Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 126 (201709) 667–674

Energy Procedia

www.elsevier.com/locate/procedia

72nd Conference of the Italian Thermal Machines Engineering Association, ATI2017, 6-8 September 2017, Lecce, Italy

Thermo-Economic Analysis of a hybrid solar micro gas turbine power plant

Maria Cristina Cameretti*, Roberta De Robbio, Emanuele Pirone,Raffaele Tuccillo

University of Napoli Federico II

Abstract

This work proposes a hybrid system based on a micro-gas turbine plant integrated with a solar field either to provide a part of the heat addition or to totally replace the combustor in the case that the only solar heat input is enough to ensure that the working fluid reaches the turbine inlet temperature. The system can operate in a pure combustion mode when solar irradiance is weak or completely absent during some hours in the day or seasons. The analysis is based on the simulation of the overall plant by the *Thermoflex software*, a modular program that allows assembling model with several components.

In particular, many calculations have been performed to simulate the solar-assisted cogenerating plant in different operating conditions in order to identify the optimum sizing of the solar system which reduces the annual costs or the fuel consumption and, consequently, the CO_2 emissions. Numerical results are compared with the data available from standard micro gas turbine plant. Finally, an economical evaluation by calculation the SPB (simple pay back) is obtained for all test cases to evaluate the benefit from Italian State incentives.

Keywords: Solar tower; microgas turbine; thermo-economic analysis.

* Corresponding author. Tel.: +39-081-7683299
E-mail address: mc.cameretti@unina.it

1876-6102 © 2017 The Authors. Published by Elsevier Ltd.
Peer-review under responsibility of the scientific committee of the 72nd Conference of the Italian Thermal Machines Engineering Association
10.1016/j.egypro.2017.08.295

1. Introduction

The climate change, the depletion of fossil fuels and rising electricity costs have become vital issues requiring investigations to increase the share of employment of renewable sources in the energy production systems. Among the various CSP technologies, over the last ten years, solar tower technology has gained considerable development.

In a solar tower system, the power collected from the elliptical field is strictly dependent on the height of the tower and its position with respect to the field. It is also to be specified that the best projects are strongly affected by the cost of the receiver, the charging rate and the maximum receiver temperature used. In [1] an example of a new procedure, with a fully thermo-economic optimization for the design of the collector field of an actual SPT system, is presented. Hybridization is a newly proposed concept in which solar thermal energy provides a portion of the required thermal input instead of fossil fuels and natural gases [2]. Storage and intermittency concerns regarding solar energy make hybridization a viable solution to increase renewable energy share in power generation Actually, the current level of maturity limits the contribution of solar energy due to intermittent and storage problems.

Thermal systems, which are generally designed and analyzed based on the nominal design point, given the intermittence of the radiation, will operate for most of the year well above or below the nominal operating point.

It is worth-noting that if a latent heat accumulator is used, the incoming temperature of the receiver can vary without problems, but presently there is a clear lack of knowledge on how to handle off-design conditions in terms of developing appropriate control strategies to maximize the heat output of the receiver and its operating range. The study [3] investigated two control strategies - a fixed receiver flow rate (FF) and fixed receiver outlet temperature (FT) - for their off-design performance in each of two off-design operational modes (storage and non-storage). Solar field utilization (SFU) is variable in non-storage mode, but in the storage mode, it is whether variable or fixed at design point. Esmail and Mokheimera [4] provide an investigation into the technical and economic feasibility of a CSP plant with the integration of a gas turbine equipped with a cogeneration plant which is progressively installed in Saudi Arabia. Different designs of hybrid solar/fossil fuel gas turbine cogeneration systems have been proposed. A solar tower plant is considered with linear parabolic collectors and Fresnel reflectors coupled respectively to a gas turbine plant. For each of these CSP alternatives, the mass flow rate and the inlet temperature of the turbine are considered to be constant as to generate electricity. A software was used to analyze the performance of the plant. As far as the economic technical comparison is concerned, reducing the CO_2 emissions. The new model presented by M.J. Santos et al [5], evaluates radiation variations and environmental conditions, considering the solar part running only when the radiation is fairly high. A combustion chamber tries to keep the temperature constant at the turbine inlet in order to obtain a constant output power. The performance of the entire plant is written as a combination of the thermal performance of the heat exchanger and the required heat exchanger. Numerical values of model input parameters are taken from a central tower installation recently developed near Seville, Spain. Research findings show that the hybrid has the right potential to generate a stable power with consumption and, consequently, reduced emissions. Real data for irradiance and external temperature are taken in hourly terms.

