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Energy Procedia 75 (2015) 1080 – 1086

Energy Procedia

The 7th International Conference on Applied Energy – ICAE2015

Thermoeconomic Analysis Of Csp Air-Steam Mixed Cycles with Low Water Consumption

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Abstract

Starting from a state of the art of CSP plants and the undergoing research in hybridization of Gas Turbine plants, the paper investigates alternative plant configurations particularly regarding the integration of CSP technology with mixed cycles because of their low water consumption and the possible use of current CSP components, assessed and compared with a through-life thermo-economic analysis.

Peer-review under responsibility of Applied Energy Innovation Institute

*Keywords:*Concentrated Solar Power, Mixed Cycles, Water Consumption, Gas Turbine, Solar Hybridization

1. Introduction

CSP technology can be combined with any traditional energy system, including unconventional cycles as researched by Jamel et al.[1], but the solar input collected by the concentrators is commercially used in steam power plants, with one or two pressure level steam turbine where the CSP system substitutes the traditional steam generator. However, Rankine cycles need a significant amount of make-up water, while the most suitable area for CSP plants (i.e. the worldwide area of the Sun Belt area where the DNI exploitable by solar receivers is high) are in desert areas. CSP Rankine cycles consume water for the continuous purge and make-up of cycle water, as well as for mirror cleaning (0.6 liters of wash water per m^2 of solar field and 73 washes per year[2]). To mitigate these problems, increase the efficiency of CSP power plants, and provide cost-effective dispatchable power, significant can be gained creating a solar hybrid gas turbine and combined cycle [3] [4][5][6].

Nowadays two solutions are under research: Integrated Solar Combined Cycle (ISCC) and Solar Hybrid Combined Cycle (SHCC). Even though SHCC plants have high efficiency and high solar share factor (SSF), unfortunately they have technological challenges related to the high temperature receiver, solar collector and the use of very hot compressed air (800°C-1000°C) in the combustion chamber. ISCC plants can exploit traditional Steam CSP technology, but they have lower SSF and efficiency. As an alternative route, steam-injection gas turbine power plants can be investigated [7]. This produces a solar hybrid mixed CSP cycle, with heat input from both solar collectors and fuel in the combustor. A thermodynamic analysis of this hybrid cycle, leading to high power augmentation compared to the simple cycle and to conventional STIG was made by Livshits and Kribus , even if in their research the steam produced by the solar field is inserted in the HRSG of the cycle [8][9].

Basing on their experience on researching mixed cycles [10] and CSP plants [11] using a thermo-economic approach and optimization tool, the Authors decided to introduce solar steam directly in the combustion chamber like in a traditional STIG cycle, they analyzed this hybrid mixed CSP cycle comparing its performance against a traditional STIG cycle focusing the attention on water consumption

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doi:10.1016/j.egypro.2015.07.489

and costs, a keynote for the installation of these plants in desert areas and Middle East-North Africa countries.

Nomenclature

CSP	Concentrated Solar Power
DC	Direct Costs
DNI	Direct Normal Irradiation
FCI	Fixed Capital Investment
ISCC	Integrated Solar Combined Cycle
LCOE	Levelized Cost of Electricity
PEC	Purchased Equipment Cost
SHCC	Solar Hybrid Combined Cycle
SSF	Solar Share Factor
STIG	Steam Injection Gas
TCI	Total Capital Investment
WTEMP	Web Thermo-Economic Modular Program

Symbols

A	Area [m^2]
Φ	humidity rate
α	Steam Air mass flow rate ratio
β	Gas turbine pressure ratio
p	Pressure

Subscripts

h	hour
reint	reintegration
sol	solar
yr	year

2. THERMOECONOMIC OPTIMIZATION APPROACH

The thermoeconomic investigation is carried out using a design point analysis optimization modular software (93 modules) named WTEMP (Web-based Thermoeconomic Modular Program) developed by the Thermochemical Power Group (TPG) at University of Genoa [12].In WTEMP each component is described by three subroutines, which define its thermodynamic, exergetic and thermo-economic performance at design point. The software is provided with cost/costing equations, which evaluate individual components capital costs on the basis of geometrical and manufacturing variables (cost equations) or on the basis of stream variables (costing equations). Cost functions allow for calculating the Purchased Equipment Cost (PEC) for each unit. From the PEC, the Total Capital Investment (TCI) of the plant can be evaluated: most of TCI items are calculated as a percentage of PEC [13]; the remaining ones are calculated as a function of Fixed Capital Investment (FCI) or Direct Costs (DC) of the plant.

