP inlet temperature	800 ºC	MP inlet temperature	575 ºC
Power plant		**Solar plant**	
Net power output	175 MW_e	Location	Ouarzazate, Morocco 30.9°N, 6.93°W
Net power block efficiency	49.4 %	Receiver outlet temperature	825 ºC

The main target of Next-CSP solar power plant concept is to maximize overall conversion efficiency to reduce electricity cost reduction. In order to do so, it is mandatory to improve the efficiency of each plant component (solar field, solar receiver, particles-based heat exchangers and power cycle). In order to maximize central receiver efficiency cavity configuration would be preferred (lower thermal losses). However, large electrical power output of the plant (175 MW_e) makes it not feasible for single cavity receiver. Instead, multiple solar fields and central tower configuration are decided in order to maximize receiver efficiency. Multiple solar fields of 75 MW using Stellio heliostat[11] have been conceived what resulted into 55 MW reaching the receiver aperture.

TABLE 2. Solar plant design point conditions

Solar Field		Solar Receiver	
Power incident on field	75.5 MW	Power onto aperture	55 MW
Number of heliostats	1731	Absorbed thermal power	44 MW
Heliostats area	49 m^2	Thermal efficiency	79.4 %
Design day	noon 21st March	Tubes height	7 m
Design DNI	900 W/m2	Number of tubes	240
Tower optical height	110 m	Particles inlet temperature	606 ºC
Aperture tilt angle	30º	Particles mass flow	165 kg/s
Aperture incident flux	2000 kW/m^2	Receiver average flux	500 kW/m^2

POWER PLANT CONTROL STRATEGY

Considering current complexity of electrical grid management produced by the large penetration of non-dispatchable renewable energies it has been decided that the power plant will not operate for baseload production. In addition, marginal cost for daytime production is almost zero in regions with high penetration of photovoltaics. For this reason, flexible electrical dispatch has been considered to maximize electricity selling during high-price hours (peak hours). Based on modular concept of Next-CSP plant and flexible management of particles-based storage system, multiple electricity dispatch strategies could be analysed. In particular, it has been decided to analyse 6 solar field plant configurations as the one shown in Figure 2. As it can be deduced from that figure, there are 6 identical solar fields and receivers as the one described in Table 2. Particles transportation system is used to connect each solar tower to centralized TES system, particles network heat exchangers and power block. Regarding the electrical dispatch of the power plant, two strategies are analysed:

- Constant power dispatch during the evening peak-load (from 5 pm to 10 pm) considering 30 minutes of ramp-up and down from idle to full load conditions.
- Variable power dispatch following grid demand during morning demand peak (from 9 am to 11 am) and evening peak (from 5 pm to 9 pm).

In both cases, electricity generation and solar energy harvesting are decoupled; the power plant operates as follows; sunlight is collected and diverted by heliostat field towards the solar receiver. There, dense particle suspension absorbs thermal energy according to bubbling fluidized bed technology[12].

Hot particles are sent to tanks where they are stored as bulk. Whenever it is needed, hot tank is discharged and hot particles transfer their heat to power cycle air using a dedicated particles heat exchanger[13]. In case that thermal energy stored as hot particles would be higher than needed for electricity generation, remaining hot particles will be kept at TES till the next day. In case that thermal energy stored as hot particles would not be sufficient to satisfy daily electricity generation (according to the dispatch strategy), power generation will be stopped once tanks are discharged.

