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Thermo-economic assessment of an externally fired hybrid CSP/biomass gas turbine and organic Rankine combined cycle

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Abstract

This paper focuses on the thermo-economic analysis of a hybrid solar-biomass CHP combined cycle composed by a 1.3-MW externally fired gas-turbine (EFGT) and a bottoming organic Rankine cycle (ORC) plant. The primary thermal energy input is provided by a hybrid concentrating solar power (CSP) collector-array coupled to a biomass boiler. The CSP collector-array is based on parabolic-trough concentrators (PTCs) with molten salts as the heat transfer fluid (HTF) upstream of a fluidized-bed furnace for direct biomass combustion. Thermal-energy storage (TES) with two molten-salt tanks (one cold and one hot) is considered, as a means to reducing the variations in the plant's operating conditions and increasing the plant's capacity factor. On the basis of the results of the thermodynamic simulations, upfront and operational costs assessments, and considering an Italian energy policy scenario, the global energy conversion efficiency and investment profitability are estimated for 2 different sizes of CSP arrays and biomass furnaces. The results indicate the low economic profitability of CSP in comparison to only biomass CHP, because of the high investment costs, which are not compensated by higher electricity sales revenues.

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Keywords: *CHP; biomass; gate cycle; concentrating solar power; ORC;*

1. Introduction

Hybrid concentrating solar power (CSP) and biomass-fired combined heat and power (CHP) plants can contribute towards the goals of EU energy policy [1]. CSP technologies generate electricity by

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concentrating the incident solar radiation onto a small area, where a heat transfer fluid (HTF) is heated. This thermal energy is then transferred by the HTF to a power-generating system to drive a thermodynamic energy-conversion cycle. The integration of thermal energy storage (TES) can make CSP dispatchable and facilitate the overall energy conversion process [2]. Nevertheless, solar energy is inherently intermittent such that even with TES the capacity ratio of solar power plants is limited; many hybrid solar/fossil-fuels plants are currently in operation to alleviate this aspect of solar power. Biomass can be an interesting fossil fuel to consider for this application. Although biomass often exhibits seasonal availability variations and there are issues concerning the logistics of supply, the hybridization of CSP with biomass combustion is complementary, both seasonally and diurnally [3]. The performance of a variety of system configurations of such hybrid plants under a variable solar input has been investigated in literature to some extent. In the case of CSP-biomass hybrid plants with a steam-turbine inlet temperature >500 °C and pressure >100 bar, solar towers emerge as the most suitable technology, with direct-steam systems preferred in plants without TES and molten salts preferred in plants with TES. However, no attention has been paid to hybrid CSP plants with PTCs and thermal source temperatures >430 °C, and their integration with gas turbines. Most of the applications of this arrangement consider the use of solar towers or dishes as solar collectors, and compressed air as HTF with an internally fired cycle configuration [4]. None of the previous research in this area has addressed the integration of parabolic-trough CSP and molten salt TES with biomass combustion in externally fired gas turbines (EFGT). The use of biomass has been widely investigated in the literature as it provides added socio-economic and environmental benefits, especially when the organic by-products are also utilized [22-24]. The influence of part load efficiencies on optimal EFGT operation was investigated in Ref. [5], while the improved energy performance and profitability of employing a bottoming ORC for both power and cogeneration has been previously investigated in different energy-demand segments [6,7,25]. The literature on ORC systems and working fluid selection for waste-heat recovery applications is also extensive [8,9,10]. In particular, a combined cycle with a 1.3-MW biomass EFGT top-cycle and 0.7-MW bottoming ORC plant was proposed in Ref. [11]. In the present paper, which goes beyond the work proposed in Ref. [11], the energy performance and economic profitability of a 2-MWe hybrid CSP-biomass EFGT with a bottoming ORC are investigated in in a CHP configuration, taking into account the influence of the heat demand, biomass cost and the electricity selling prices for the solar and biomass fraction available in the Italian energy framework. Two different CSP sizes are considered, with corresponding TES capacities. Baseload operation (constant output power with a modulating biomass combustor) is also compared to a variable CHP output (constant biomass reactor output). The aim of the paper is thus to propose a standard thermo-economic methodology for energy balances and the financial appraisal of hybrid CSP/biomass CHP plants in a number of energy-demand segments. The methodology adopts a combination of a solar-energy yield assessment, a simplified representation of the load demands, a costs assessment and a discounted cash-flow analysis. The paper aims to evaluate if, and at what extent, the investment costs for the CSP section of such a plant are justified by the increased plant operational flexibility, conversion efficiency and electricity sales revenues, in comparison to a 100% biomass-only fired power-generating plant.

