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Preliminary analysis of solarized micro gas turbine application to CSP parabolic dish plants

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Abstract

This work presents a preliminary thermodynamic assessment of a Concentrating solar power (CSP) system made up of a micro gas turbine (MGT) coupled with a parabolic dish concentrator. The thermal engine characteristics are representative of state-of-the art of MGTs (Net power=31.5kWe Turbine Inlet Temperature (TIT)=850°C) while the "solar section" (thermal receiver and parabolic mirror) performance are modelled in accordance with current research outcomes. The overall system is designed and a second law analysis is reported. An estimate of yearly electricity yield is performed (83.98 MWhe) and the obtained sun-to-electricity efficiency (about 18.3%) reveals energetic competiveness with other CSP solutions (parabolic trough and solar tower). A simplified economic analysis (Levelized cost of electricity (LCOE) is 165.7 €/MWh) highlights how Solarized Micro Gas Turbine (SMGT) is a promising CSP technology whose improvements perspective can drive dedicated R&D activities.

Keywords: Solar energy; Concentrating Solar Power (CSP); Parabolic dish; Solarized micro gas turbine

1. Introduction

Concentrating Solar Power (CSP), which exploits the direct component of solar radiation (Direct normal irradiance - DNI), can be a promising and viable response to the growing demand of carbon-free and renewable electric energy able to replace/reduce the fossil fuel consumption in regions characterized by high solar radiation. Open cycle gas turbine technology coupled with both solar tower or parabolic dish has been intensively studied with the aim of exploiting the potentiality offered by the high concentration ratio [1-4] and to positively respond to the

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growing attention on water consumption in CSP plants. This work focuses on parabolic dish, recognized, theoretically, as the most efficient solution to exploit solar energy thanks to the ability of tracking the sun without generating any incidence angle effect. In particular, the main potential of solarized (parabolic dish) micro gas turbine (SMGT) is expected for small scale (10-100 kW_e) decentralized and off-grid applications; however, large scale solutions can be designed exploiting the system modularity. The SMGT has been recognized as a viable alternative to Stirling engine, which represents the state-of-art of parabolic dish engine. Gas turbine technology undoubtedly represents a viable solution to overcome reliability and cost issues that afflict Stirling engine [5], taking advantage of high production quantities in the stationary market. It is worth underlying that the small size of SMGT (10-100 kWe) can help the bankability of both research projects and pilot plants erection through the exploitation of the emerging paradigm of "getting bigger by going smaller" [6]. In this work, a preliminary thermodynamic assessment of a SMGT system is carried out. In accordance with micro gas turbine (MGT) state-of-the-art, the maximum temperature is set to 850°C. Part-load behavior is discussed and an estimate of both yearly energy yield and levelized cost of electricity (LCOE) is performed.

Nomenclature

SMGT	Solarized micro gas turbine
TIT	Turbine Inlet Temperature (°C)
HP	High Pressure
LP	Low Pressure

2. Design performance

The coupling of MGT with parabolic dish takes into account standard MGT (power output equal to approximately 30 kWe and TIT equal to 850°C) with characteristics similar to Capstone C30 model [7] (current state-of-the-art). In accordance with the reduced power size, the MGT implements a recuperative Brayton cycle (without blade cooling) that is recognized as the optimal solution [8,9].

Concerning the "solar section", the main bottleneck is represented by the development of a receiver able to withstand high temperature and achieving good thermal efficiency. TIT equal to 850°C (together with air pressure lower than 4 bar) is well within the applicability range of current solar receiver; nevertheless few data are available in literature. In particular, a thermal efficiency of 89% seems to be reachable by indirectly-irradiated receiver as the one studied by ETH [10]. Parabolic mirrors are characterized by more advanced development status thus, mirror reflectivity of 0.94 and diameter equal to 15m are recognized as reasonable. As far as the receiver optical efficiency is concerned, a value of 88.3% is confirmed by raytracing simulation performed in Soltrace [11-13].