In this study contingencies were assumed at the 24% of FCI for the CSP Mixed Air Cycle, while for the STIG plant was assumed at the 8% of the FCI. These different values are assumed to underline that CSP cycles are not yet a commercial technology, so a technologic risk factor was considered during the thermoeconomic analysis.

In this research a CSP Solar Field model realized for previous research [11] was used. To realize this module, a Direct Normal Irradiation (DNI) solar curve has been implemented in the model referred to Sicily latitude referred to Sicily latitude, but any other solar curve can be implemented in the model[14]. The cost functions reported are considered for parabolic through technology exploited in commercial CSP Steam plants, they were furnished by a manufacturing partner (FERA srl). The model was validated both from the economic and thermodynamic point of view according to a real plant performances [11].

The economic input file contains a section describing the economic scenario where the plant is operating.
a) **Natural gas cost** is assumed equal to 0.40 €/m^3, typical market value in Italy and in Europe[15].
b) Electricity selling price is assumed equal to 0.068 €/kWh, typical market price for the Italian and European scenario in 2014 as reported in [16].
c) Renewable solar energy selling price is assumed equal to 0.22 €/kWh, which is the feed-in-tariff set in Italy since 2011 for electricity produced by CSP solar plants [17].

3. DESIGN POINT OF THE HYBRID MIXED CSP CYCLE

In such configuration, the steam produced by a parabolic through solar field is mixed with the steam produced by the Heat Recovery Steam Generator before being injected on the compressed stream (fig.1).

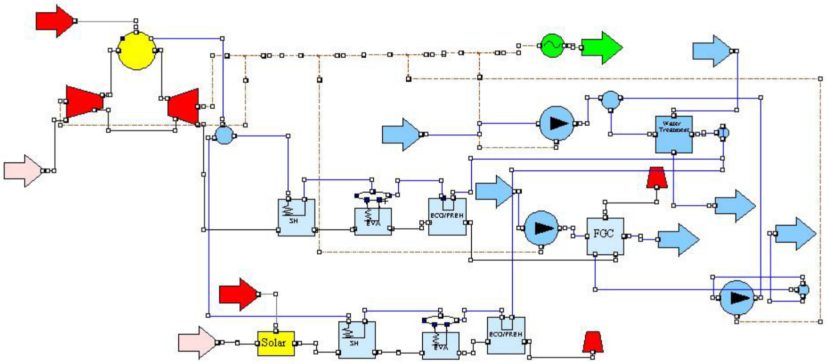

Fig. 1 – Hybrid mixed CSP plant WTEMP plant layout

In order to make feasible the new plant in desert areas and to reduce the variable costs of the plant, the focus was on closing the cycle thanks to a flue gas condenser (FGC), which can recover water from the flue gases, thus reducing as much as possible the make-up water (depending on the temperature of the cold sink, water net production is possible, in principle).
The design point features of the FGC were studied, reducing the reintegration of deminaralized water from 0,3 kg/sMW$_e$ to 0,002 kg/sMW$_e$ and the yearly variable costs linked to demineralized water from 10,2 M€ to 0,68 M€ (cost of demineralized water: 40 €/m^3 – yearly operating hours: 5000 h).
The operating parameters chosen for the gas turbine plant and for the solar field are described in tab.1

Solar field surface	15000 m^2
Air mass flow in the GT	53 kg/s
Steam pressure	1,25 β
TIT	1300°C

Blade cooling efficiency	0,55
Cooling flow/inlet flow ratio	0,1797
Combustion chamber efficiency	0,985
Turbine/Compressor adiabatic efficiency	0,92 – 0,87
Solar Steam Generator Heat Transfer Coefficient [W/m²k]	85
FGC Heat Transfer Coefficient [W/m²k]	100

Tab. 1: CSP STIG Solar Field and GT parameters

Hybrid mixed CSP cycles require smaller collector surface area, and the role of the storage is not so important, since the natural gas supply can compensate for reduced solar irradiation periods, despite affecting the solar share factor. These operating parameters will guarantee, varying the pressure ratio and the operating conditions, a net power of 47-53 MW, a SSF of 10% and a reintegration mass flow rate which can be evaluated in less than the 1% of the cycle water flow rate. After the definition of these parameters, a parametric analysis was made, varying the pressure ratio (β), evaluating the performances of the plant and keeping always monitored the water consumption and the steam/air ratio. (tab.2)