2. Technology description and thermodynamic modelling

The proposed hybrid CSP-biomass EFGT configuration is shown in Fig 1. The solar-collector section is based on ENEA technology [13] and produces heat at ~550 °C. This technology is based on PTCs and a mixture of molten salts (sodium and potassium nitrates) both as the HTF and as the TES medium. These salts are liquid at 240 °C and stable up to 600 °C [1,14]. PTC technology is the most widespread CSP solution, and the proposed configuration adopts a receiver with a novel selective coating (high absorbance

at solar wavelengths, low emissivity at higher wavelengths), is stable to 600 °C, with concentration system and connectors tailored to for high temperatures and limited costs.

The TES section is a typical two-tank molten-salt system, where a higher temperature difference between the two tanks of molten salts (260 °C instead of the 100 °C employed in conventional systems) allows for reduced tank size and limited heat losses [15]. This technology was firstly tested at lab scale in a PTC facility at the ENEA Casaccia Research Center (Rome, Italy) and then demonstrated in the Archimede demonstration plant in Priolo Gargallo (Syracuse, Italy) [13].

The solar collector field is sized to supply 50% of the total rated thermal input to the plant. It is assumed that the compressed air is heated in the PTC field up to 500 °C, which corresponds to a thermal energy input of 3670 kWt. The required area of the solar field is evaluated assuming a standard direct normal irradiance (DNI) of 800 W/m2. Each solar collector measures 5.9 × 12 m with a useful intercepting area of 67.3 m2. The Solar Collector Assembly (SCA) is composed of 8 collectors controlled by a central driving unit, and each solar field line has 8 SCAs. The net photo-thermal efficiency is 65%.

The solar plant is sized assuming two scenarios of 1.3 and 5.0 hours of TES capacity (charging time 6 hr), with multiple solar ratios and total required ground area respectively of 1 - 1.5 and 21,253 and 32,300. The required ground area is estimated assuming a distance between each collector line of 2.5 times the PTC aperture size. The site of Priolo Gargallo (Siracusa, Italy, Latitude 37°08'04", Longitude 15°03'00", 30 m a.s.l., solar collector positioning N-S) has been selected, resulting in a DNI of 2,256 kWh/m2yr and an effective radiance of 1,760 kWh/m2yr. Adopting the methodology proposed in Ref. [16] and assuming an annual system availability of 95%, collector thermal losses of 50 kW per line, network losses of 60 W/m (300 m pipe length) and subtracting the rejected energy losses when exceeding the TES capacity of the tanks (due to daily solar irradiance fluctuations) that amount to 12 and 13% in the small and large TES-size scenarios respectively, the useful solar thermal energy input to the CHP plant is 8,229 and 12,202 MWh/yr for the two assumed CSP and TES sizes (Cases B,D and C,E in Table 3, respectively).

