Exergoeconomic and Exergoenvironmental Analysis of an Integrated Solar Gas Turbine/Combined Cycle Power Plant

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Abstract:

Integration of solar power to existing or foreseen Gas Turbine/Combined Cycle Power Plants (CCGT) is a solution attracting increasing interest, bridging solar thermal technology to a well-proven and developed energy conversion solution for the market. The integration is attractive for countries passing to natural gas as an energy feedstock, and it can improve the environmental performance with respect to the use of the single fossil fuel. In order to identify the performance and environmental benefits, a model of the plant was applied covering a one-year operation period and including the effects of surroundings variables (sun radiation and temperature of the surrounding). The model is able to predict the power plant performance, and calculates a complete exergy balance for all the components of the complex plant (both the original CCGT and the Integrated Solar CCGT (ISCCGT), including solar collectors performance with variable radiation and advanced control laws, maximizing the instant exergy collected).

A complete exergoeconomic and exergoenvironmental model was applied at the design conditions after evaluating the cost of equipment and their environmental score using a detailed Life Cycle Assessment (LCA) modelling tool. The results, applied to a power plant in Southern Poland, show that the solution can be attractive for improving the environmental performance of a CCGT, and that the capital cost is only slightly increased so that the rate of return of the investment is only marginally affected.

Keywords:

Combined-Cycle Power Plants, Solar Thermal Integration, Economics, Exergoenvironmental Analysis, Life Cycle Analysis.

1. Introduction

One of the greatest challenges of the 21st Century is to provide a dependable energy supply, limiting climate change issues connected to greenhouse gas emissions and also considering economic aspects which are necessary in light of a sustainable development. Therefore, the future requirements for the design of energy conversion systems is to reduce environmental impacts with limited drawbacks on costs.

In this light, the integration of solar power into existing or foreseen gas turbine/combined cycle power plants is a solution attracting increasing interest, bridging solar thermal technology (presently an expensive alternative when implemented alone) to a well-proven and developed energy conversion solution for the market. The integration is particularly attractive for countries such as Poland passing to natural gas as major energy feedstock, and it can improve the environmental performance with respect to the use of fossil fuels. This form of hybridization takes advantage of existing infrastructure at a conventional thermal power plant, including power transmission links to the grid and availability of space around the power plant. Nevertheless, in addition to the supplementary expense for their construction and operation, integrated solar power plants imply some environmental drawbacks in terms of land occupation, use of metal-based raw materials and possibly intensive high-technology fabrication processes.

In order to identify the advantages of technical performance, costs and environmental benefits, a comparison between a conventional combined cycle gas turbine (CCGT) and an integrated solar combined cycle gas turbine (ISCCGT), both applied to the reference case of a power plant in Southern Poland, was carried out. A model of the plant was developed covering a one-year operation period and including the effects of climatic variables (complete simulation of the solar resource profile, and off-design effects for the gas turbine performance). The model is able to predict the power plant performance, and also calculates a complete exergy balance including all the components of the complex plant in both cases (CCGT or ISCCGT).

An exergoeconomic and exergoenvironmental analysis is then performed, reconstructing the overall inventory of the two power plants (CCGT and ISCGGT) and previously running a detailed Life Cycle Assessment. The results are critically reviewed in the light of evidencing the advantages of solar integration, and of proposing possible improvements to the design configuration.

2. Methodology: Exergy, Exergoeconomic and Exergoenvironmental Analysis

The fundamental idea behind the three methodologies – exergy, exergoeconomic and exergoenvironmental analysis - is that in energy conversion systems, exergy represents the only rational basis for assigning costs and environmental impacts to the energy carriers and to the inefficiencies within the system. The exergoeconomic analysis is a well-established methodology which – following an exergy thread – identifies the most relevant components in order to achieve the cost reduction of products (electricity, heat or process streams) at the design phase [1-3].

In analogy to the exergoeconomic analysis, the exergoenvironmental analysis was developed on the same fundamental approach of the exergoeconomic methodology (Fig. 1), replacing economics with the environmental impacts associated to the energy conversion process, always considering the exergy streams within the system and using a well-established tool – Life Cycle Analysis – for the construction of the inventory and the quantification of the impacts [4-6].

As shown in figure 1, the concept of exergoeconomic and exergoenvironmental analysis consists mainly of the following three steps:

- Exergy analysis of the investigated system;
- Total revenue requirement cost analysis and life cycle assessment of each system component and system input flow;
- Assignment of costs (Exergoeconomic Analysis) and environmental impacts (Exergoenvironmental Analysis) to each exergy flow.

By applying both methods (exergoeconomic and exergoenvironmental) to the same process, it may be expected that in most cases the same process components are identified for improvement, but the results are not equivalent in general. The reason is the methodical difference between the two methods in the calculation of the construction-related effort (and economic or resource investment, respectively).

2.1. Exergy Analysis

Only an exergy analysis can identify the specific irreversibilities (or thermodynamic inefficiencies) and is uniquely required to provide guidance for system effectiveness needed in the design process. The definition of "exergy" for a thermodynamic second-law analysis is made by Rant in the Fifties [7], but the concept was developed by Gibbs in 1873 [8].