The OMSoP project [6], funded by the European Commission, aims to use a Brayton cycle with a gas microturbine replacing the more conventional Stirling engine in order to increase the relationship between the electric power generated by the collected solar energy and improving the operability in relation to solar energy short time fluctuations. The work deals with the activities carried out so far by ENEA, which is principally involved in the development and experimental characterization of the dish component, and in the integration of the complete system, both in terms of modeling and realization. In [7] the authors find similar behaviors of the two solutions at the same area as the solar collectors, by comparing the behavior of a hybrid solar gas turbine cycle, in which the compressed air exiting the compressor is sent to the solar tower before entering the combustion chamber, and a combined cycle coupled with a linear parabolic collector. They evaluated the performance of the plants under real operating conditions due to the use of commercial software. The interest in solar-turbine (HSGT) turbine systems in solar tower systems is growing. This is due to the high conversion efficiency and low water consumption that is obtained when a combined cycle is implemented. J. Spelling et al. [8] have developed a dynamic simulation model of a solar-hybrid system with the aim of determining its thermodynamic and economic characteristics. The end is to determine the optimal design by minimizing the cost of energy and CO_2 emissions. The simulated plant has a power of 15 MW which must reach the different solar irradiation conditions. The solar-gas turbine hybrid solution is the best solution to reduce CO2 emissions from an open gas turbine cycle. As a result, the energy cost of the energy has a slight increase. Comparing the LECs obtained from the optimization results with that of the existing plant there is a reduction of 10% to 34% with a level of reduced CO_2 emissions between 10% and 43%. In the future, they will try to increase the working temperature of the receiver in order to save even more fuel. It should be noted that water consumption is significantly lower than that of linear parabolic collector technology. This will facilitate development in desert areas. According to L. Aichmayer et al [9] in Micro Gas-Turbine Design for Small-Scale Hybrid Solar Power Plants, the solar hybrid solution - micro gas turbine, in terms of cost of electricity and emissions, is one of the most promising ones that have been evaluated. Compared to a diesel generator, the cost of a hybrid source is between 10% and 43% lower. While CO_2 emissions are reduced by 20% -35%. In [10] the authors proposed the integration of a combined power plant, with a micro gas turbine (MGT) and an ORC system, and a solar field that allows a temperature increase of the air at the MGT recuperator inlet.

This paper, starting from a previous work [11] that confirms the benefits in terms of fuel consumption and emissions of a hybrid solar tower and microturbine plant, analyzes a hybrid plant with a solar tower and a 30-kWmicro-gas turbine, in terms of economic and environmental convenience.

Nomenclature

CHP	Combined Heat and Power
T	Temperature
TIT	Turbine Inlet Temperature
2r	Air conditions after recuperator
2s	Air conditions after solar heating
P	Electric Power
SPB	Simple Pay Back
FS	Total Fuel Saving
FEUF	Fuel Energy utilization factor
PES	Primary Energy Saving
E_{CHP}	Electric energy
H_{CHP}	Thermal energy
MGT	Micro Gas Turbine

2. Numerical calculation

The authors performed several numerical simulations with reference to a micro gas turbine based CHP plant, fueled by natural gas, integrated by a concentrated solar power system. A representative scheme is shown in Figure 1. The power unit is a 30 kW Capstone micro-gas turbine and in table 1 the datasheet is reported. The solar integration is obtained by means of a solar tower: the air path through this component is located between the recuperator and the combustor. In the hot gas side, after the recuperated process, the flue gas enters an additional heat exchanger for hot water production. The air flows through the compressor (points 1-2 in figure 2), and then it is preheated through the recuperator cold side. Subsequently it passes first through the solar tower channels (2r – 2s) and then it accesses the combustion chamber (2s-3), so reaching the *TIT*. The combustion gases coming from combustion chamber expand through the turbine and then proceed towards the recuperator hot side and a heat recovery system before reaching the stack. The energy contribution of solar tower depends on daytime and weather conditions, so that the fuel amount to the combustion chamber varies in order to keep maximum temperature at its set point value: the lower the solar contribution the higher the fuel flow rate to the combustion chamber. The plant has been simulated by using a commercial software (Thermoflex) which reads the operating maps for compressor and turbine, so allowing a realistic simulation of the plant off-design response for changes in the environmental conditions during the year. The system can operate in a pure combustion mode when solar radiation is relatively low. This happens during some hours of the day or in some periods of the year. Plant design mainly consists of the definition of the number of heliostats, the height of the solar tower structure, and the surface of the heliostat field, i.e. setting the exit air flowT_{2s} temperature from solar tower. In figure 2 the thermodynamic cycle of the gas turbine.