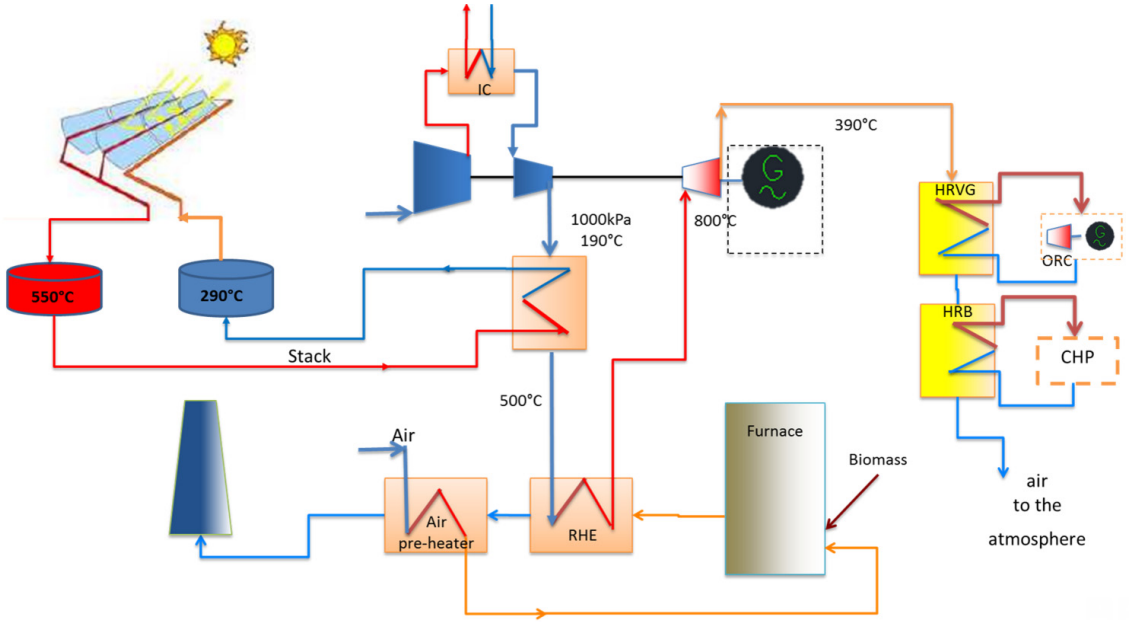


Figure 1. Layout of the hybrid solar-biomass EFGT-ORC combined cycle power plant

A detailed thermodynamic analysis of the EFGT with bottoming ORC is described in Ref. [11], considering only biomass input fuel. The overall cycle pressure ratio is 12, and the TIT is 800 °C; this low temperature allows a low cost for the heat exchanger material (steel). Combustion air in the furnace is taken from the ambient for a more flexible regulation, since the circuit of the working air flowing into the turbine and the circuit of the combustion air flowing into the biomass furnace are independent. Furthermore, the gas exiting the turbine is pure air, without impurities coming from combustion. Since the temperature of the compressed air entering the furnace is high (500 °C), a pre-heater for the combustion air and intense flue-gas recirculation is adopted in order to obtain an acceptable value of the furnace combustion efficiency.

The bottoming cycle of the combined cycle is realised by an ORC in recuperative configuration, with the adoption of a Recuperative Heat Exchanger (RHE) and a "dry" fluid (toluene) as described in Ref. [11].

The rated electric power is 2,083 kWe, with an auxiliary consumption of 6%, a thermal power output for CHP of 960 kW at 104 °C, a condenser temperature of 40 °C (a low-grade thermal-energy demand is assumed), a $\Delta T_{\min}$ of the CHP heat exchanger of 10 °C (resulting in a 60% heat recovery). The modelling results report a net electric efficiency (electricity/input biomass energy at nominal solar energy input) of 23% for the 100% biomass (Case A) and 46% for the hybrid cycles (Cases B to E). The part load efficiency of the biomass boiler in Cases B and D has been neglected, and a biomass furnace efficiency of 80% has been assumed, with LHV = 2.86 kWh/kg. The selected case studies are given in Table 1.