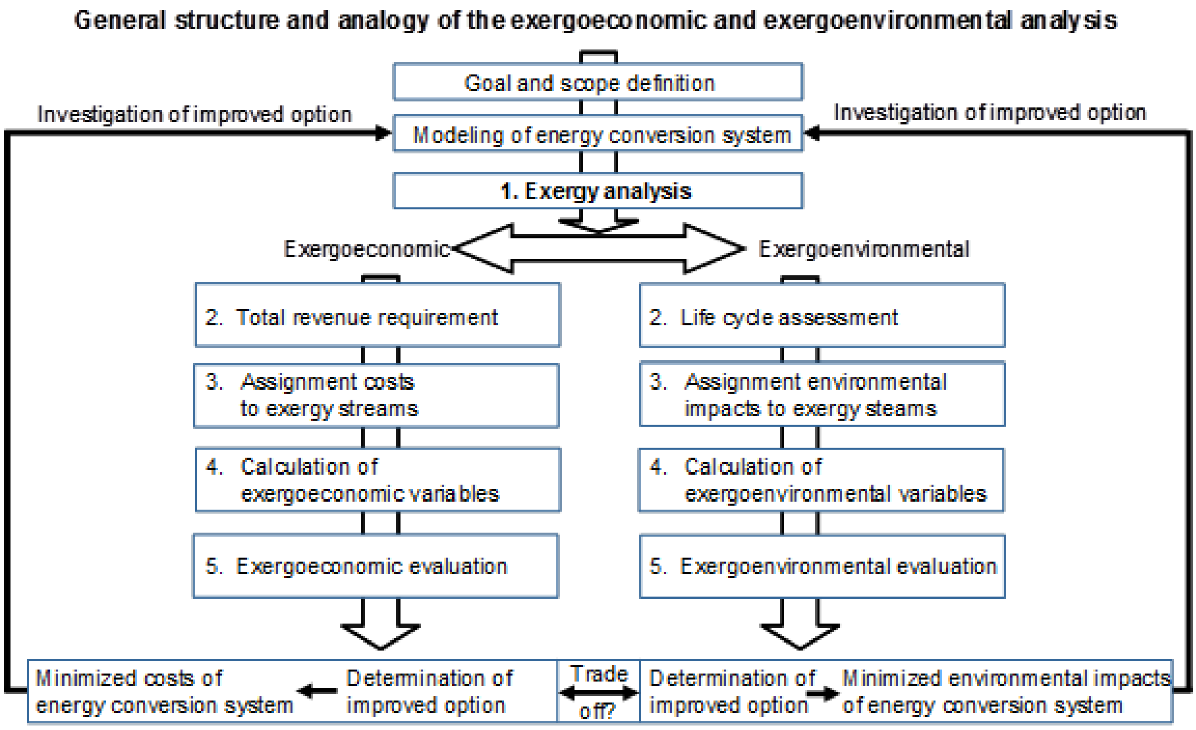

Fig. 1. Exergy, Exergoeconomic and Exergoenvironmental analysis – General structure, steps and analogies.

For exergy analysis, first, the boundaries of the system and the components involved must be defined. All relevant system sub-units that have a productive purpose should be regarded as separate components [2, 9]. Next, the exergy values of all material and energy flows within the system must be determined. The exergy of the material flows can be calculated as the sum of their physical, chemical, kinetic, and potential exergy values. In many applications of energy conversion processes kinetic and potential exergy can be neglected [2]. In exergy analysis, each component k is characterized by the definition of its exergy of product, $\dot{E}_{P,k}$ and exergy of fuel $\dot{E}_{F,k}$ shown in fig. 2.

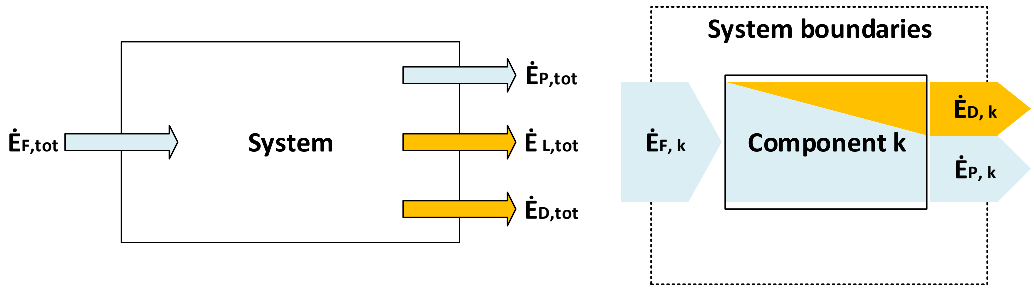

Fig. 2. Basic exergy balance for the total system and for component k.

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \quad (1)$$

$$\dot{E}_{F,tot} = \dot{E}_{P,tot} + \dot{E}_{D,tot} + \dot{E}_{L,tot} \quad (2)$$

The Exergy Destruction $\dot{E}_{D,k}$ in the k-th component is a direct measure of its thermodynamic inefficiency and can be calculated by (1). The exergy analysis provides answers to where thermodynamic inefficiencies occur in the system and allows a fair comparison of irreversibilities of different nature in a complex power plant.

2.2. Exergoenvironmental Analysis

The exergoenvironmental analysis combines an exergy analysis of the energy conversion system with an environmental analysis based on the LCA method, which considers the entire life cycle of the system and determines the environmental impacts [12]. Next, these are propagated by the exergy flows in the process. Then exergoenvironmental variables are calculated and the exergoenvironmental evaluation is carried out. At the development of the exergoenvironmental analysis, the Eco-Indicator 99 method was applied to calculate the environmental impacts for life cycle impact assessment; here, the more recent ReCiPe life cycle impact assessment method - a further development of Eco-Indicator 99 - is applied [10]. The reason for replacement is that ReCiPe includes extended environmental aspects (e.g. eutrophication of marine and freshwater aquatic environment and issues of ecotoxicity in marine water).