In Figure 1, the recuperative SMGT layout is depicted with the main components highlighted. It is worth noticing that, although this work is focused on "solar-only operation", the presence of a natural gas burner in series with the solar receiver is able to increase the energy dispatchability when solar energy is not sufficient, otherwise the burner can be bypassed.

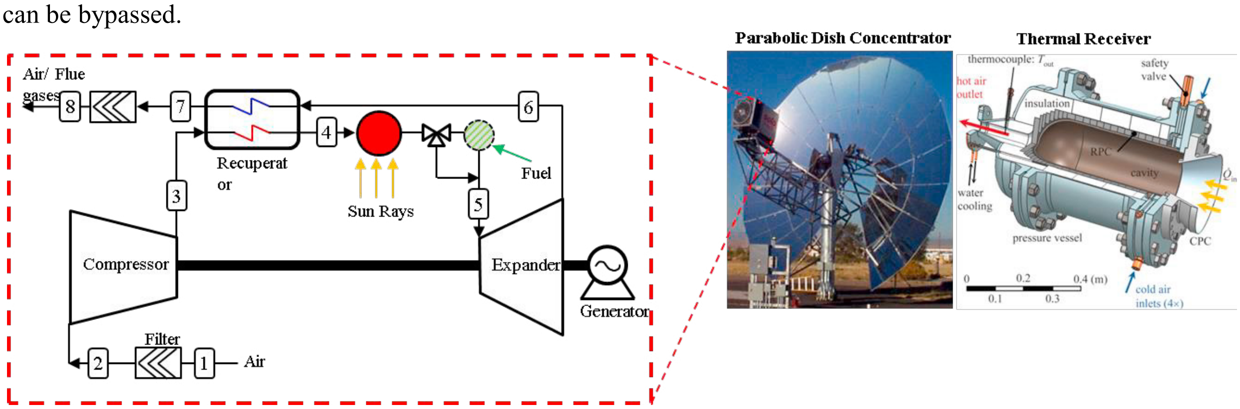

Figure 1 Scheme of the coupling between MGT and parabolic dish [14]. Thermal engine is placed at focus of parabolic mirror.

The system is designed in "solar-only" conditions; in particular, the main design assumptions, covering thermal engine, parabolic dish collector and thermal receiver are summarized in Table 1 together with the design performance.

Table 1 Main design assumptions for the micro gas turbine and results.

Design Parameter	Value	Design Parameter	Value	Results	Value
Turbine Inlet Temperature (°C)	850	Mirror Area (m^2)	176.7	Net Power (kW)	31.5
Compression ratio (β_{compr}) (-)	3.64	Mirror reflectivity (ρ) (-)	0.94	Net Cycle efficiency (%)	24.5
Recuperator effectiveness (ε) (-)	0.86	Optical efficiency (-)	0.883	Solar-to-electric efficiency (%)	19.8
Isentropic efficiency (η_{is})compr/exp	0.79/0.86	Receiver thermal efficiency (-)	0.89	Exhaust temperature (°C)	273.0
$\Delta p/p$ HP/LP side of recuperator (%)	3/5	$\Delta p/p$ receiver (%)	5	Available solar power (kW)	159.0
$\Delta p/p$ in/out (%)	0.5/1	DNI (W/m^2)	900	Recuperator thermal power (kW)	140.0
Mechanical/Electrical efficiency (-)	0.98/0.92	Ambient Temperature (T_{amb}) (°C)	35	Thermal power discharged (kW)	93.7

Second law analysis is performed in order to complement the results of the thermodynamic study and to identify irreversibilities (exergy losses) associated with real processes. In SMGT, irreversibilities are caused by: i) optical losses of the concentrator and receiver, ii) conversion of radiation energy to thermal energy in the receiver, iii) heat transfer through finite temperature difference in recuperator, iv) gap between isentropic process and real process in turbomachinery, v) fluid mechanical friction, vi) conversion of Euler work to electricity (i.e. mechanical and electrical losses of power conversion unit) and vii) hot air discharge at temperature higher than ambient temperature.