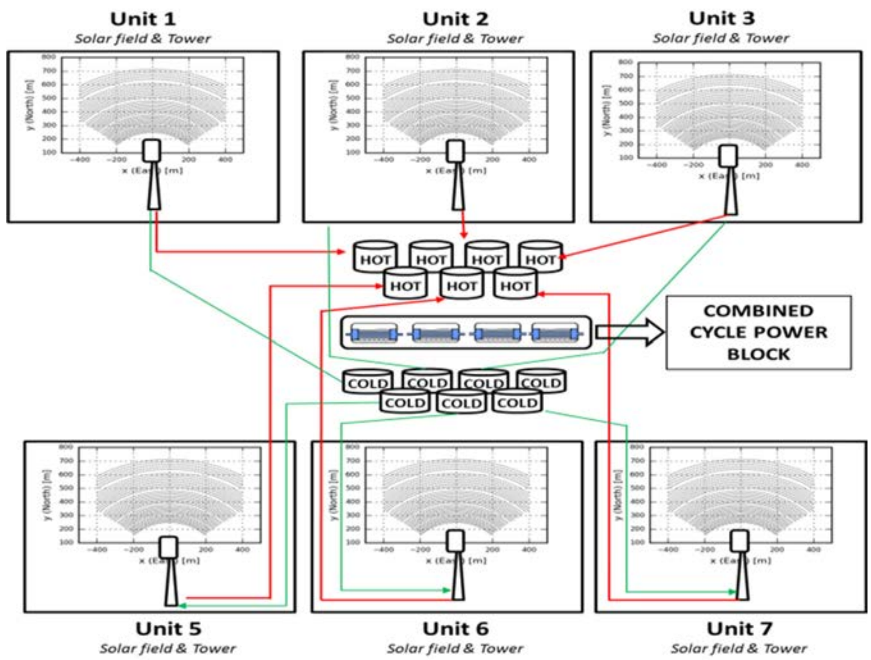


FIGURE 2. Multi-tower solar plant configuration layout

Working Conditions Input

In this section, modelling boundary conditions for the solar power plant are presented. Figure 3 shows instantaneous DNI for solar plant location while black series represents instantaneous electric demand. Grid demand has been derived from smart-meters information and is representative from Mediterranean area.

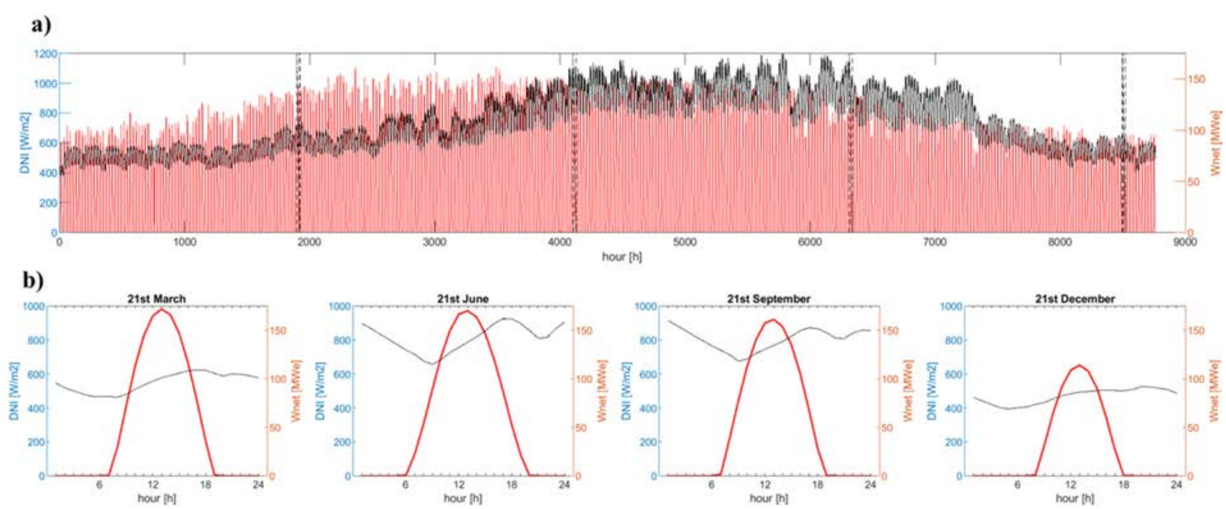


FIGURE 3. Modelling inputs; solar DNI (in red) and electricity demand (in black). **(a)** Annual data, **(b)** relevant days