Table 1. C30 micro gas turbine datasheet

Recuperator Efficiency	**0.877**
Pressure Ratio	**3.45**
Turbine inlet temperature (K)	**1173**
Net Power output	**28 kW (+/-1)**
Exhaust Mass flow (kg/s)	**0.3**
N (rpm)	**96000**
Exhaust gas temperature (K)	**548**
Compressor polytropic efficiency	**0.78**
Turbine polytropic efficiency	**0.80**

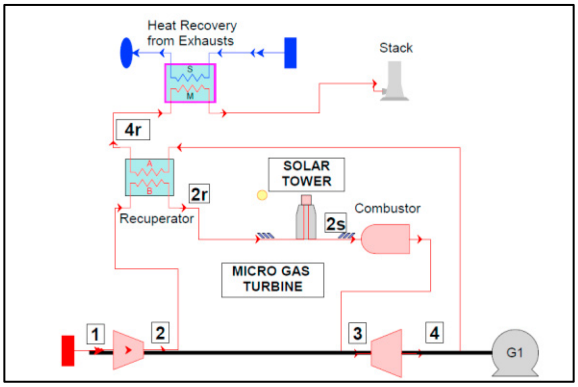


Figure 1. Layout of the solar integrated MGT

The fuel utilization factor, the primary energy saving and *FS* are calculated for each case as:

$$FEUF = \frac{L_U + Q_U}{m_c H_i} \quad (1); \qquad PES = \left(1 - \frac{1}{\frac{CHPH\eta}{RefH\eta} + \frac{CHPE\eta}{RefE\eta}}\right) * 100 \quad (2)$$

$$FS = \frac{E_{CHP}}{\eta_{eRIF}} + \frac{H_{CHP}}{\eta_{tRIF}} - F_{CHP} \quad (3)$$

Where $CHPH_\eta = \frac{H_{CHP}}{F_{CHP}}$; $HPE_\eta = \frac{E_{CHP}}{F_{CHP}}$; $RefH_\eta$ is the reference value for the separate thermal production; $RefE_\eta$ is the reference value for the separate electric production. The *FS* Fuel Saving is the global amount of fossil fuel that can be saved by the CHP plant.

2.1 Test cases

Table 2. Test Cases

	T_{2s}	Target
Case Base	-	-
Case#1	**900 C**	**Minimal cost**
Case#2	**900 C**	**Minimal CO_2**

Initially, the fuel consumption during a year of the MGT plant without solar tower (named *Base Case*) is estimated in order to compare its performances with those obtained by integration with the solar tower system. The estimate of the fuel mass flow is considered during the daylight hours and the night ones. In figure 4 the results are reported, considering the ambient temperature in the year 2016 (in the figure 3 the temperature graph is referred to 12:00 pm, as example) and considering the full load. This implies a grid-connect operation. In daytime hours 37691.58 kg / year of natural gas is used. In table 3, the results are reported in terms of main performance data of the micro gas turbine together with the CHP indices. The fuel cost is calculated on the basis of the current price of 0.40 €/Sm^3 (0.552 €/kg).