Table 1. Description of the five case studies considered in the present work

Case study	A	B	C	D	E
Biomass furnace size (kW_t)	9,050	9,050	9,050	4,523	4,523
Biomass input (t/yr)	25,694	22,865	21,462	13,999	13,999
Net electric generation (MWh/yr)	15,741	15,741	15,741	10,761	11,818
Equivalent operating hours (hr/yr)	8,040	8,040	8,040	5,496	6,036

Operating strategy. Case A: baseload with fixed biomass input; Cases B and C: baseload with modulating biomass boiler; Cases D and E: variable with fixed biomass input.

3. Thermo-economic analysis

A profitability assessment of the hybrid CSP-biomass combined EFGT-ORC CHP plant is proposed in this section. For each case study, the scenarios of: (1) only electricity generation, and (2) cogeneration of heat and power, as well as a sensitivity analysis to the heat demand intensities and the biomass purchase price are considered. A basic strategy is assumed here of electricity fed into the grid, given that CHP plants are eligible for feed-in tariffs in the Italian energy market.

3.1 Costs assessment

The turnkey costs were estimated by means of interviews and data collection from manufacturers of the selected technologies [11]. In particular, the following sources have been considered: Saturn 20 Solar Turbines; Turboden for the ORC genset; Uniconfort for biomass boiler, hot air genset and heat exchanger (maximum temperature of 800 °C). For the CSP section, PTCs and TES costs were derived from NREL cost figures [18-20], according to the lessons learnt from ENEA/Enel Archimede project [21]. In particular, unitary PTC costs of 250 Eur/m2, TES costs of 25 kEur/MWh and a 30% cost increase for

installation, piping and the HTF are assumed. The annual O&M costs are assumed 4% of the turn key cost and the ash discharge are accounted for assuming unitary cost of 70 Eur/t ash.

3.2 Energy revenues and financial assumptions

The financial appraisal of the investment is carried out assuming the following hypotheses: (i) 20 years of operating life and feed-in tariff duration for renewable electricity; no 're-powering' throughout the 20 years; zero decommissioning costs, straight line depreciation of capital costs over 20 years; (ii) maintenance costs, fuel supply costs, electricity and heat selling prices held constant (in real 2016 values); (iii) cost of capital (net of inflation) equal to 5%, corporation tax neglected, no capital investments subsidies. Electricity is sold to the grid at the feed-in electricity price available in the Italian energy market [12], which is 231 and 420 Eur/MWh respectively for biomass electricity (including the High Quality CHP premium) and CSP electricity (subsidy plus electricity selling price). These figures are valid in the considered power size range, TES size, adoption of BAT for air emissions abatement, and use of agricultural by-products from local and sustainable supply chains [12]. The electricity generation is calculated at 8,040 operating hours per year. Thermal energy cogenerated is sold at 80 Eur/MWh.

4. Cost of energy and profitability assessment results

Figure 2 reports on the energy performance (global electricity efficiency and solar share) and Levelized Cost of Energy (LCE) at different biomass supply costs (in the case of electricity-only production). The global electricity efficiency is the ratio of electricity annual sales and biomass energy input, while the solar share is the percentage of solar energy input on a yearly basis. The profitability assessment results are shown in Figures 3 and 4, which report respectively the NPV and IRR as a function of the biomass supply cost, for electricity-only and cogeneration scenarios. The hybridization of the biomass EFGT with CSP allows a higher global electricity efficiency to be achieved, given the reduced biomass requirements, but increases the LCE and reduces the IRR in all scenarios. In fact, despite the increased global energy efficiency of the solar input, and the higher electricity selling price of the solar-based fraction, the investment costs of the PTCs with molten salts as HTF are very high and make this investment not competitive, in particular at small scale as in the proposed application. This is more evident at higher solar shares (Cases C and E, in comparison to Cases B and D) where the larger PTC areas (and consequently investment costs) make the investment less profitable.