The results of the LCA (expressed in ReCiPe points) are assigned to the corresponding exergy flows by calculating the specific environmental impact rate of each material and energy flow b_j (expressed in ReCiPe points per exergy unit). The latter depends on the environmental impact rate $\dot{B}_j$ and the exergy rate $\dot{E}_j$ of the *j-th* stream:

$$b_j = \frac{\dot{B}_j}{\dot{E}_j} \quad (3)$$

The environmental impacts associated with the supply of an input stream (e.g. the impacts of extraction, transport and conditioning of natural gas) can be calculated directly. To calculate the values for internal streams as well as for output flows, the functional relations among the system components have to be considered. This is done by formulating environmental impact balances for all components k of the system:

$$\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out} \quad (4)$$

Basically, all environmental impacts entering a component have to exit the component associated with all output flows. Therefore, there is not only an exergy flow through the system but also a flow of environmental impacts. Besides the environmental impacts associated with incoming exergy flows, also component-related environmental impacts $\dot{Y}_k$ associated with the k_{th} component are considered. The environmental impacts that occur during the three life cycle phases construction $\dot{Y}_k^{CO}$, operation and maintenance $\dot{Y}_k^{OM}$ and disposal $\dot{Y}_k^{DI}$ constitute the component-related environmental impacts and are obtained by LCA:

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \quad (5)$$

On the basis of the exergy and environmental impact rates and the specific environmental impacts of each exergy stream in the process, the exergoenvironmental variables can be calculated for every process component. Of specific interest is the environmental impact rate $\dot{B}_{D,k}$ associated with the exergy destruction $\dot{E}_{D,k}$ in the k_{th} component, which is calculated by applying the following equation, being based on established rules for the definition of exergetic fuel and product [12]:

$$\dot{B}_{D,k} = b_{F,k} \cdot \dot{E}_{D,k} \quad (6)$$

The exergy destruction rate is multiplied by average specific environmental impacts of the exergetic fuel of the kth component $b_{F,k}$.

2.3. Exergoeconomic Analysis

The procedure for exergoeconomic analysis is analogous to that of the exergoenvironmental analysis. It combines an exergy analysis of the energy conversion system followed by an economic analysis based on the method of total revenue requirements (TRR), which considers the entire life cycle of the energy conversion system [3]. At the beginning, the total capital investment is calculated; then, based on assumptions for economic, financial, operating, and market input parameters, the yearly total revenue required is computed. This TRR value represents the production cost of the system products, and compensates all the expenditures incurred each year of the project economic life to guarantee an economic plant operation. Afterwards, the yearly variable product costs associated with the investment, operating, maintenance, fuel supply, and other expenses (cost categories) are levelized. These means are converted to an equivalent series of constant payments called annuities. In the next step, the costs are assigned to the corresponding exergy flows by calculating the specific cost rate of each material and energy flow.

Since exergoeconomic analysis is well-established, only formulae in analogy to those used for exergoenvironmental analysis are presented in Table 1.

3. Combined Cycle Gas Turbine (CCGT) Layout

A power plant under construction in Stalowa Wola, Poland is the reference case and the starting point for the following solar energy integration study. The system under investigation is a CCGT with a three-pressure level Heat Recovery Steam Generator (HRSG). A model of the CCGT was preliminary built with the use of Equation Solver Modular System (ESMS), a simulation tool developed for complex power plant simulations [12] [7]. The power plant is equipped with the 9F.05 gas turbine produced by General Electric - a 50 Hz heavy-duty gas turbine with a design power output of 299 MW [13]. The gas turbine is synthetically represented – for the purpose of the CCGT - by the values of temperature, mass flow rate and by the composition of the flue gases. The mathematical model of the three-pressure HRSG and of the steam plant island follows the scheme represented in fig.2. The cycle layout machine has double-casing turbines with combined HP-IP sections and double flow in the low-pressure section; steam reheating at the intermediate pressure level is included [14].

