A DETAILED TECHNO-ECONOMIC ANALYSIS OF GAS TURBINES APPLIED TO CSP POWER PLANTS WITH CENTRAL RECEIVER

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ABSTRACT
The present work presents a very detailed techno-economic analysis of the technology made up of two complementary models. A performance model implemented in Thermoflex environment is used to explore alternative integration layouts to enable the simultaneous operation on solar and fossil energy. Then, a detailed cost analysis approaches the capital and operation costs of the plant from an EPC (Engineering, Procurement and Construction) standpoint. These two models are then combined in annual simulations to obtain the final Levelized Cost of Electricity from which a solid conclusion about the true potential of solar gas turbines can be ascertained. A sensitivity analysis with respect to the main boundary conditions is also provided.

NOMENCLATURE

\( \text{BEC} \) Breakeven Electricity Cost \([\text{c€/kWh}]\)
\( C \) Cost \([\text{€}]\)
\( CC \) Combustion Chamber (Combustor)
\( COP \) Compressor Outlet Pressure \([\text{bar}]\)
\( CSP \) Concentrated Solar Power
\( D \) Tower diameter \([\text{m}]\)
\( DNI \) Direct Normal Irradiance
\( GG \) Gas Generator [-]
\( H \) Tower Height \([\text{m}]\)
\( HT \) High Temperature [-]
\( LCoE \) Levelized Cost of Electricity \([\text{c€/kWh}]\)
\( LT \) Low Temperature [-]
\( P \) Pressure \([\text{bar}]\)
\( TLCC \) Total Life Cycle Cost \([\text{€}]\)
\( TIT \) Turbine Inlet Temperature \([\text{°C}]\)
\( TIP \) Turbine Inlet Pressure \([\text{bar}]\)
\( T \) Temperature \([\text{°C}]\)
\( W_{GT} \) Gas Turbine Output \([\text{kWe}]\)

INTRODUCTION
Solar Thermal Electricity (STE) has always been seen as a very interesting complement to the portfolio of renewable energy technologies. This is particularly true for facilities using central receiver (tower) layouts, owing to their potentially higher operating temperatures and, therefore, efficiency. Nevertheless, pure Concentrated Solar Power facilities, i.e. power plants operating on solar energy only, have found it difficult to achieve costs of electricity as low as other power generation technologies, either renewable or non-renewable. This is shown in Figure 1 where the reported Levelized Cost of Electricity of different tower projects is presented along with the current cost of commercial Wind, Nuclear and Photovoltaic technologies.

Two routes to lower LCoEs in CSP-STE plants are usually claimed. Hybridization is seen as a means to increase the annual yield, thus reducing the specific capital cost, and to enable much higher operational flexibility. Jamel et al.’s review of hybrid solar power plants presents several integration layouts either in steam, combined cycle or even geothermal power plants [1]. In these, solar heat addition to the feedwater heaters or to the steam generator are the most usual integration options. Integrated Solar Combined Cycles (ISCC) were introduced in the early 1990s [2][3] and became a commercial reality in plants like Ain Beni Mathar [4], Hassi R’Mel [5], Kuraymat or Waad Al Shamal. Unfortunately, even if the technology is already mature, it holds an inherent limitation in regards to the low peak temperature and solar share that are attainable.

The second route is utilizing gas turbines which enable smaller footprint and water consumption than state-of-the-art steam-based CSP plants whilst, at the same time, increasing the flexibility of the system further. This can be done through either volumetric or tubular air receivers which, in the most efficient
configuration, heat up the air delivered by the compressor before injecting it into the combustor [6]. There are also different potential locations of the gas turbine: on the ground or atop the tower [7] or with original layouts like the beam-down reflection proposed in [8]. Schwarzbözl performs a technical assessment of solar gas turbines for three commercial engines in [9] whilst a techno-economic analysis for multi-tower solar fields is provided by Partzinger in [10]. Spelling’s work on the techno-economic analysis of solar gas turbines is noteworthy [11].