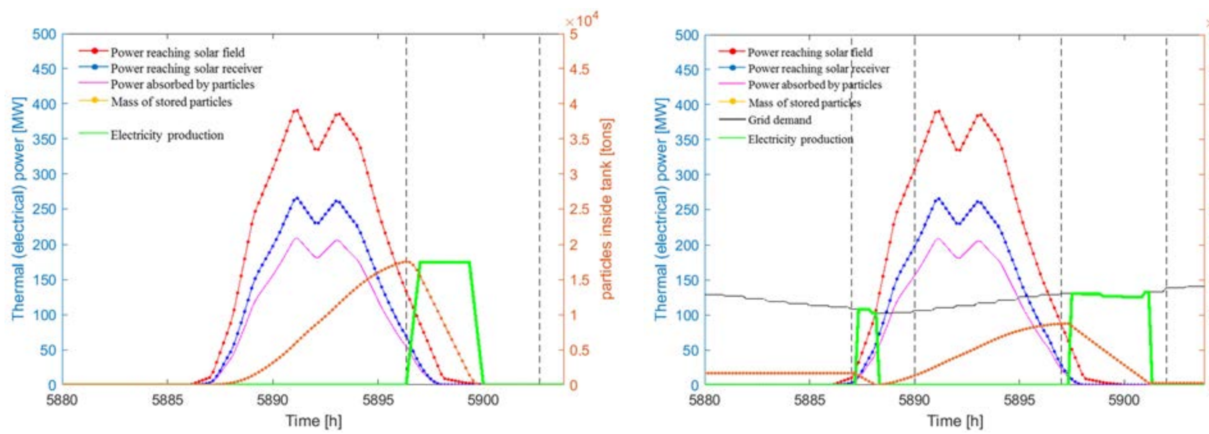
RESULTS ANALYSIS

In this section, results analysis of the Next-CSP plant modelling is presented for both dispatch strategies (constant and flexible power output). Modelling results are shown on a daily-basis, annual-basis and accumulated in the following subsections.

Daily Operation Analysis

Figure 4 represents solar field, solar receiver, power block and thermal storage performance for (246th day of the year - 3rd of September). As it can be deduced, energy harvesting and electricity production are decoupled since power cycle operates using thermal energy stored as hot particles (orange curve) while red curve represents the total power reaching the solar field and the blue curve the power reaching the solar receiver. Ratio between both curves stands for instantaneous solar field efficiency while pink curve represents thermal power absorbed by particles inside solar receiver. Green curve shows electricity power output of the power block and black line instantaneous grid demand (only for flexible dispatch case shown in Fig.4-b) while dashed vertical lines indicate desired dispatch strategy.

For the case of evening peak electricity dispatch strategy (Fig.4-a), storage tanks need to be sized taking into account that the electricity production will start once the solar radiation is getting down (from 5 pm) and therefore should contain hot particles for the whole day. However, for the two-period dispatch strategy case (Fig.4-b), peak production in the morning (from 9 am till 11am) significantly reduces the amount of hot particles stored from the previous day (mainly during summer period) and energy harvested during first hours of the day. As it can be observed on Fig.4-b, TES tanks were not emptied at the beginning of the day what means that from previous day there was an excess of thermal energy stored as hot particles. However, particles stored from previous day are used to generate electricity from 9 am according to the dispatch strategy. Despite the increasing solar radiation from 9am onwards and the existing stored particles, thermal energy is not enough to keep power production during morning peak for that day.



(a) constant power output

(b) following grid demand

FIGURE 4. Power block dispatch strategy. (a) Daily operation for constant power dispatch strategy. (b) Daily operation for two-periods of variable demand dispatch strategy.

Annual Operation Analysis

In this section production annual results are shown for both control strategies. Results are presented in terms of hour of the day (y-axis) and day of the year (x-axis) with a colour map that is representing the parameter under study. As it can be observed from Fig.5-a, during winter months there is not enough thermal power from the solar field to dispatch 5 hours of constant power output. It can be noticed as well part-load operation of the power block during the ramp-up (before 5pm) and ramp-down (after 10pm or whenever TES tanks are at its minimum capacity).