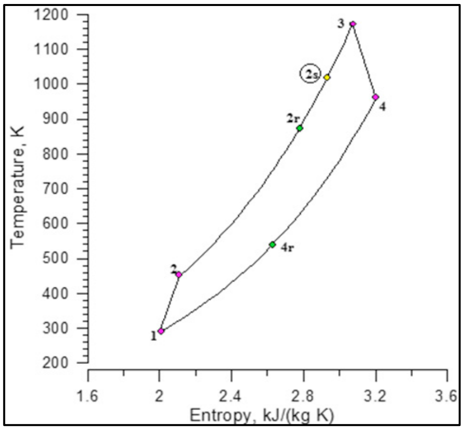


Fig. 2. Thermal cycle of the MGT

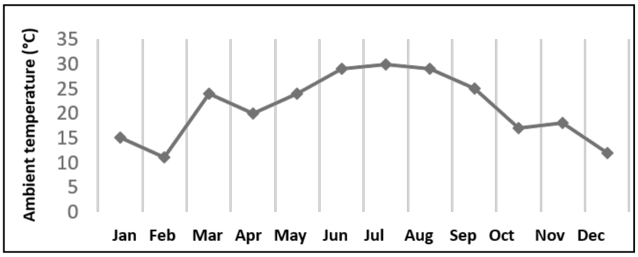


Fig. 3. Ambient temperatures at 12:00 during the year 2016

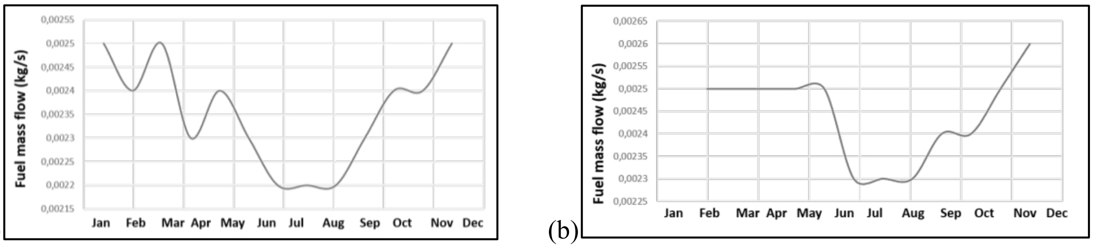
(a)  (b)

Fig. 4. Diurnal (a) and night (b) fuel mass flow during the year. Base Case without solar tower

Table 3. Base Case Results

Fuel Thermal power [kW]	**111.84**
Yearly Fuel cost [€/year]	**50430**
Electric Energy[kWh]	**265866**
FEUF%	**71.22**
PES%	**8.99**
FS [MWh]	**96.74**
CO_2 [kg/kWh]	**0.842**

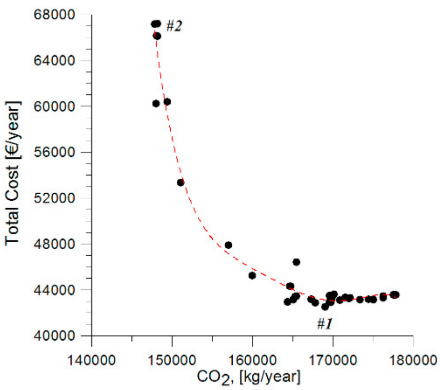


Fig. 5. Total cost versus CO_2 emission

The procedure for the plant performance estimation can be outlined as follows: the solar field was designed by considering the radiation intensity for each month at four hours in a day (8:00; 12:00; 16:00; 19:00). In this design phase, the software calculates the solar system size according to variations of the solar radiation in a year, basing on the target set. The design point is then established by determining the heliostat surface that allows achievement of the desired turbine inlet temperature. For each total surface of the heliostat field, the off-design operation of the solar-MGT integrated CHP plant was predicted over the whole year, so determining the cost related to fuel consumption and the investment cost per year. Consequently, the total cost per year is estimated, together with the overall production of electrical and thermal energy and the yearly CO_2 emission. Figure 5 shows that two conflicting objectives could pursued, say either the minimum cost over a one year operation or the minimum in yearly production of carbon dioxide. The same figure highlights that the points corresponding to the several design criteria can be assembled in a sort of a Pareto front. Therefore the optimal choice should be determined by a multi-objective optimization.