Figure 2 shows the results of the second-law analysis, expressed in terms of exergy, applied to the SMGT; in particular, starting from exergy associate with solar radiation (147.78 kW_e) [15], exergy loss of each transformation lead to net electricity output (31.5 kWe).

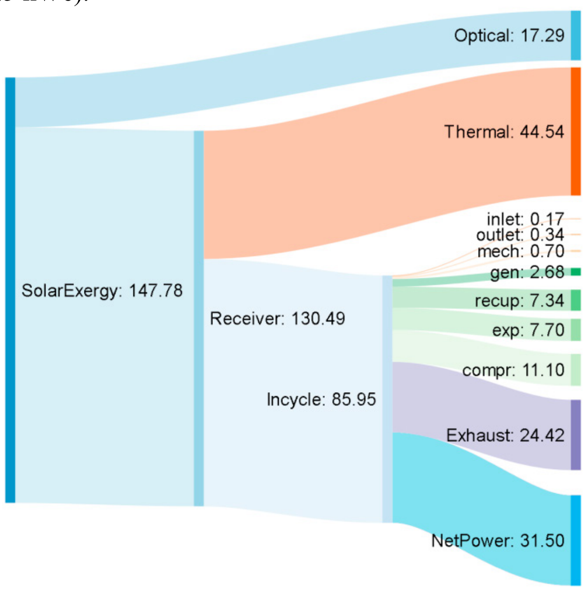

Figure 2 Sankey diagram representing second-law analysis outcomes [16].

Approximately 42.0% of available exergy is destroyed by the "solar section"; in particular, thermal receiver is responsible of the highest exergy loss due to energy degradation that occurs during the conversion of concentrated solar energy (impinging onto the receiver) to thermal energy transferred to the cycle working fluid (air).

This consideration identifies the thermal receiver as a fundamental component that deserves particular attention and R&D efforts with the aim of increasing the heat input temperature; in particular, this goal can be approached by increasing the TIT and/or augmenting the receiver inlet air temperature (implementing high effectiveness recuperator). The 16.5% of exergy loss is imputable to exhaust discharge in ambient thus indexing towards the implementation of an heat recovery system based on Organic Rankine cycle (ORC), which suits well to temperature (273°C) level and power size (approximately 100kW$_t$), able to exploit exhaust thermal energy to produce more electricity. Future research activities will identify if the proposed ways to increase energetic performance are able to compensate the additional cost requested (i.e. higher recuperator weight, improved turbomachinery efficiency etc.).

3. Part-load modelling and yearly results

Due to the variability of ambient conditions (ambient temperature and DNI), the prediction of the system performance are demanded to an in-house model (developed in Matlab®) able to identify the operating parameters (TIT and shaft rotational speed) that maximize the system efficiency for each ambient conditions without violating the operational constraints of each component (e.g. compressor surge margin, maximum recuperator inlet temperature, min/max load etc.). The code takes into account turbomachinery operating maps (compressor and expander), recuperator heat transfer dependence on mass flow, pressure loss dependence on volume flow rate and mechanical efficiency and power conversion system efficiency change in function of power load (components modelisation is reported in details in [17]).

Figure 3(left) shows the behaviour map of the SMGT, whose characteristics are reported in Table 1, at different ambient conditions; in particular, it is worth noticing the reduction of TIT from nominal value (850°C) in order to respect the constraint on the maximum allowable recuperator inlet temperature in case of low DNI. In conditions with high DNI and low ambient temperature, a reduction of TIT is necessary to avoid overcoming the maximum load threshold (+15% of the on design net power value). Figure 3 (right) represents, in temperature-entropy space, the thermodynamic cycle to show changes in part-load operation; in particular, a reduction of TIT (from design value of 850°C to 790°C) is noticed together with an increase of sun-to-electric efficiency (lower T_{amb}, increased recuperator ε and lower pressure drop counterbalance penalties due to lower TIT and lower turbomachinery η_{is}).