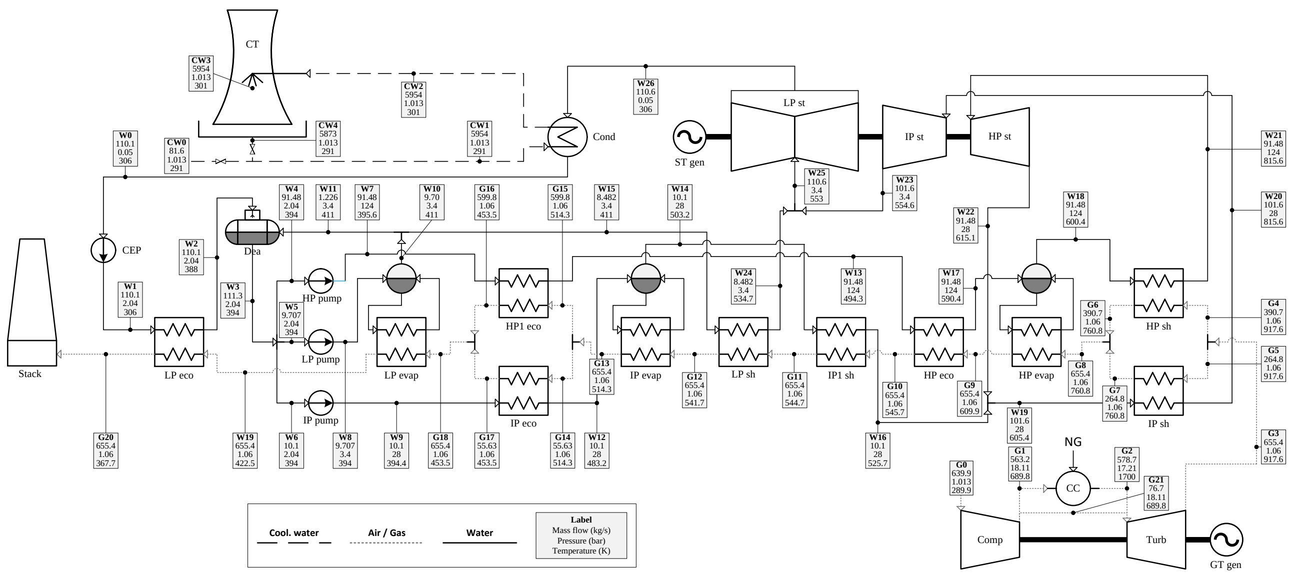

Fig.2 Combined Cycle Gas Turbine layout.

Table 1. Main equations for exergoeconomic and exergoenvironmental analyses.

Exergoeconomic Analysis	**Exergoenvironmental Analysis**
Exergy stream cost rate: $\dot{C}_j = c_j \cdot \dot{E}_j$	Exergoenvironmental stream impact rate: $\dot{B}_j = b_j \cdot \dot{E}_j$
Component cost balance: $\sum \dot{C}_{j,k,in} + \dot{Z}_k = \sum \dot{C}_{j,k,out}$	Component environmental impact balance: $\sum \dot{B}_{j,k,in} + \dot{Y}_k = \sum \dot{B}_{j,k,out}$
Component-related cost rate: $\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM}$	Component-related environmental impact rate: $\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI}$
Component relative cost difference: $r_k = \frac{c_{P,k} + c_{F,k}}{c_{F,k}}$	Component relative environmental impact difference: $r_{b,k} = \frac{b_{P,k} - b_{F,k}}{b_{F,k}}$
Component exergoeconomic factor: $f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$	Component exergoenvironmental factor: $f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + \dot{B}_{D,k}}$

The modelling approach requires the definition of specific temperature differences between flue gases and water inside the HRSG. The design-point analysis indicated that it is possible to produce 288 MWe by the gas turbine and 152 MWe by the steam turbines with a 57,9% overall plant electric efficiency. After sizing the heat exchangers, it was possible to perform also an annual off design analysis, where the ambient conditions affect gas turbine performance. A detailed description of the reference design data assumed and results in terms of energy and exergy can be found in [15].

3.1. Solar Thermal Integration Concept

Solar thermal hybridization is in principle an advantageous improvement, consisting in the addition of a solar heat generating field to an already existing fossil fuel power plant. However, the scope of the integration must be clearly defined. In practice, a solar thermal integrated power plant may be operated flexibly in the fuel saving or power boosting mode. Various hybrid installations can be exemplified: PTC50 Alvarado (Acciona Energy Company) is a 50 MWe solar power plant integrating a central receiver solar system with biomass and natural gas firing [16]. A second hybrid Concentrated Solar Power-Biomass plant using parabolic-trough solar field is also operated in Spain by Thermosolar [17]. The only coal-hybrid CSS Colorado Integrated Solar Project was decommissioned [18]. The idea of integration presented in this study is to reduce the bottlenecks of the evaporation process by adding solar heat in parallel. Three groups of solar collectors assembled in solar fields support evaporators operating inside the HRSG (see fig. 3 for a concept layout). The solar integration is designed taking care that the addition of supplementary heat to evaporators from a parallel solar heat exchanger contributes to diminishing the local temperature difference between the water/steam and gas streams in the HRSG; this increases the power plant energy efficiency through the boost of the steam cycle power output, resulting from the extended heat recovered in the HRSG; consequently, it determines a decrease of the stack temperature. Thereby, the solution here proposed produces both a fuel saving (substituting fuel with solar integration) and a power boosting effect (due to solar integration and improvement of exhaust gas recovery).

