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# High performance integrated solar combined cycles with minimum modifications to the combined cycle power plant design

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The integration of solar energy into natural gas combined cycles has been successfully demonstrated in several integrated solar combined cycles since the beginning of this decade in many countries. There are many motivations that drive investments on integrated solar combined cycles which are primarily the repowering of existing power plants, the compliance with more severe environmental laws on emissions and the mitigation of risks associated with large solar projects. Integrated solar combined cycles are usually developed as brownfield facilities by retrofitting existing natural gas combined cycles and keeping the existing equipment to minimize costs. In this work a detailed off-design model of a 390 $MW_e$ three pressure level natural gas combined cycle is built to evaluate different integration schemes of solar energy which either keep the equipment of the combined cycle unchanged or include new equipment (steam turbine, heat recovery steam generator). Both power boosting and fuel saving operation strategies are analyzed in the search for the highest annual efficiency and solar share. Results show that the maximum incremental power output from solar at design solar irradiance is limited to 19 $MW_e$ without modifications to the existing equipment. Higher values are attainable only including a larger steam turbine. High solar radiation-to-electrical efficiencies in the range 24–29% can be achieved in the integrated solar combined cycle depending on solar share and extension of tube banks in the heat recovery steam generator. Compared to power boosting, the fuel saving strategy shows lower thermal efficiencies of the integrated solar combined cycle due to the efficiency drop of gas turbine at reduced loads. Without modifications to the existing equipment the maximum solar share of the total generated electricity is only about 1%.



## 1. Introduction

Several integrated solar combined cycles (ISCCs) are in operation all around the world (North Africa, Iran, Italy, USA) and many projects are underway (Mexico, China, USA), as reviewed in [1]. ISCCs offer many advantages compared to solar thermal power plants, primarily associated with the higher solar energy conversion efficiency and the lower investment costs [2]. Investors and owners are attracted by the mitigated risk associated with the construction of smaller solar fields compared to solar thermal power plants [3].

Many papers have appeared since the late nineties [4] about the thermodynamic analysis of ISCCs focusing on the optimum integration point of solar energy into the combined cycle. Kelly et al. [5] demonstrated that the most efficient way for converting solar thermal energy into electricity is to withdraw feed water from the heat recovery steam generator (HRSG) downstream of the last economizer, to produce high pressure saturated steam and to return the steam to the HRSG for superheating and reheating. Rovira et al. [6] end up with the same conclusion finding that the highest incremental solar thermal-to-electrical efficiency (44.6%) is achieved when solar heat is used for the evaporation process and eventually for superheating, but not for preheating feed water. Li and Yang [7] proposed a novel ISCC where both high and low pressure saturated steam are generated from solar to increase the solar share. This system was found to reach high solar radiation-to-electric efficiency (up to 30%) due to the improvement of the thermal match in the HRSG. Montes et al. [8] considered a 50 $MW_{th}$ hybridization size in a 220 $MW_e$ natural gas combined cycle (NGCC) with the preheating and boiling processes directly accomplished in the parabolic trough collectors. The incremental electricity from solar compensated the gas turbine power drop at high ambient temperatures. Baghernejad and Yaghoubi [9] quantified the exergy destruction in all plant subsystems and found that the least efficient component is the solar collector. Libby et al. [10] showed that the highest thermodynamic performance is obtained

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**Nomenclature**

| | |
|---|---|
| $A$ | heat transfer area, $m^2$ |
| ANI | aperture normal irradiance, $W/m^2$ |
| LMTD | log-mean temperature difference, K |
| $\dot{m}$ | mass flow rate, kg/s |
| $p$ | pressure, bar |
| $q$ | heat load, kW |
| $T$ | temperature, °C, K |
| $U$ | overall heat transfer coefficient, $W/(m^2 K)$ |
| $\dot{W}$ | power output, kW |

*Greek symbols*

| | |
|---|---|
| $\varphi$ | flow function |
| $\eta$ | efficiency |
| $\rho$ | density, $kg/m^3$ |
| $\Delta T_{min}$ | minimum temperature difference, °C |
| $\Delta \dot{W}$ | power output difference, kW |

*Subscripts*

| | |
|---|---|
| *amb* | ambient |
| *coll* | solar collector |
| *corr* | corrected |
| *DP* | design point |
| *EXG* | exhaust gases |
| *in* | inlet |
| *incr* | incremental |
| *out* | outlet |
| *sol* | solar |
| *ST* | steam |
| *th* | thermal |