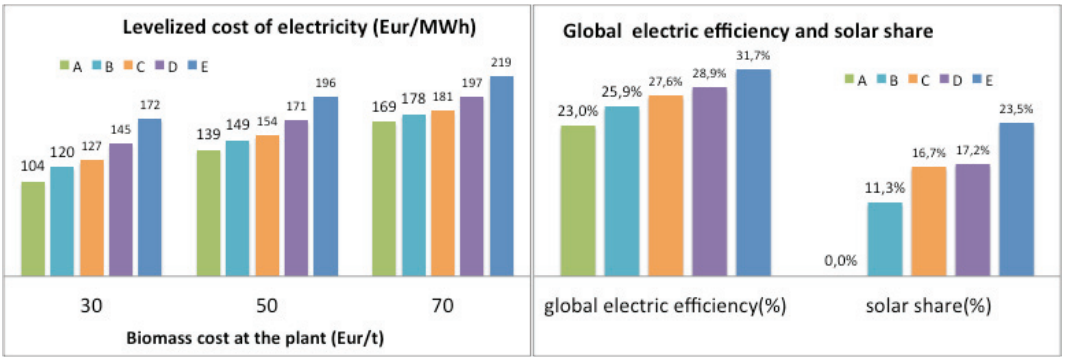


Figure 2. LCE as a function of the biomass purchase price (left) and energy balances as resulting from thermodynamic modelling (right) for Cases A to E

Moreover, the option of fixed biomass furnace operation and variable electricity output (on the basis of the solar input energy fluctuation) in Cases D and E is also less profitable than the corresponding cases of baseload operation (Cases B and C), despite being more efficient for the higher solar share. The NPV, as opposed to the IRR, increases when increasing the solar share (Cases B and C) because of the higher revenues from electricity sales; this is more evident the higher is the avoided biomass supply cost.

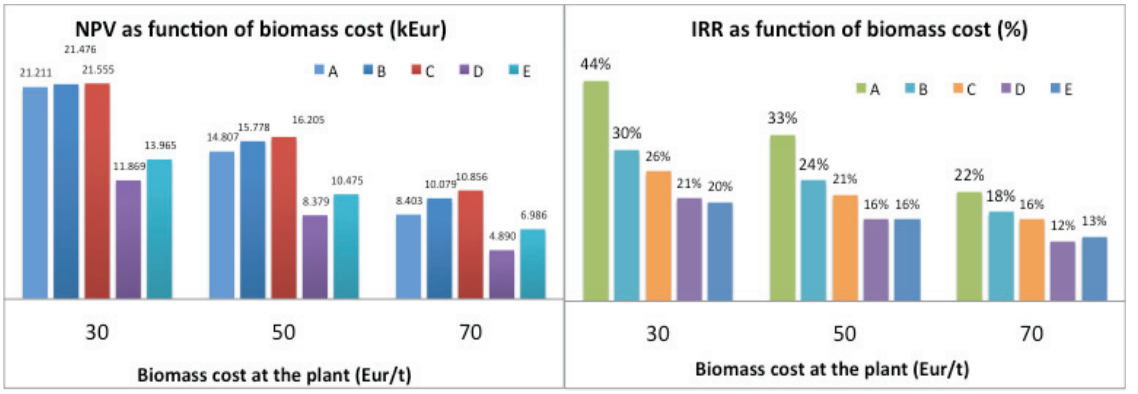


Figure 3. NPV (left) and IRR (right) for Cases A to E as a function of biomass supply cost for electricity- only sales scenario