To yield an accurate estimate of the Levelized Cost of Electricity which can be supported by a realistic methodology and by actual cost data provided by the industry.

As a complementary consideration to the last bullet point, it is also relevant to highlight that Concentrated Solar Power technologies have usually been regarded as expensive technologies which could become competitive in subsidized scenarios only. Whether be it through incentives (bonus on the kWh produced), priority access to the grid or tax credits, the industry has usually incorporated these secondary economic metrics to the financial analysis of business cases. The approach employed in this paper is nevertheless different. It is the authors’ opinion that in order to ensure the long term prosperity of CSP technology without harmful effects on the global cost of energy for the end user, it must be able to compete directly against conventional fossil fuel and nuclear power plants. This is why the paper intentionally leaves out any incentive and puts the focus on the actual subsidy-free cost of electricity of CSP gas turbines. It is thought that, if this raw LCoE turns out to be competitive, any additional benefit coming from tax credits or CO₂ credits will do nothing but increase the interest of investors and policy-makers and will make the 100% renewable scenario more feasible.

**SYSTEM INTEGRATION**

**Integration layout**

Solar receivers for gas turbines have been under development since decades ago. The various technologies available can be classified according to the heat transfer fluid: pressurized air, molten salts [19], micro/nano-particles [20] or even supercritical carbon dioxide. When using pressurized air, this can be injected directly into the combustor (direct heating) or used as a heat source for the working fluid of the engine (indirect heating). In this work, a direct heating layout has been considered for economic reasons. Also, with regards to the engine location, it has been assumed that the gas turbine is located atop the tower, given that the power output is not foreseen to exceed 50 MWe. This yields the following advantages: (i) higher efficiency thanks to the reduced pressure loss across the interconnecting pipes; (ii) lower risk due to the absence of a long high pressure and temperature pipe connecting the receiver and engine (should this be on the ground); (iii) lower risk to run into surge under dynamic operation due to a much smaller volume between compressor and turbine; and (iv) higher technology readiness thanks to the lessons learned in past projects with similar configuration [16] [17].

**Operating strategy**

The engine layout and, in particular, the interconnecting elements between major components (compressor, receiver, combustor and turbine-generator) are key design features. The
simplest layout has the main components connected in series without control elements, as shown in Figure 2.1, with the main advantage of simplicity and capital cost. Nevertheless, this layout has two main shortcomings. The air delivered by the compressor flows entirely through the receiver, regardless of the available solar heat input, bringing about large changes in receiver outlet (combustor inlet) temperature. This increases the thermal cycling of the receiver and the complexity of the combustor design. Also, having air flowing through the receiver even in periods where solar energy is not supplied to the system increases the pressure and heat losses across this component, hence reducing the efficiency of the engine. The SOLHYCO project was based on this configuration [21].

![Figure 2. Possible integration layouts](image)

The outlet temperature from the receiver (and hence the corresponding thermal cycling) can be controlled by simply adding a high-pressure, mid temperature (350-500°C) by-pass valve at the compressor discharge, Figure 2.2. This layout was adopted in SOLUGAS, enabling to by-pass the receiver in periods with low DNI. Nonetheless, even if the elements required to implement this system are commercially available, the design of the combustor is still challenged by a very wide operating range in terms of inlet temperature.

In order to control the inlet temperature to the combustor in series with the receiver, a low-temperature combustor can be added in parallel with the solar receiver, Figure 2.3. The combustor (CC1) would raise the temperature of the by-pass air not flowing through the receiver, matching the same outlet value as the receiver in order to ensure that the boundary conditions of the high temperature combustor remain as constant as possible. Moreover, given that the expected receiver outlet temperature is not higher than 800°C, a fairly simple diffusive flame combustor design could be adopted for CC1 without further concerns about NOx formation. On the contrary, the high temperature combustor operating at an outlet temperature higher than 1200°C must be of the lean premixed type.