β	η	Net power [MW]	Specific work [kJ/kg]	Steam pressure [bar]	$T_{out\,FGC}$ [°C]	SSF [%]	α [%]	Water reintegration [%]	LCOE [c$/kWh]	Condenser cooling flow [kg/s]	A_{FGC} [m²]	Solar steam m_{vap} [kg/s]	% of Solar Steam
5	0,388	47,67	899,5	7	54	8,42	43,4	0,85	19,09	483	34000	6,42	18,9
10	0,497	50,09	945,0	13	51	9,25	38	0,92	15,41	387	21381	6,27	26,1
15	0,542	48,62	917,3	19	48	9,78	30	0,039	14,35	349	14160	6,16	30,9
20	**0,563**	**47,51**	**896,5**	**25**	**47**	**9,96**	**27,8**	**0,16**	**13,98**	**327**	**11968**	**6,08**	**33,7**
25	0,578	45,87	865,5	32	46	10	26	0,21	13,84	310	10158	6,003	36,1
30	0,586	44,14	832,8	38	46	10,1	24	1,64	13,88	293	8707	5,94	38,3

Tab.2 - Parametric Analysis of an hybrid mixed CSP Plant Varying Pressure Ratio

Looking at the performance reported in tab. 2 and analyzing the efficiency-specific work curve (fig.2) and the values of the water reintegration flow rate (fig.3), the optimum design point was evaluated choosing the best economic and operating performance. A pressure ratio of 20 was chosen, guaranteeing a 10% SSF and lower LCOE compared to the CSP steam plants one [1][2][11].

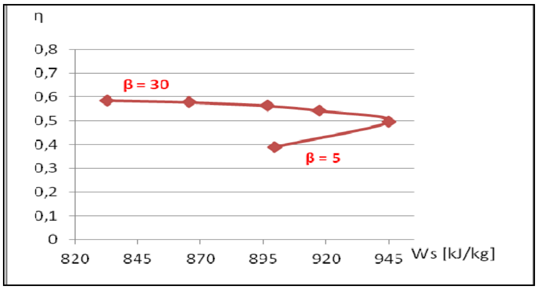

Fig. 2 - Performance Curve of an hybrid mixed CSP Plant varying Pressure Ratio

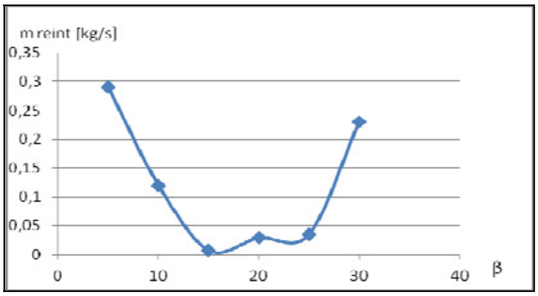

Fig. 3 - Water Reintegration of an hybrid mixed CSP Plant varying Pressure Ratio

3.1 Design Point of a traditional STIG Competitor Cycle

Using the same approach reported in the previous paragraph, the performance of a traditional STIG cycle, with a steam pressure of 1,25*β, is particularly interesting to be compared with the hybrid cycle (tab.3).

β	η	Net Power P [kW]	Specific Work Ls [kJ/kg]	Steam Pressure [bar]	T_{FGC} [°C]	α [%]	Water reintegration [%]	Water reintegration m_{reint} [kg/s]	LCOE [c$/kWh]	Condenser mass flow rate m_{sea} [kg/s]	A_{FGC} [m^2]
5	0,364	51389	685,2	7	50	32,6	0,087	0,026	18,39	500	33371
10	0,457	52274	697	13	46,5	23,1	0,38	0,073	15,21	395	17116
15	0,49	50145	668,6	19	45	19,2	1,46	0,22	14,22	351	11005
16	0,493	49719	602,9	20	44,6	18,4	1,93	0,29	14,17	347	10118
20	0,501	48037	640,5	25	43	15,8	4,66	0,55	14,02	337	8674
25	0,51	45402	605,4	32	42	13,5	8,6	0,86	14,16	290	6900
30	0,514	42777	570,4	38	41	12,5	12,5	1,13	14,38	267	5735

Tab. 3 - Parametric Analysis of a conventional STIG Plant Varying the Pressure Ratio

So a lower pressure ratio of 16 was chosen as design operating, It is worth underlining that a traditional STIG cycle has to work a higher air mass flow rate in the cycle in order to have the same power output of the hybrid mixed CSP. The steam-air ratio α are significantly lower as the solar steam is not present, and water reintegration becomes higher, while the FGC has lower heat exchanging area, particularly at high β.