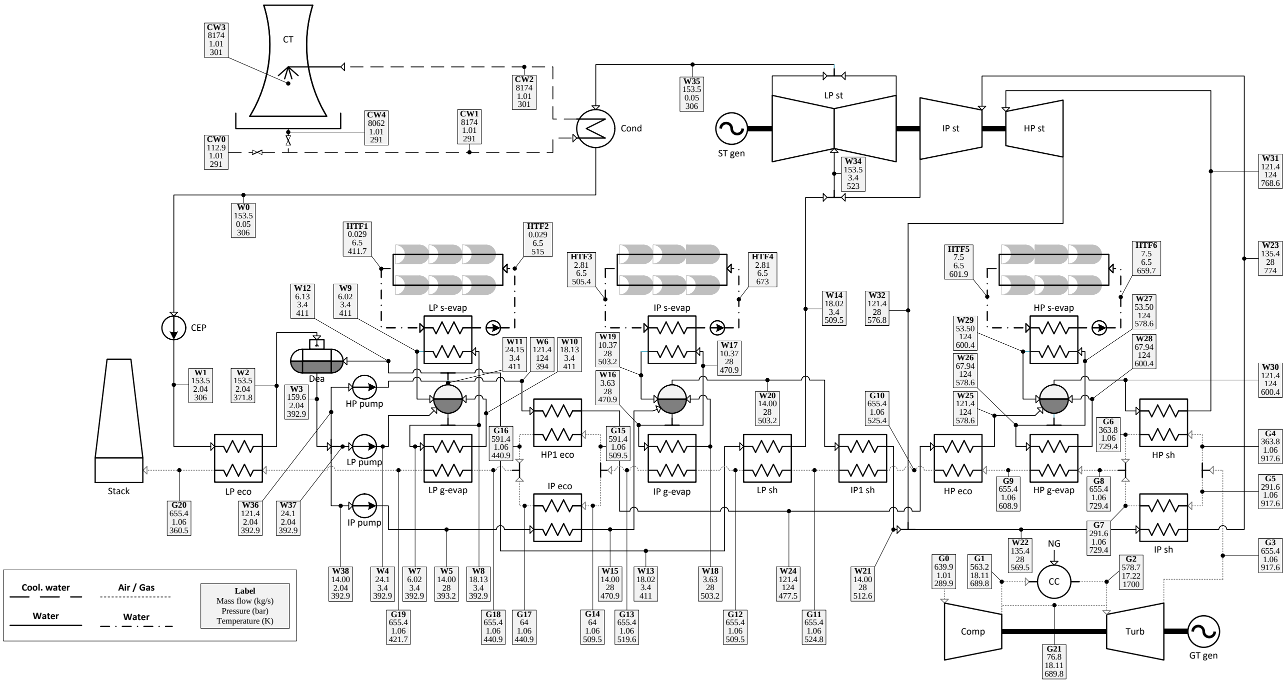

Fig.3 Integrated Solar Combined Cycle Gas Turbine concept layout.

3.2. ISCCGT model

The Integrated Solar Combined Cycle Gas Turbine (ISCCGT) plant model demands the definition of the design (solar-provided) heat rates supporting each level of evaporation. The detailed methodology is described in [15]. The useful heat gain from each solar collector loop was calculated multiplying the solar collector efficiency by the solar radiation reaching the collector surface. The solar collector model is based on the 2-nd order Bliss Equation [19]:

$$\eta_{SC} = \eta_0 - a_1 \frac{\Delta T_m}{G} - a_2 \frac{\Delta T_m{}^2}{G} \tag{7}$$

Where

$$\Delta T_m = T_{HTF} - T_{amb} \tag{8}$$

The efficiency parameters were provided by manufacturers. The LP evaporator is supported by a solar field using *PolyTrough* 1800 collectors with pressurized water as heat transfer fluid, manufactured by *NEP SOLAR AG* [20]; for the high and intermediate HRSG pressure levels EuroTrough collectors *ET-150* are considered [20] with SYLTHERM *800* [21] as heat transfer fluid. The whole year simulation of solar collectors revealed that the design morning hour of 17th July provided one of the highest useful heat gain output from the collectors, with an ambient temperature close to ISO standards (16.7°C). The scale of evaporator support and the size of solar fields were defined for this design condition. A satisfactory level of the design heat duties of the solar back-up evaporators was found performing a sensitivity analysis. The integration should assure an effective decrease of stack temperature of more than 5 K. Consequently, 40, 20 and 70 MW of thermal energy should be provided by the solar fields at the low, intermediate and high-pressure evaporator levels respectively.

An innovative concept applied to this solar integration case was to arrange the collector loops for the high and intermediate pressure evaporators collectors as a flexible (dynamic) solar field. Firstly, following good practice in solar thermal energy conversion systems, a solar multiplication factor SF=1.5 was applied. The configuration and amount of loops dedicated to the intermediate or high-pressure evaporators can be adapted by a simple collector switching arrangement to the meteorological conditions, with priority given to IP solar field as less demanding and capable of operating at higher efficiency (because of the lower absorber temperature). Additionally, the solar collector control mode was enhanced implementing a control routine determining the correct increase of HTF temperature. Rather than setting $\boldsymbol{\Delta} T_{HTF}$ as a fixed value, its value is dynamically adapted according to the radiation and environmental conditions. The fundamental idea of this control law is to maximize the collector exergy efficiency [22][23].

4. Results

For the ISCCGT, the design hour simulation indicated that the steam power output can be increased to 194 MWe and the fossil full power plant electric efficiency can reach 63.45%. The energy efficiency of the ISCCGT is calculated with a marginal approach, that is, assuming that only natural gas contributes to the energy input. Hence, the marginal electrical efficiency is raised more than 5 percentage points. The CO_2 emission factor is decreased from 346 gCO_2/kWh to 315 gCO_2/kWh. The exhaust gas temperature at the stack is reduced from 367.7 K to 360.5 K [15], thereby proving that the hybridization process is effective and reaches its design goals.

At design conditions, the exergetic efficiency decreases to 47.85 % with respect to the CCGT value of 55.7 %. This results from the fact that solar radiation is considered as a high-exergy resource. Indeed, if solar radiation were taken as a free exergy input, the marginal (fuel-only) exergetic efficiency would instead rise to 60.99 %.