As it can be observed from Fig.5-c, particles tanks are emptied by the end of the day during the whole year under proposed dispatch strategy and solar plant sizing. Even during summer months, tanks are emptied and production target cannot be fully covered. As it was mentioned above, energy harvesting and power production are decoupled what can also be observed on Fig.5-c where the maximum amount of stored particles occurs by 5pm just when name-plate capacity starts. From that amount of particles, TES tanks sizing for bulk storage can be deduced.

Fig.5-b and Fig.5-d show power plant operation under 2-times period strategy following electric grid demand. As it can be observed, during winter months, solar input is lower and also less hours of sunlight. Despite the electric demand is lower too, the power block is not able to satisfy the electric demand and the tanks remain empty during the day. Even there are not enough hot particles to produce electricity during the morning production period. However, during spring months the solar input and the electric grid demand were moderated as it was observed on Fig.3. That resulted into an excess of thermal power that was kept as hot particles at tanks as it is observed on Fig. 5-d. It can be noticed that the maximum amount of particles stored still occurred around 5pm when evening peak production begins. As it can be observed, hours of electricity production are totally covered during spring months and extra particles are stored. In fact, the amount of particles stored under two-period flexible dispatch strategy is twice the ones stored under constant power output strategy what will result into twice TES tanks size.

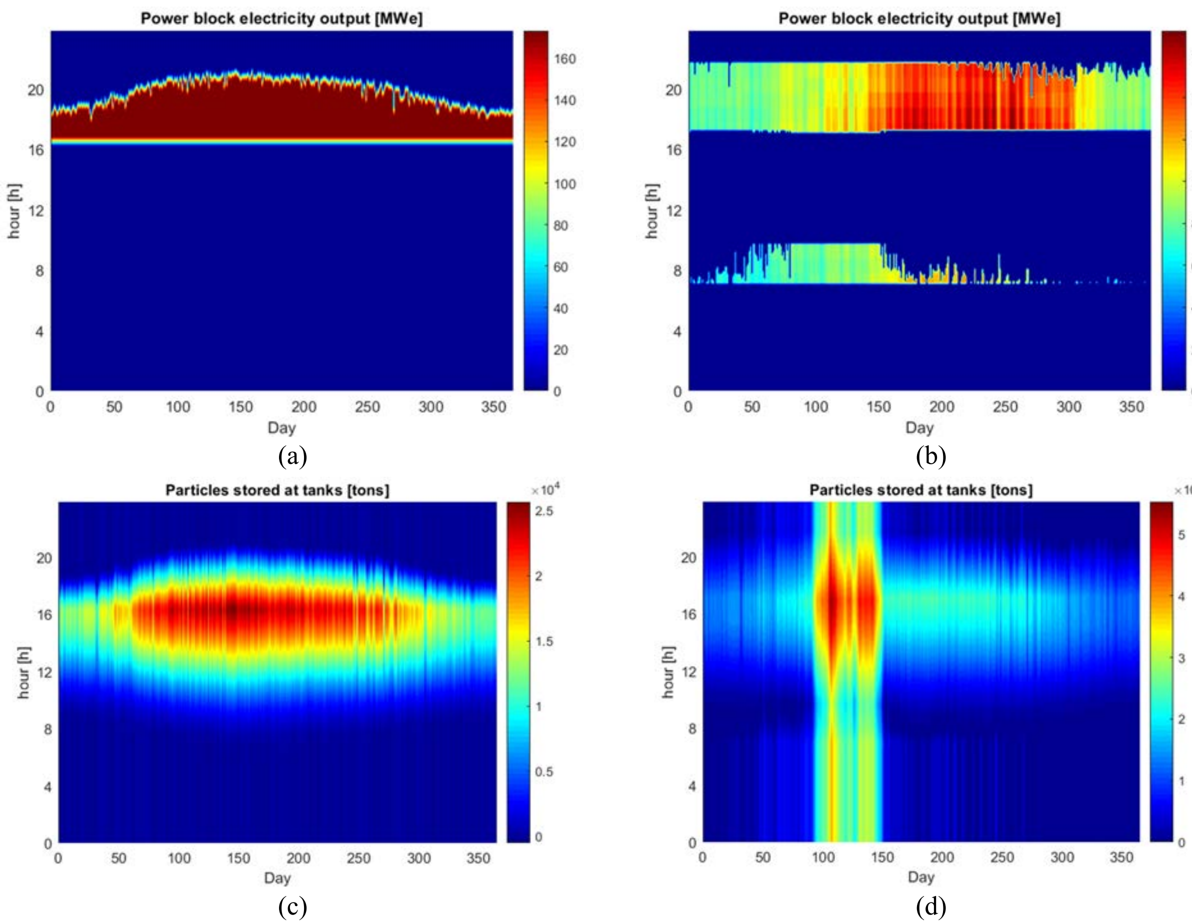
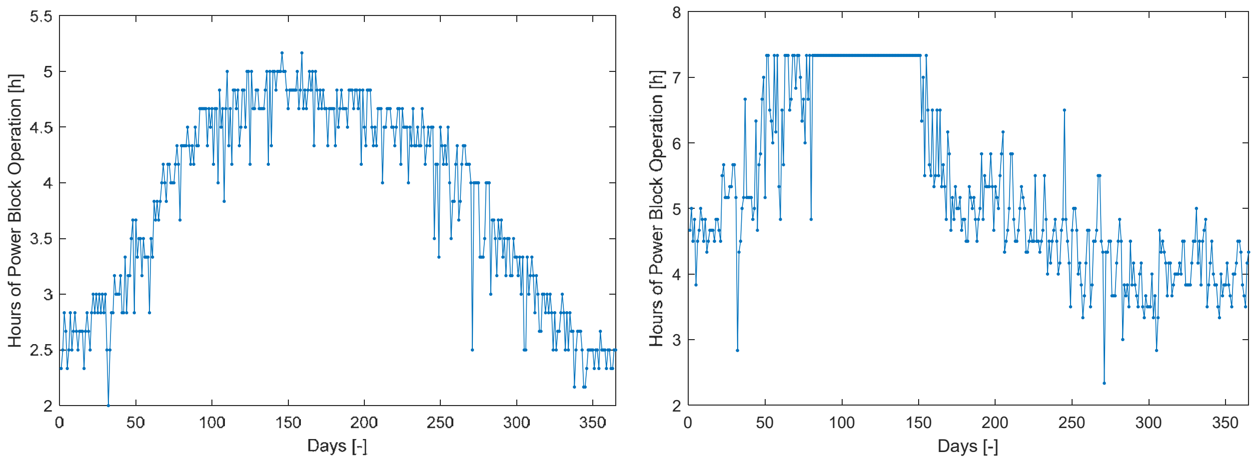