*Acronyms and abbreviations*

| | |
|---|---|
| CCT | minimum load to keep steam superheating and reheating temperatures at nominal values |
| CMA | minimum load to keep gas turbine emissions below environmental limits |
| CMT | minimum load to preserve the equipment |
| CNC | continuous nominal load |
| CSP | concentrating solar power |
| GT | gas turbine |
| HP | high pressure |
| HPT | high pressure turbine |
| HRSG | heat recovery steam generator |
| IP | intermediate pressure |
| IPT | intermediate pressure turbine |
| LCOE | levelized cost of electricity |
| LP | low pressure |
| LPT | low pressure turbine |
| PR | pressure ratio |
| ST | steam turbine |
| VGV | variable guide vanes |

with solar steam generated at the highest temperature and pressure and fed upstream the high pressure turbine. Peterseim et al. [11] compared different concentrating solar power (CSP) technologies (parabolic trough, linear Fresnel and solar tower) for integration of 80 $MW_{th}$ from CSP into a 200 $MW_e$ NGCC on the basis of various criteria related to feasibility, risk, environmental impact and levelized cost of electricity (LCOE). They found that Fresnel solar collectors ranked best followed by parabolic troughs using thermal oil as heat transfer fluid.

The higher conversion efficiency of solar energy in ISCCs in combination with the equipment shared with the NGCC results in a lower solar LCOE compared to solar thermal power plants which could be the driving force for a massive deployment of this technology. For instance, in [12] the solar LCOE were calculated equal to 9.8 and 11.3 c$/kW h for an ISCC and a solar thermal power plant, respectively, both located in Barstow (CA, USA). In [13] the cost of electricity of the overall ISCC power plant was estimated in the range between 4.5 and 5.7 c€/kW h depending on the extension of the solar field. A higher value of approximately 7.5 c$/kW h was calculated for the overall plant in [14] due to the higher solar share. Antonanzas et al. [15] evaluated the potential of solar thermal integration into thirty NGCCs in Spain without modifications to the existing design. A similar analysis carried out in [16] for three NGCCs in Algeria showed that the increase in yield was up to 9.2 GW h/year for each power plant and the solar incremental LCOE was only 9.5 c$/kW h. On the other hand, Trad and Ali [17] calculated a much higher LCOE approaching 25 c€/kW h for a 100 $MW_e$ solar thermal power plant located in Algeria. This marked spread between solar thermal plants and ISCCs clearly asks for a new pricing regulation promoting the deployment of the latter and, in general, of hybrid solar-fossil fuel power plants with a relatively low solar share. In countries with high coal consumption like China the interest is on the hybridization of coal-fired power plants [18] in so-called "solar aided coal-fired power generation systems" (SACPGS), which enables high solar-to-electricity conversion efficiencies as well. Peng et al. [19] analyzed the hybridization of a 330 $MW_e$ coal-fired power plant where a solar-driven feed water heater is added in parallel with the last preheater to reduce the extraction from the steam turbine. They found that the solar radiation-to-electrical efficiency can reach 27.3% (1.4%-points higher than the solar thermal power plant) and that the LCOE can be reduced to 12.6–15.8 c$/kW h, about 20–30% lower than solar thermal power plants.

The main limitation in both ISCCs and SACPGS is the low solar share achievable. A concept to increase the solar share is to co-locate CSP facilities with simple-cycle gas turbines which transfer the exhaust heat to the heat transfer fluid of the solar plant [20]. Guédez et al. [21] evaluated the performance of such a plant including a 100 $MW_e$ gas turbine and a 60 $MW_e$ molten-salt solar tower with storage and calculated LCOE values for the total plant in the range 11.0–12.2 c$/MW h. A higher solar share up to 90% [22] is achievable when solar energy is integrated in the topping part of a NGCC to preheat compressed air ahead of the combustion chamber, an integration scheme that has already demonstrated technical feasibility in the Solugas project [23].

The development of several ISCCs projects, in a country like Italy, having a high natural gas consumption and a high availability of solar energy can represent an important step for a gradual abatement of $CO_2$ emissions in the generation sector, and for the promotion of cost-effective CSP technologies. The optimization of the annual performance and the selection of a proper design point are critical for the economics of such systems. Combined cycles with solar integration often operate at off-design conditions due to the intrinsic variable nature of solar energy and because of retrofit schemes searching for minimum modifications to the existing equipment (steam turbines, HRSG). Thus, to check both feasibility