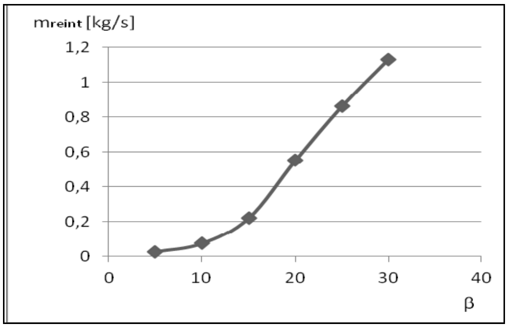

Fig. 4 - Water make-up in the analyzed STIG Cycle Varying the Pressure Ratio

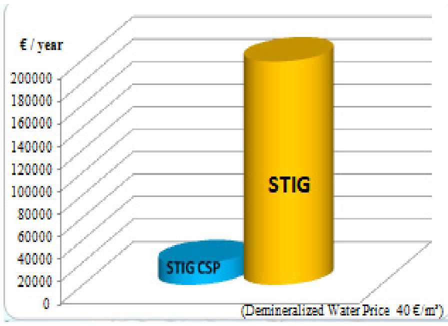

Fig. 5 - Water costs Comparison between STIG and hybrid mixed CSP cycle

Comparing the water consumption of traditional STIG and the hybrid mixed CSP cycles, the new cycle water , thanks to the steam contribution of the solar field (from 14,47 kg/s to 17,75 kg/s for the defined optimum design point), can be easier recovered in the FGC, reducing water integration and costs due to the lower oxygen content in the exhausts (combustion closer to stoichiometric conditions).

The previous results are related to a humidity tax of 20%,typical of Sun Belt and desert areas. Nevertheless a comparative analysis evaluating LCOE, water reintegration and its impact on plant variable costs varying humidity tax (Φ) was made (from 0% to 60%) , in order to evaluate the installation of these cycles also in the borders area of the Sun Belt (fig.6) and how the presence of water in the air influences the water recovery. In a traditional STIG water reintegration increases at low Φ, particularly at high β because as the outlet turbine temperature decreases, steam production is lower and less water is recoverable: this effect, that increases LCOE of 0,5 c€/kWh is less sensitive in temperate and more humid areas where it is possible to choose flexibly the pressure ratio. This effect is less sensitive in CSP hybrid mixed cycles too thanks to the additional solar steam that guarantees a constant water supply also at higher β and humidity doesn't affect so much water recovery (and the relative variable costs and LCOE).

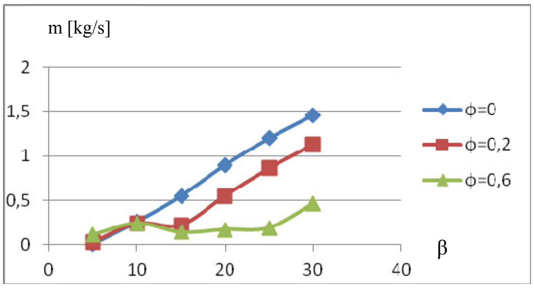

Fig. 6 - Water make-up in the traditional STIG Cycle Varying β and Φ

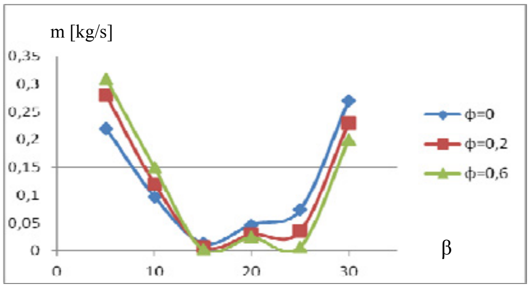

Fig. 7 - Water make-up in the hybrid mixed CSP Cycle Varying β and Φ

4. CONCLUSIONS

In this paper an innovative plant layout of an hybrid mixed CSP cycle has been proposed, in order to couple the current CSP technology (mirrors, receiver) with state of the art steam injected gas turbines. The main advantage would be low technical risk, higher efficiency, high specific work (close to 900 kJ/kg thanks to the additional solar steam) and high water recovery potential thanks to the quasi-stochiometric combustion. The plant would retain competitive LCOE (14 – 15 c€) according to present feed-in policies, by reducing variable costs for natural gas and demineralised water consumption.
A special focus on water consumption of these plants is reported. In hybrid mixed CSP cycles, thanks to the solar steam, water can be easier recovered in the FGC, reducing water integration and costs due to the lower oxygen content in the exhausts (combustion closer to stoichiometric conditions).
The humidity effect is less sensitive in CSP hybrid mixed cycles too thanks to the additional solar steam that guarantees a constant water supply also at higher β and so humidity rate doesn't affect so much water recovery (and the relative variable costs and LCOE), making CSP hybrid mixed cycles a suitable and sustainable solution for solar gas turbine hybridization and CSP production in all the Sun Belt countries particularly for middle size power plant (~50 MW) and CHP-trigenerative solutions.