FIGURE 5. Power plant annual production. (a) Electrical dispatch strategy for constant power output (MWe). (b) Dispatch strategy for two-periods of variable demand output (MWe). (c) Particles stored at tanks (tons) for constant power output strategy. (d) Particles stored at tanks (tons) for two-periods variable demand.

Previous information can be translated into hours of power block operation that are shown in Figure 6 for both constant power output strategy (a) and two-period flexible dispatch (b).

As it can be observed, under constant power output strategy (Fig.6-a), power block operation varies from 2.5 to 5 hours per day depending on the period of the year. Its maximum is reached by the end of the spring and beginning of summer coinciding with the largest amount of stored particles.

Under two-period power output strategy, the power block can operate longer than 7 hours (including ramp-ups and downs) per day during spring months (between day 90th and day 150th). That is represented as a flat curve on Fig.6-b. Indeed, there is an excess of thermal power that is stored as hot particles and that cannot be used during those days as it can be derived from Fig.5-d.

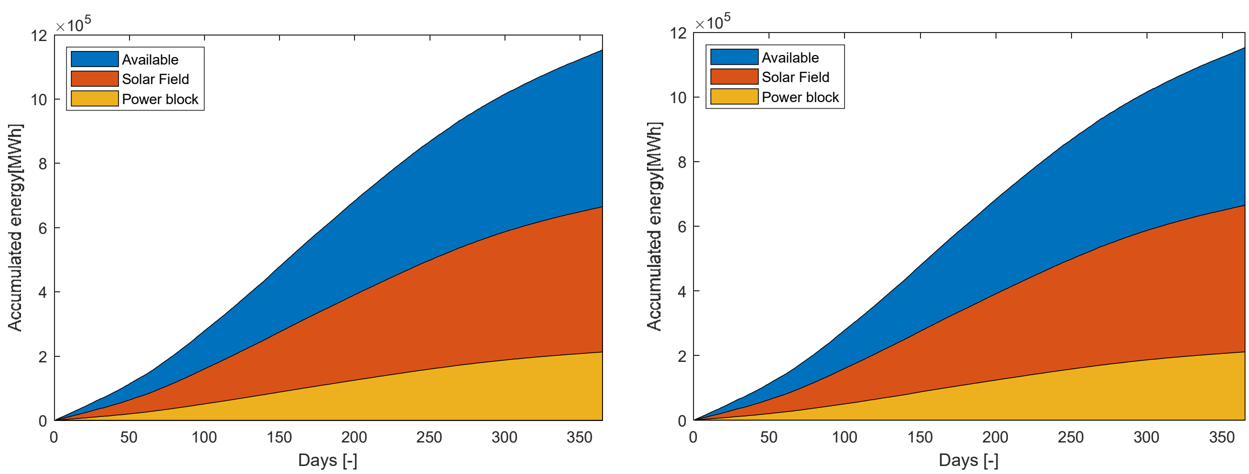


(a) (b)

FIGURE 6. Hours of power block operation. (a) Constant power output strategy. (b) Two-period flexible dispatch strategy.

Accumulated Results Analysis

Detailed results from daily simulations (like the ones shown in Figure 4) have been taken and shown in Figure 7 as the accumulated energy production of the power cycle (named as power block and indicated in orange color at the bottom of the plot). In blue it is marked the total solar energy reaching the heliostat field (blue sector named as available) and the red sector in the middle (solar field) indicates the energy that departing from the solar field reaches the central receiver.



(a) (b)

FIGURE 7. Accumulated annual energy production (MWh). (a) Constant power output strategy. (b) Power output following 2 periods demand.

As it can be observed on Table 3, accumulated electricity production of the plant (yellow sector) is fairly the same at the end of the year under both strategies since the solar field and solar receiver were the same in both cases. The lower accumulated energy production for the two-period flexible strategy is due to the ramp-up and downs for both production periods. Annual capacity of the solar plant can be calculated taking into account the number of hours that the power block can cover the electricity demand. As it can be observed, for constant output strategy plant capacity is close to 14% while for two-period flexible dispatch it increases up to 23%. Sun-to-electricity efficiency has been determined using accumulated data from the electricity production of the power block (orange section in Fig.7) and the accumulated solar energy reaching the solar field (blue section in Fig.7). As it is gathered on Table 3, sun-to-electricity efficiency is above 18%. That value takes into consideration the different losses and irreversibilities of solar plant components (solar field, particles receiver, storage tanks, particles-based heat exchanger) and power block (pumps, compressor, turbines) during transient behavior.

TABLE 3. Modelling summary results

Parameter	Units	Constant output strategy	Two-period flexible strategy
Accumulated electricity production	GWh	212.8	211.3
Annual plant capacity	%	13.88	22.95
Total hours of electricity dispatch	h	1398	1941
Averaged sun-to-electricity efficiency	%	18.44	18.32

CONCLUSIONS

In this work, it has been investigated about the dispatch strategy of particles-based combined cycle power plant. Two dispatch strategies have been considered for production studies; (i) constant power output dispatch during the peak evening period (5 hours) and (ii) flexible power output during morning and evening periods (7 hours in total). In both cases, the solar power plant was optimized for maximum conversion efficiency on design point (21st March). That was translated as large thermal energy stored as hot particles during spring days (high solar irradiation with moderated electric demand) mainly under two-period flexible dispatch strategy. Results analysis shown that ISCC plant can follow different dispatch strategies and achieve annual sun-to-electricity efficiency above 18%.

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