4.1. Results - Exergoeconomic Analysis

The Exergoeconomic Analysis is run for the design operating conditions. The results show that the cost of exergy destruction in the combustion chamber is dominant for both power plant configurations, on account of the high irreversibility of the combustion process. Reduction of this term depends on materials and cooling techniques applied, and on the gas turbine pressure ratio. This type of improvement is beyond the scope of the present analysis.

The impact of hybridization on the Power Plant Capital Costs is relevant, as is shown in Table 2. A cost breakdown referring to the major components is shown in Table 3. However, the economic balance is dominated by the cost of natural gas, so that a substantially higher capital cost exposure can be well motivated (the economic payback return time being about 5 years).

Considering the ISCCGT plant, a large component-related cost (indeed the second contribution in overall relative terms) is associated with the solar collectors. The capital + O&M cost for the three solar fields represents more than 40% of the overall power plant investment costs. Parabolic trough solar technology is the most proven solar power technology; however, the capital cost of the solar collector fields represents a major add-on with respect to that of the conventional combined cycle. This is an important limit for the large commercial-scale development of CSP technology; however, ISCCGT power plants represent a bridging technology with respect to solar-only power plants of similar size, because solar energy represents on the whole a marginal support to the HRSG, substituting partially natural gas and improving – in the present case – the flue gas heat recovery process. In terms of fuel cost, since that of solar energy is assumed to be zero, the resulting cost of exergy destruction for the collectors is accounted as 0 $/hour.

Other meaningful components to the cost build-up are the condenser, HP evaporator, HP superheater and steam turbine for both CCGT and ISCCGT. The low values of related f_c suggest that a decrease in cost rate of exergy destruction of these components is possible by a higher investment cost. This solution would lead to an improvement of the system performance.

Table 3. Specific capital cost for the two different power plant configurations ($/kW).

Component	ISCCGT	CCGT
HRSG	121	101
Gas turbine	366	401
Steam turbine	199	188
Condensing system	139	111
Solar collectors	395	0
Others	62	67
Total	**1282**	**867**
Fixed O&M ($/kW-y) or [$/kWh]	20.73 [0.0026]	13.80 [0.002]
Fuel-related running cost ($/kWh)	0.0628	0.0633

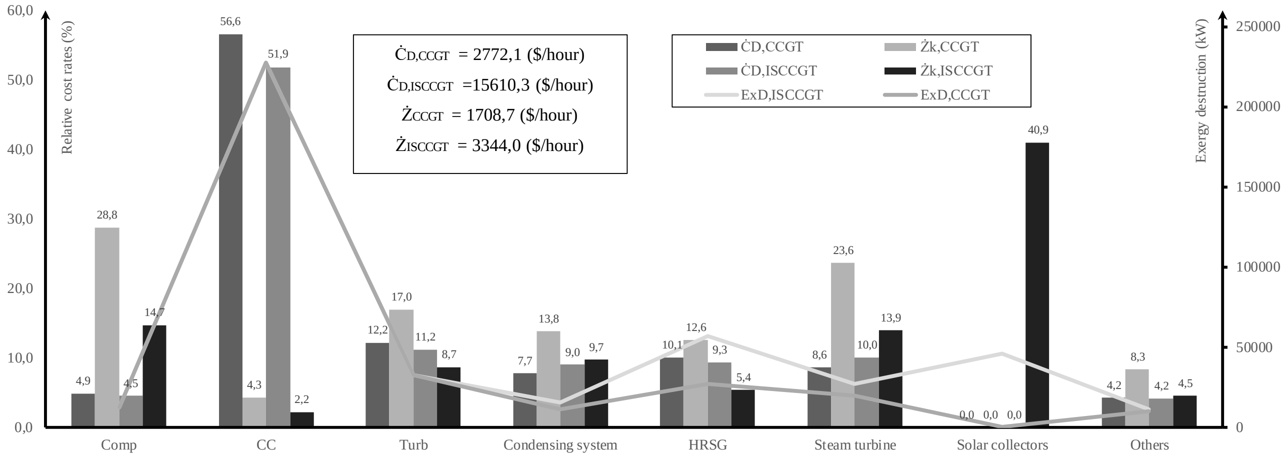

Fig. 4 Relative exergy destruction and component-related cost rates.

4.2. Results –Exergoenvironmental Analysis

Following the results of the LCA inventory, the major contributions to the system-related environmental impact rate come from those components construction requiring significant amounts of metals for construction, such as generators, HRSG and steam turbine. When considering the ISCCGT configuration, the construction of the solar fields is dominant within the system-related environmental impact rate. However, this contribution is not comparable to that of the combustion chamber, since the environmental burden of the gas turbine emissions is completely allocated to this component.