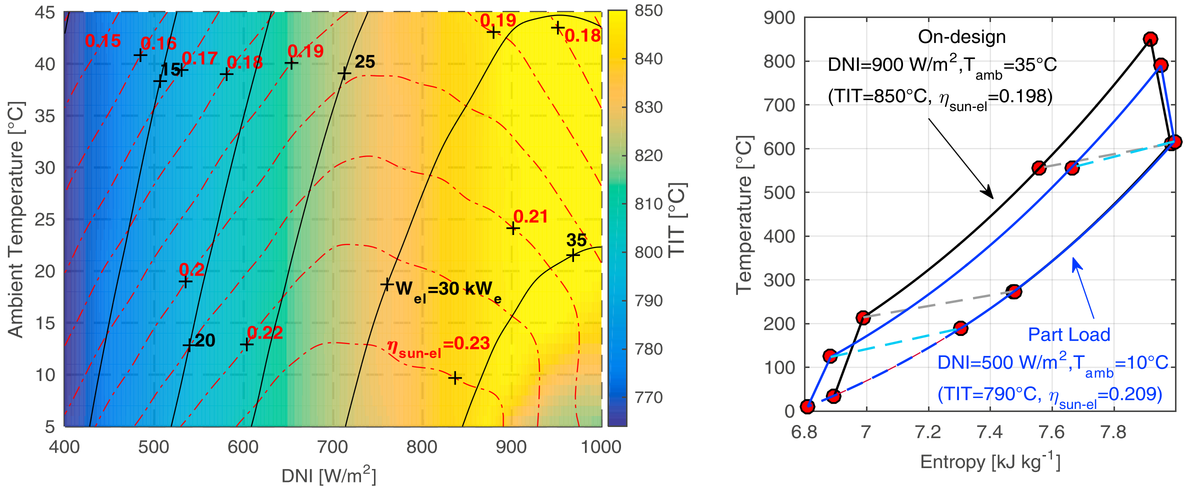

Figure 3 (left) Part-load map for different DNI and ambient temperature. (right) Thermodynamic cycle for on-design conditions and part-load conditions (DNI=500 W/m^2 and T_{amb}=10°C).

Minimum load threshold is 20% of the on design net power. Although dynamic behavior is neglected (no thermal inertias effect are considered), a minimum DNI start-up of 250 W/m^2 is considered in order to take into account the heating time of system.

Taking into account weather data of Las Vegas (36.083 N, -115.15 W, 2592 kWh/m^2-y), the yearly electricity yield is equal to 83.98 MWh with a solar-to-electric efficiency of 18.3%.

The energetic performance of the SMGT strongly benefits from the higher yearly optical efficiency compared with standard CSP technologies (parabolic trough, solar tower) (88.3% vs ca. 52 %) caused by the intrinsic ability of parabolic dishes to perfectly track the sun without generating incidence angle effects (e.g. heliostats shading/blocking, cosine losses etc.) that penalise optical efficiency. Nevertheless, the thermodynamic cycle efficiency, which is undoubtedly lower than conventional technologies based on Rankine cycle (24.5% vs 33%-39%), penalizes the energetic performance of the system leading to a sun-to-electric efficiency not so different from CSP state-of-art solutions (18.3% vs 16%-18.5%)[18-20]. It is worth underlining that SMGT has a reduced demand of water (mirror cleaning only) that represents an important peculiarity for application in desert areas.