As examples, two test cases are considered by fixing the T_{2s} temperature from solar tower at 900C and by varying the target, as reported in Table 2. In particular, the aim is to reduce either the total cost (including the solar tower and the fuel consumption) or the CO_2 emissions (points #1 and #2 in figure

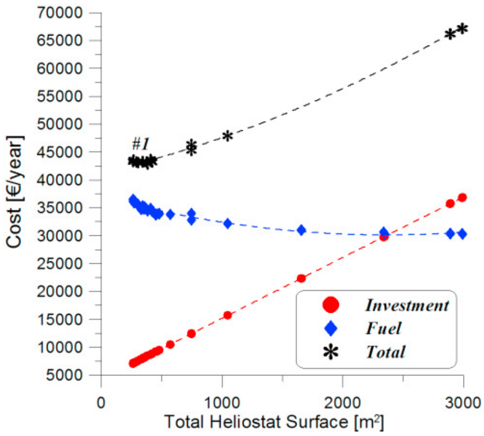


Fig. 6. Total yearly costs

5) respectively. Of course, these points represent the extreme conditions of design, while intermediate solutions could allow a good compromise between both targets.

In the *Case#1* (T_{2s}=T_3=900 C) the target considered is the minimal total cost. In figure 6 the costs are reported as a function of the heliostat surface and the minimal value of total costs is reached in correspondence with June at 12:00. Therefore, optimal choice for the solar field is obtained in correspondence with this time. In the figure 7 the trends of net power and thermal inputs, from both fuel and solar source, at *8:00 am* are reported in off-design conditions in a year. In some hours, the combustor can be by-passed, since the output tower temperature (T_{2s}) reaches the maximum thermal cycle temperature (*TIT*).

A similar procedure is then adopted also for the case #2, so examining the influence of both the objective functions (minimum cost or CO_2). In the *Case#2* the plant is designed for the day of the year that minimizes fuel consumption and the CO_2 emissions consequently (*December, 8.00 am*). In figure 8 the thermal and electrical power is shown for a particular hour in a day (8:00 am), as an example. In this last case, the thermal input is exclusively due to solar contribution. As it is self-evident, such a solution leads to a relevant fuel saving but to an excess in the heliostat surfaces. Actually, since the solar field has been determined for a minimum irradiance, this choice would imply that most of the heliostat should be set out of work for large periods in the year.

In table 4 a summary of the results is reported: integrating solar technology, the specific cost of energy may undergo either an increase or a decrease depending on the plant layout. However, the solution that minimizes this cost is obtained when planning for June at the hours of maximum irradiance (*Case#1*). In this case, greenhouse gas emissions will drop down by about 51% compared to the base case.

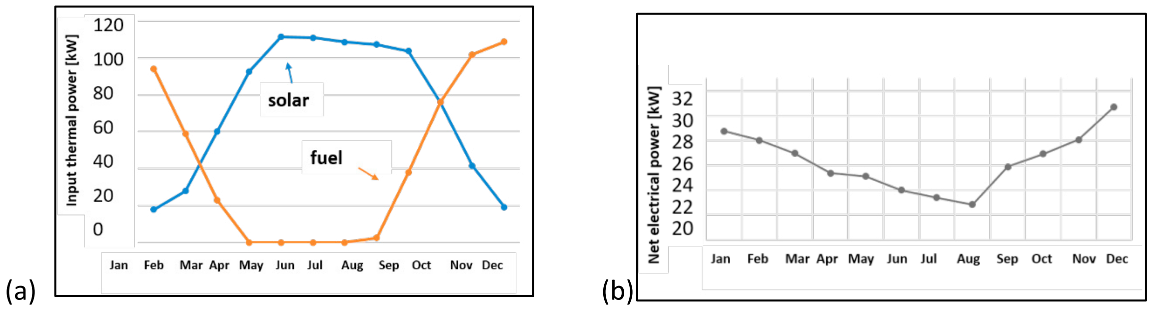


Fig. 7. Thermal input (a) and net electrical power(b) calculated at 8:00 pm (case#1)