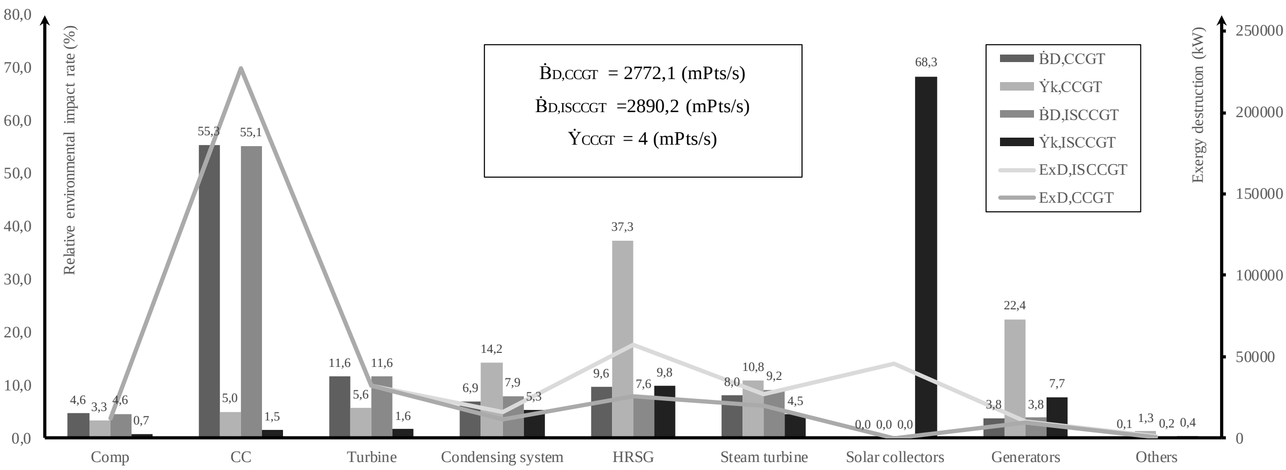

Fig. 5 Relative exergy destruction and component-related environmental impact rates.

Despite the increase in $\dot{Y}_{tot}$, the specific environmental impact per unit of energy produced by the integrated solar power plant (38.9 Pts/kWh) is lower than that of the conventional combined cycle (40.2 Pts/kWh). Further insight can be gained re-interpreting the impact with traditional LCA methodology. Figure 6 presents the main reductions of the specific impact achievable by solar integration sorted by category and referred to the functional unit (1 kWh). Some of them, such as land occupation and metal depletion, have negative values. In particular, the metal depletion for the ISCCGT is higher than that of the CCGT due to the materials stock needed for the construction of the solar fields. The most significant savings are linked to climate change and to depletion of fossil fuels. This result is confirmed by the carbon footprint, whose profile is resumed in terms of a return payback analysis, presented in Figure 7. The hybrid power plant, thanks to its diminished consumption of natural gas has a lower CO_2-Eq. emission per kWh of energy. This fact leads to an important reduction of CO_2-Eq. emissions throughout the lifetime of the power plant.

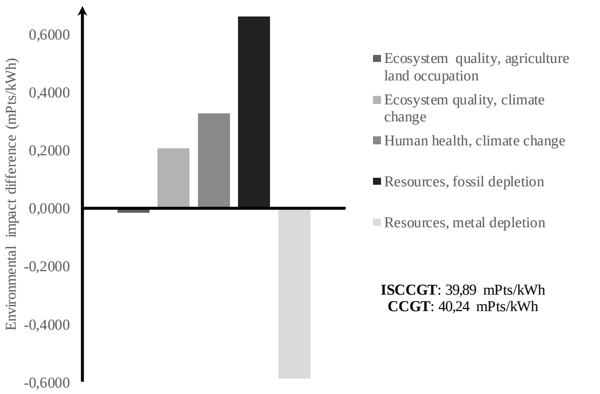

Fig. 6 Environmental impact reduction by ReCiPe impact category.

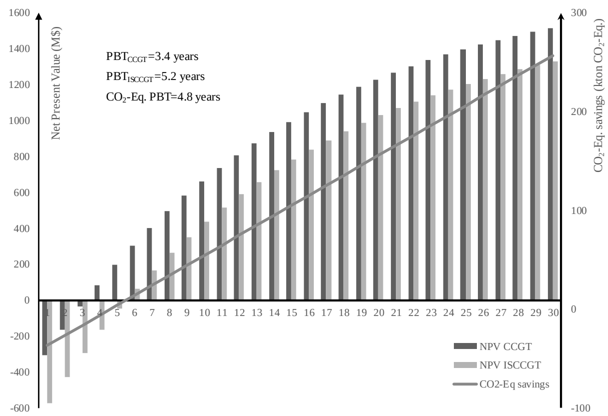

Fig. 7 Lifetime NPV (left scale) and greenhouse emissions (right scale)analysis.

5. Conclusions

The present work investigates the environmental and economic performance of an ISCCGT and compares it with that of the correspondent conventional CCGT by a detailed exergoeconomic and exergoenvironmental analysis.

Specifically, the ISCCGT hybridization was aimed to improve heat recovery in the HRSG, reducing pinch problems and achieving a lower stack temperature; moreover, a dynamic allocation of the CSP solar fields supporting the mid- and high-pressure evaporators, and flow rate control minimizing the solar collectors exergy destruction + loss are applied, providing notable results for the year-round off-design operation of the plant.

The capital cost is increased about 48% by solar hybridization, but the rate of return of the investment (5,2 years) is only marginally affected because of the combined effect of saving the expensive natural gas resource and power boosting. In addition, it should be considered that the power plant is located in a region that does not offer an optimal solar irradiation. The solar field surface, and so the investment cost, is then larger than what would be needed in areas with better climate conditions.

The exergoeconomic and exergoenvironmental analyses, including a detailed LCA, were applied to the design operating conditions. The results confirm that, despite a higher $\dot{Y}_{dot}$, the ISCCGT technology offers significant environmental advantages thanks to its lower consumption of fossil fuel per unit of produced energy, with consequent reduction of greenhouse gases emissions throughout the operational lifetime.