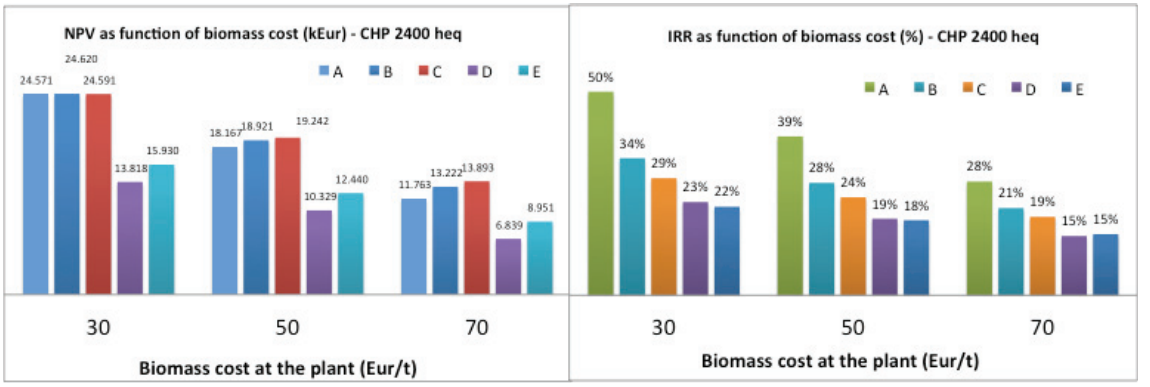


Figure 4. NPV (left) and IRR (right) at equivalent heat demand of 2,400 hours/year and biomass supply cost in CHP scenario

5. Conclusions

A thermodynamic and economic analysis has been performed on a hybrid (solar-biomass) combined cycle featuring by a linear parabolic trough collector field with molten salts as the heat transfer fluid delivered at a maximum temperature of 550 °C, upstream of a 9 MWt fluidized-bed biomass combustor, with thermal energy storage. The heat sources drive an externally fired gas turbine top cycle and a bottoming organic Rankine cycle. Both electricity-only and combined heat and power generation scenarios have been considered at a proposed scale, based on an application in the Italian energy market. The thermodynamic modelling has been performed by considering different CSP sizes, storage levels and biomass combustor operation modes. The energy performance results report higher global conversion efficiencies when using CSP integration and the thermo-economic analysis reports a higher NPV of the

investment when integrating solar energy, due to the avoided biomass supply costs and the higher value of solar-based electricity. However, the IRR decreases when increasing the solar share because of the high investment costs of the parabolic trough collectors. A baseload operation strategy which maximizes the electricity output and compensates the solar input energy fluctuations with a modulating biomass furnace proves to be more profitable option (but less efficient in terms of global energy performance) in comparison to a strategy with a fixed biomass consumption rate and variable electricity output.

References

[1]. European Commission web site: http://ec.europa.eu/clima/news/articles/news_2014102401_en.htm accessed Nov 2014

[2]. Liu, M., Steven Tay, N. H., Bell, S., Belusko, M., Jacob, R., Will, G., … Bruno, F. (2016). Review on concentrating solar power plants and new developments in high temperature thermal energy storage technologies. Renewable and Sustainable Energy Reviews, 53, 1411–1432.

[3]. Anuradha Mishra M, Chakravarty N, Kaushika N. Thermal optimization of solar biomass hybrid cogeneration plants. J Sci Ind Res 2006;65(4):355–63.

[4]. European Concentrated Solar Thermal Road-Mapping (2005), SES6-CT-2003-502578, DLR http://www.promes.cnrs.fr/uploads/pdfs/ecostar/ECOSTAR.Roadmap.pdf

[5]. Camporeale S, Turi F, Torresi M, Fortunato B, Pantaleo A, Pellerano A (2015) Part load performances and operating strategies of a natural gas-biomass dual fuelled microturbine for CHP operation, Journal for Engineering for Gas Turbines and Power, 137(12)

[6]. Barsali S; Giglioli R; Ludovici G; Poli D. (2011). A micro combined cycle plant for power generation from solid biomass: coupling EFMGT and ORC. In 19th European Biomass Conference. Berlin: ETA-WIP,

[7]. Bagdanavicius, A., Sansom, R., Jenkins, N., & Strbac, G. (2012). Economic and exergoeconomic analysis of micro GT and ORC cogeneration systems. In ECOS 2012 (pp. 1–11).

[8].OA Oyewunmi, AI Taleb, AJ Haslam, CN Markides (2014). An assessment of working-fluid mixtures using SAFT-VR Mie for use in organic Rankine cycle systems for waste-heat recovery, Computational Thermal Sciences 6 (4) 301-316.