4. Cost of electricity

In order to estimate the potential of the proposed SMGT, an economic evaluation of the studied SMGT, expressed in terms of investment cost and LCOE, is proposed. Starting from the yearly electricity yield (E_{el}), investment cost (C_{inv}) and O&M cost, LCOE can be computed as:

$$LCOE = \frac{C_{inv}FCR}{E_{el}} + \frac{O\&M}{E_{el}} \tag{1}$$

Table 2 summarizes the main assumptions considered [17]. The cost of installing the thermal engine at parabolic dish focus is contained in the MGT investment cost. Terrain area is considered 25% greater than mirror area.

It is worth to notice that the main uncertainty is concentrated in the "solar section", which accounts for approximately 62% of the investment cost, because of the early development stage of these components (particularly for the thermal receiver). For this reason the investment cost (3273 €/kW$_e$) and LCOE (165.7 €/MWh$_e$) have to be considered as indicative values that can give a first view of the SMGT economic figure.

Table 2 Investment cost of the SMGT.

Design Parameter	Value	Design Parameter	Value
Thermal engine cost (€/kWe)	850	Electricity (MWh)	83.98
Parabolic concentrator (€/m^2)	250	O&M (%Investment)	3
Thermal receiver (€/kWt)	135	Fixed Charge Rate (FCR) (%)	10.5
Terrain (€/m^2)	17.7	Overall Investment (€/kWe)	3273
Other (% Investment)	10	Levelized Cost of Electricicty (LCOE) (€/MWh)	165.7

LCOE 165.7 €/MWh$_e$ is far from reaching the target of about 100 €/MWh$_e$ (identified as a goal for solar-only CSP plant) [21]. It is important to underline that SMGT can cover both small size plants and large scale plants (>1 MWe) thus representing an advantage over others CSP technologies. In particular, the obtained LCOE has to be compared with small scale plants (e.g., parabolic trough with Organic Rankine Cycle) that are characterised by higher electricity cost than the one commonly found in literature that are related to large scale plants.

In addition, it is worth underlying that parabolic dish, particularly coupled with MGT, is undoubtedly the least developed CSP technology, thus, it would receive the highest benefits from mass-production (foreseen investment cost reduction approximately equal to 25-40%) [22].

5. Conclusions

This work discusses a preliminary assessment of the application of MGT in CSP sector through the coupling with parabolic dish concentrator (point focus). The study takes into account the adaptation of MGT similar to commercial one (TIT=850°C, W_{el}=31.5 kWe) with 15m diameter parabolic dish. Indirectly-irradiated receiver is considered and its performance is taken from literature.

On-design solar-to-electric efficiency is 19.8% is comparable with conventional CSP. With the aim of enhancing the competiveness of SMGT, as shown by the outcomes of second-law analysis, an increase of overall efficiency can be attained by the adoption of a bottoming ORC that exploits the thermal energy of exhaust (273°C). Another option is moving towards high temperature solutions (TIT greater than 1000°C), which forces the switch to ceramic turbine technology and to advanced solar receiver design that, nowadays, are both in a very early development stage.

Within the economic scenario, the LCOE (about 165 €/MWh) identifies SMGT, as technology not ready yet to compete with conventional power generation technologies but at least comparable with conventional CSP and PV.

Nevertheless, it is reasonable to foreseen a reduction of investment cost due to mass-production effects and to consider the application of SMGT in remote zones (often characterized by high cost of electricity), in assistance to Diesel genset if operated in "solar-only" mode.

For sake of completeness, SMGT could be considered for large scale plants too, nevertheless, as first market penetration stage, the intrinsic characteristic of installation flexibility (i.e. hillside, irregular areas) worth to be exploited for small scale plant.

It is important to underline how the absence of affordable thermal energy storage technology, which is one of the main obstacles to SMGT establishment, can be easily overcome by fossil fuel hybridization that can increase the dispatchability of generated electricity (and consequently its value on the market).

From the outcomes of this preliminary study, it can be concluded that SMGT shows good perspective of competiveness within CSP market that can drive dedicated R&D activities devoted to improve components performance.

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