Nomenclature

a_1 collector constant, m^2K/W
a_2 collector constant, m^2K^2/W
$\dot{B}_j$ environmental impact rate of the j-th material flow, ReCiPe mPoints/s
b_j specific environmental impact with the production of the j-th material flow per exergy unit of the same flow, ReCiPe mPoints/GJ
$\dot{C}_j$ cost rate of the j-th material flow, \$/h
c_j specific costs with the production of the j-th material stream per exergy unit of the same flow, \$/GJ
$\dot{E}$ exergy rate, MJ/s
G overall radiation, W/m^2
$\dot{Y}$ component-related environmental impact rate associated with the life cycle of the component, ReCiPe mPoints/s
$\dot{Z}$ component-related cost rate associated with the life cycle of the component, \$/h

Greek symbols

Δ variation
η efficiency

Subscripts and superscripts

amb ambient
D destruction
F fuel
HTF heat transfer fluid
P product
0 optical
sc solar collector

References

[1] Tsatsaronis G., Combination of Exergetic and Economic Analysis in Energy Conversion Processes. In: Reis, A.; Smith, I.; Peube, J.L.; Stephan, K. (Ed.): Energy Economics and Management in Industry - Proceedings of the European Congress, Algarve, Portugal, April 2-5 1984. Volume 1: Energy Economics Oxford et al. Pergamon Press: 151-157.

[2] Bejan A., Tsatsaronis G., Moran M., Thermal Design and Optimization. New York, USA, John Wiley, 1996.

[3] Tsatsaronis G., Cziesla F., Thermoeconomics. In: Meyers R, editor: Encyclopaedia of Physical Science and Technology, Volume 16, New York: Academic Press., 2002: 659-680.

[4] Meyer L., Buchgeister J., Schebek L., Tsatsaronis G., Formation of Environmental Impacts in Energy Conversion Processes revealed by a novel Exergoenvironmental Analysis", Proceedings of ASME IMECE 2007, Nov. 11-15, 2007, Seattle, WA, USA. IMECE2007-42210.

[5] Meyer L., Tsatsaronis G., Buchgeister J., Schebek L., Exergoenvironmental analysis for evaluation of the environmental impact of energy conversion systems. Energy 2009, 34(1):75-89.

[6] Buchgeister J., Exergoenvironmental analysis - A new approach to support design for environment of chemical processes? Chem. Engineering & Technology 2010, 33(4): 593–602.

[7] Rant Z., Exergie, ein neues Wort für "Technische Arbeitsfähigkeit". Forschung auf dem Gebiete des Ingenieurwesens 1956, 22:36-37.

[8] Gibbs J., A method of geometrical representation of thermodynamic properties of substances by means of surfaces. Trans. of the Connecticut Academy, 1873, II: 382-404.

[9] International Organization for Standardization (ISO), Environmental Management - Life Cycle Assessment. European Standard EN ISO 14040 and 14044, 2006, Geneva, Switzerland

[10] Goedkoop M., Heijungs R., Huijbregts M., De Schryver A., Struijs J., van Zelm R., ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. Report I: Characterisation, Ministry of Housing, Spatial Planning and Environment (VROM), The Netherlands, 2009.

[11] Lazzaretto A., Tsatsaronis G., SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. Energy 2006;31(8-9):1257–1289

[12] Carcasci C., Facchini B., A numerical method for power plant simulations, Journal of Energy Resources Technology 1996,118: 37-43.

[13] General Electric, GE Power Generation. Available at:<https://powergen.gepower.com/heavy-duty-gas-turbines/9f-05-gas-turbine.html>. [Accessed 27th March 2016].

[14] Doosan Skoda Power, Products and Customer Service, 2015.

[15] Petela K., Manfrida G., Liszka M., Carcasci C., *Integrating Solar Power in large Combined-Cycle Power Plants*, Proceedings of ECOS 2015- the 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, June 30th -July 3rd, 2015, Pau, France, ISBN: 978-295555390-9

[16] Baharoon D.A., Rahman, H.A., Omar, W.Z.W., Historical development of concentrating solar power technologies to generate clean energy efficiently – A review, Renewable and Sustainable Energy Reviews 41, 2015: 996-1027.

[17] Collective work, Thermosolar Borges, The first commercial CSP hybridized with biomass in the world, Abantia brochure, April 2012.

[18] National Renewable Energy Laboratory, Concentrating Solar Power Projects, Project overview- Available at: http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=75. [accessed 09.2.2014].

[19] Duffie J. A., Beckman W. A., Solar Engineering of Thermal Processes, Wiley, 1991.

[20] Collective work of SPF Institut für Solartechnik, Technical data of *PolyTrough* 1800, ordered by NEP SOLAR AG, test report No.: *C1549LPEN*.

[21] Collective work, Extension, Test and Qualification of EUROTROUGH at Plataforma Solar de Almeria, Project funded by the European Community under the Non-Nuclear Energy Programme, 2003 report No.: ERK6-CT1999-00018.

[22] Collective work, Syltherm 800 technical data sheet, the Dow Chemical Company, 2001, report No.: CH-153-311-E-1101.

[23] Manfrida G., Gerard V., Maximum Exergy Control of a solar thermal plant equipped with direct steam collectors, Int. J. of Thermodynamics 2008, 11: 143-149.

[24] Manfrida G., Kawambwa S.J.M., Exergy Control for a Flat-Plate Collector/Rankine Cycle Solar Power System, Journal of Solar Energy Engineering, 1991, 113: 89-93.