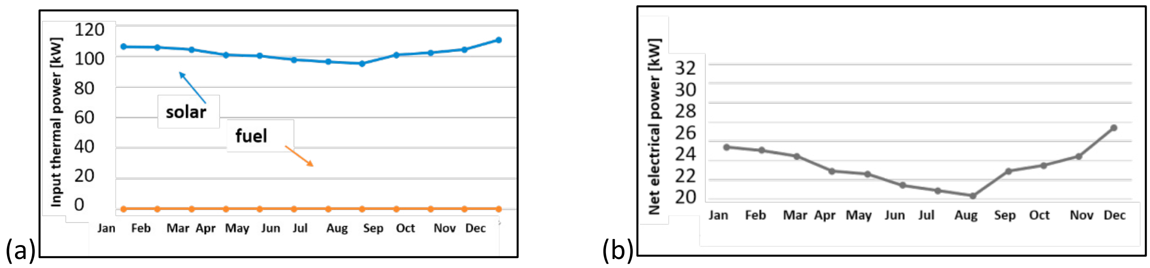


Fig. 8. Thermal input (a) and net electrical power (b) calculated at 8:00 pm (case#2)

As stated before, the solution that minimizes greenhouse gas emissions is obtained when the combustion chamber is by-passed. CO_2 emissions drop by 73% compared to emissions obtained without solar integration. However, this solution implies a very high annual cost, due to the excessive number of heliostats (67) corresponding to 2991,6 m^2 needed. The above considerations refer only to what happens during the hours of the day. In fact, during the night hours, the operation of the system is independent of the presence of the solar tower, which is then by-passed.

2.2 Economic estimate

The results in table 4 highlight that, besides a significant reduction in CO_2 emission, the solar integration solution can also reduce the specific cost of the electrical energy produced. This suggests that the actual return from the major investment costs should be estimated more properly by payback based methods. Therefore, in this section, an estimate of the eventual benefits from this hybrid plant investment is discussed. Following the provisions on thermodynamic solar systems of the Italian regulations and laws on renewable sources, the solar plant can access incentives even though there is no thermal accumulation system. In addition to such incentives, the cost of the fuel saving and the return from the cogeneration incentives should be considered. The avoided fuel cost (CEC) is calculated as:

$$CEC = C_{FC} - C_{FCsolar} \tag{4}$$

Where C_{FC} is the yearly fuel cost without solar integration; $C_{FCsolar}$ is the yearly fuel cost with solar integration. They are referred only to the diurnal hours because with or without solar input the fuel cost during the night is invariant. The return for cogeneration plant is estimated as follows:

$$\Delta R = R_{rsolar} - R_r \tag{5}$$

R_{rsolar} is the revenue per year with solar integration; R_r is the revenue without solar integration. The increase in this incentive is obviously due to the higher primary energy saving that is obtained through the solar integration.
It is possible to determine the *Simple Payback Period* (SPB), the repayment period, i.e. an index of the number of years needed to recover the investment:

$$SPB = \frac{I_S}{CEC+\Delta R+\Delta R_{is}} \tag{6}$$

I_s being the cost of the solar system and ΔR_{is} ($€/year$) the return due to the incentives for thermodynamic conversion of solar energy, calculated according to the most recent ministerial decree, that depends on the rate of electrical energy produced from solar power and sold to the grid – connected users. In the table 5 the evaluation of CEC and *SPB* is reported for two test cases examined. Two limit scenarios have been considered: the first one, refers to a stand-alone operation of the CHP plant, so that only the ΔR incentive is considered. The other scenario assumes that the whole amount of electrical energy produced by the solar contribution is sold, so exploiting only the ΔR_{is} incentive. This allows evaluation of two distinct SPB periods, like reported in table 5.
The minimum payback solution is obtained for *Case#1*, which pursued minimum costs. The use of the incentives provided by current regulations allows us to lower this index by about 6 –10 years, depending on the type of connection of the power plant to the electrical grid. In fact, the presence of the solar tower implies an increase in the *PES* and, consequently, of the *FS* involved in the *SPB* calculation. As expected *Cases #2* is not of interest in terms of payback, since the estimated period (if more than 30 years) is longer than the solar tower life which is conventionally assumed to be of about 25 years. Actually, this case requires very large solar fields with high investment costs. In a real application, supposedly the solar field should be less than 1000 m^2, the cases involving a relatively low total cost represent the right choice decreasing the CO_2 amount, as shown in Figures 5 and 6.