REFERENCES

[1] M.S.Jamel, A.Abd Rahman, A.H.Shamsuddin, 2013, "Advances in the integration of solar thermal energy with conventional and non –conventional power plants", Renewable and Sustainable Energy Reviews, 20, 71–81
[2] C.S.Turchi, M.J.Wagner, C.F.Kutscher . "Water Use in Parabolic Trough Power Plants: Summary Results from WorleyParsons' Analyses" - Technical Report NREL/TP-5500-49468, December 2010
[3] J. Spelling, B. Laumert, A. Martin, G. Augsburger, 2011, "Thermoeconomic Optimization of a Combined-Cycle Solar Tower Power Plant", Energy, Vol. 41, pp. 113-20.
[4] J. Spelling, D. Favrat, T. Fransson, 2013, "A Comparative Thermoeconomic Study of Hybrid Solar Gas-Turbine Power Plants", Proceedings of ASME Turbo Expo 2013, GT2013-94046.
[5] R. Hosseini, M. Soltani, G. Valizadeh, 2005, "Technical and economic assessment of the integrated solar combined cycle power plants in Iran", Renewable Energy, Vol. 30, pp. 1541-1555.
[6] M. Kane, D. Favrat, K. Ziegler, Y. Allani, 2000, "Thermoeconomic analysis of advanced solar-fossil combined power plants", Int. Journal of Applied Thermodynamics, Vol. 3, pp. 191-198.
[7] M. Livshits, A.Kribus, 2012, "Solar Hybrid Steam Injection Gas Turbine (STIG) Cycle", Solar Energy, Vol. 86, pp.190–199.
[8] M. Livshits, A.Kribus, "Water Consumption of the Solar STIG Cycle," SolarPACES 2011, Granada, Spain
[9] M. Livshits, A.Kribus, "Solar Hybrid STIG Cycle," SolarPACES 2010, Perpignan, France,September 21–24.
[10] A.Traverso, A.F. Massardo, 2002, "Thermo-economic analysis of mixed gas steam cycles", Applied Thermal Engineering, Vol. 22, pp. 1-21

[11] S.Barberis, M.Rivarolo, A.Traverso, 2014, "Thermoeconomic Optimization Of CSP Hybrid Power Plants With Thermal Storage" – ASME Turbo Expo 2014, ASME Paper GT2014-25137
[12] A.Traverso, A. F. Massardo, W. Cazzola, G. Lagorio, 2004, "WIDGET-TEMP: A Novel Web-Based Approach for Thermoeconomic Analysis and Optimization of Conventional and Innovative Cycles", ASME Paper GT2004-54115.
[13]Bejan A,Tsatsaronis G.,Moran M. – "Thermal Design and Optimization" – 1996,John Wiley & Sons Inc.,CAN
[14] ENEA – Atlante Italiano della Radiazione Solare - http://www.solaritaly.enea.it – last access 14/10/2014
[15] Cassa Depositi e Prestiti –Market Analysis "Il Mercato del Gas Naturale in Italia: lo sviluppo delle infrastrutture nel contesto europeo" – Italy, March 2013
[16] EUROPEAN COMMISSION STAFF WORKING DOCUMENT – "Energy prices and costs report", Brussels, 17/3/2014
[17] Government Decree, D.M. 11th April 2008, modified by D.M. 6th July 2012 – Feed-in Tariff Policy for CSP Power Plants – Italian Republic

Biography

Stefano Barberis was born in 1988, he's PhD Student at University of Genoa and his research is focused on the integration of thermal and electrical storages in poligenerative district and grids, thermoeconomics and Concentrated Solar Power.

Alberto Traverso was born in 1976, he's professor of Energy Systems at University of Genoa and he's author of more than 150 scientific publications and several industrial patents. His research is focused in dynamics and innovative controls of energy systems, fuel cell hybrid systems, thermoeconomics and poligeneration.