[9]. OA Oyewunmi, AI Taleb, AJ Haslam, CN Markides (2016). On the use of SAFT-VR Mie for assessing large-glide fluorocarbon working-fluid mixtures in organic Rankine cycles, Applied Energy 163, 263-282. doi:10.1016/j.apenergy.2015.10.040

[10]. OA Oyewunmi and CN Markides (2016). Thermo-Economic and Heat Transfer Optimization of Working-Fluid Mixtures in a Low-Temperature Organic Rankine Cycle System, Energies 9 (6), 448:1-21;

[11]. Camporeale S, Pantaleo A, Ciliberti P, Fortunato B, Cycle configuration analysis and techno-economic sensitivity of biomass externally fired gas turbine with bottoming ORC, Energy Conversion and Management 105 (2015) 1239–1250

[12]. Italian Ministry of Economic Development, Incentives for energy from electric not-photovoltaic renewable sources, Legislative decrees of 07.06.2016

[13]. ENEA Working Group. Solar thermal energy production: guidelines and future programmes of ENEA. ENEA Report. Available at http://www.solaritaly.enea.it/Documentazione/Documentazione.php; 2001.

[14]. Turchi C, Mehos M, Ho C M, Holb G J, (2010) Current and future costs for parabolic trough and power tower systems in the US market, SolarPaces 2010, Perpignan, FR, September 21-24

[15]. Herrmann, U.; Kelly, B.; Price, H. (2004). Two-tank molten salt storage for parabolic trough solar power plants. Energy, Vol. 29, No. 5-6, 883-893.

[16].V. Russo , CSP Plant Thermal-hydraulic Simulation, Energy Procedia, Volume 49, 2014, Pages 1533-1542, Proceedings of the SolarPACES 2013 International Conference

[17]. http://www.asimptote.nl/software/cycle-tempo

[18]. C. Turchi, M. Mehos, C.K. Ho, G.J. Kolb, Current and Future Costs for Parabolic Trough and Power Tower Systems in the US Market, NREL/CP-5500-49303, SolarPACES 2010, Perpignan, France, September 21-24, 2010.

[19]. Turchi, C., “Parabolic Trough Reference Plant for Cost Modeling with the Solar Advisor Model (SAM),” Technical Report, NREL/TP-550-47605, July 2010.

[20]. Sargent & Lundy Consulting Group, May 2003, "Assessment of Parabolic Trough and Power Tower Solar Technology Cost and Performance Forecasts", NREL SL-5641, Chicago, IL, USA.

[21].Archimede solar power plant, https://en.wikipedia.org/wiki/Archimede_solar_power_plant

[22]. Pantaleo A, Giarola S, Bauen A, Shah N (2014) Integration of biomass into urban energy systems for heat and power. Part II: methodology application and key factors assessment, Energy Conversion and management, 83, 362-376;

[23]. Pantaleo A, Carone MT, Pellerano A (2009). Potentials and feasibility assessment of small scale CHP plants fired by energy crops in Puglia region (Italy). Biosystems engineering, p. 344-358

[24]. Jablonski S Pantaleo A, Bauen A Pearson P, Panoutsou C, Slade R (2008). The potential demand for bioenergy in residential heating applications (bio-heat) in the UK based on a market segment analysis. Biomass and bioenergy, vol. 32, p. 635-653

[25]. A. Pantaleo, S. Camporeale, N. Shah (2014) Natural gas – biomass dual fuelled microturbines: comparison of operating strategies in the Italian residential sector ,(2014) Applied Thermal Engineering, 71, 686-696



Biography

Antonio Pantaleo obtained his PhD at the Centre for Process Systems Engineering, Imperial College in bioenergy systems optimization. He is assistant professor at DISAAT Department, University of Bari, and visiting researcher at Imperial College since 2006. His research interests include spatially explicit modelling of bioenergy systems, CHP planning and optimization.