Conclusion

This study is focused on the thermo-economic investigation of a hybrid power plant integrated by a solar tower. Like for all combined energy systems the typical objectives that should be pursued are the fuel energy and cost saving, the CO_2 reduction and an attractive payback period. Such objectives are typically conflicting, so that different design choices can be adopted. The examples discussed in the previous sections clearly confirm that relevant differences in the solar field extension arise, depending on the single objective established for the plant design. In particular, the cases aiming at the maximum CO_2 reduction are characterized by unacceptable investment costs, while more affordable solutions are attained if pointing directly to yearly cost minimization. This consideration suggests that the future authors' work should be deeply addressed to the set-up of a multi-objective of the solar tower integrated micro gas turbine in order to reach the best compromise between the several requirements.

Acknowledgements

The plant simulations are performed by the *THERMOFLEX* software, licensed by Thermoflow Inc.

Table 4. Results summary

	Design	Yearly specific cost [€/kWh]	Solar field [m^2]	CO_2%	PES%
Base Case	-	0.189	-	-	8.99
Case#1	Jun.12:00pm	0.172	262	-51.6	56.01
Case#2	Dec. 8:00pm	0.277	2.992	-73.0	76.13

Table 5. Economic evaluation

	Is (€)	CEC(€/year)	ΔR cog (€/year)	SPB1 (years)	ΔRis (€/year)	SPB2
Case#1	186275	12520	5850	10.1	19159	5.9
Case#2	964996	18620	7587	36.8	24094	22.6

References

[1] Collado, F., Guallar, J., 2016, "Two-stages optimised design of the collector field of solar power tower plants", Solar Energy, vol.135, Pges 884-896.
[2] Saghafifar, Mohammad; Gadalla, Mohamed, 2016, "Thermo-economic analysis of air bottoming cycle hybridization using heliostat field collector: A comparative analysis", APPLIED ENERGY Volume: 190 Pages: 686-702 .
[3] Tehrani, S. Saeed Mostafavi; Taylor, Robert A., 2016 "Off-design simulation and performance of molten salt cavity receivers in solar tower plants under realistic operational modes and control strategies", APPLIED ENERGY Volume: 179 Pages: 698-715.
[4] Mokheimer, Esmail M. A.; Dabwan, Yousef N.; Habib, Mohamed A., 2015, "Performance Comparative Analysis of Three Different CSP Technologies Integrated with Gas Turbine Cogeneration Systems in Saudi Arabia", Energy Procedia Volume: 75 Pages: 527-532.
[5] M.J. Santos, R.P. Merchán, A. Medina, A. Calvo Hernández, 2016, "Seasonal thermodynamic prediction of the performance of a hybrid solar gas-turbine power plant"ENERGY CONVERSION AND MANAGEMENT Volume: 115 Pages: 89-102
[6] M. Lanchi, M. Montecchi, T. Crescenzi, D. Mele, A. Miliozzi, V. Russo, D. Mazzei, M. Misceo, M. Falchetta, R. Mancini, 2015, "Investigation into the Coupling of Micro Gas Turbines with CSP Technology: OMSoP Project", Energy Procedia, Volume 69, Pages: 1317-1326.
[7] Barigozzi, G., Franchini, G., Perdichizzi, A., Ravelli, 2014,"Simulation of Solarized Combined Cycles: Comparison Between Hybrid Gas Turbine and ISCC Plants", JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME Volume: 136 Issue: 3 Article Number: 031701.
[8] Spelling, James; Laumert, Bjorn; Fransson, Torsten, 2012, "Optimal Gas-Turbine Design for Hybrid Solar Power Plant Operation", JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME Volume: 134 Issue: 9 Article Number: 092301.DOI:10.1115/1.4006986.
[9] Aichmayer, L., Spelling J., Laumert, B.,Torsten, Fransson, 2013, "Micro Gas-Turbine Design for Small-Scale Hybrid Solar Power Plants", JOURNAL OF ENGINEERING FOR GAS TURBINES AND POWER-TRANSACTIONS OF THE ASME Volume: 135 Issue: 11 Article Number: 113001.
[10] Cameretti M.C., Ferrara, F., Gimelli, A. Tuccillo R, 2015, "Employing Micro-Turbine Components in Integrated Solar – MGT - ORC Power Plants", Proceedings of ASME Turbo Expo 2015: ASME paper GT2015-4257.
[11] M. C. Cameretti, G. Langella, S. Sabino, R. Tuccillo, 2015, "Modeling of a hybrid solar micro gas-turbine power plant", Energy Procedia. 82 (2015) 833 – 840.