A fourth layout would incorporates an additional by-pass valve at the receiver outlet in order to improve the start-up and transient characteristics of the engine, Figure 2.4. Unfortunately, this layout requires high pressure, high temperature valves operating at 800°C which are not currently available in the market for such large flows. The installation of both combustor in series with the solar receiver is also discarded for the reasons cited above in regards to the cumulative pressure loss of the system when operating without solar energy supply.

Based on the discussion in this section, the third layout is deemed most balanced and technically feasible and, accordingly, it is adopted in the reference power plant.

**TECHNICAL MODEL**

The technical model comprises three submodels: (i) solar field, (ii) solar receiver and (iii) gas turbine. These models are run in independent environments, being later integrated in a dedicated Visual Basic tool in Excel. The model is run on an hourly basis to avoid errors incurred by average DNI values in longer periods of time. Additionally, in the absence of a specific demand profile, the following operating strategies are considered:

- **Base load operation**: 24 hours a day, 365 days a year.
- **Daily operation**: the gas turbine runs whenever there is solar energy supply. During the night and in heavily cloudy periods, the engine is shut down.

In both cases, the gas turbine runs at full capacity using natural gas to make up for the potential lack of solar energy.

**Solar Field**

The solar field is modelled with NREL’s System Advisor Model (SAM). SAM is used to produce look-up tables relating field efficiency to field size and tower height. Such model is then integrated with the cost model (see later) in order to find the optimum design features of the solar field (number of heliostats and height of tower). The methodology has been validated against the performance of the solar fields in the PS10 and PS20 solar towers [22].

**Solar Receiver**

The receiver used in the SOLUGAS project [16] is an open cylinder with the absorber tubes evenly distributed on the inner wall and connecting the inlet and outlet toroidal collectors. In this work, four flat receivers (the bundle of absorber tubes forms a vertical wall) are used instead, based on the very difficult up-scale of the former design as noted by the original design team in SOLUGAS; this is shown in Figure 3. The difference between both designs is shown in Table 1 where the receiver size \( W_H, L_u \) is case-specific. It is noted that, due to confidentiality, the actual performance of the receiver in SOLUGAS cannot be disclosed. Therefore, only relative differences between the performance of this receiver and the receiver model developed in this work are given.
Figure 3. Sketch of the receivers used in SOLUGAS (right) and in this work (left)

Table 1. Receiver performance comparison: SOLUGAS and this work (Data with * are taken from Solugas directly)

<table>
<thead>
<tr>
<th></th>
<th>( \Phi_{\text{model}} )</th>
<th>( \Phi_{\text{Solugas}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross heat input [MWt]</td>
<td>0.138</td>
<td>0.131</td>
</tr>
<tr>
<td>Reflective loss [MWt]</td>
<td>0.131</td>
<td>0.131</td>
</tr>
<tr>
<td>Radiation loss [MW/%]</td>
<td>-0.296</td>
<td>-0.296</td>
</tr>
<tr>
<td>Convection loss [MWt]</td>
<td>0.199</td>
<td>0.199</td>
</tr>
<tr>
<td>Conduction loss [MWt]</td>
<td>0.047</td>
<td>0.047</td>
</tr>
<tr>
<td>Total loss [MWt]</td>
<td>0.082</td>
<td>0.082</td>
</tr>
<tr>
<td>Net heat input [MWt]</td>
<td>0.055</td>
<td>0.055</td>
</tr>
<tr>
<td>Efficiency [pp]</td>
<td>-0.9</td>
<td>-0.9</td>
</tr>
</tbody>
</table>

Input data from Solugas

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlet temperature [ºC]</td>
<td>330*</td>
</tr>
<tr>
<td>Inlet temperature [ºC]</td>
<td>990*</td>
</tr>
<tr>
<td>Mass flow rate [kg/s]</td>
<td>5.75*</td>
</tr>
<tr>
<td>Pressure loss [%]</td>
<td>2.5*</td>
</tr>
</tbody>
</table>

The performance model of the solar receiver is based on heat transfer equations applied to the radiative, convective and conductive heat exchange between the tubes in the three vertical bundles in the cavity, the field of heliostats and the environment (losses) [23]. Additionally, the main design specifications like materials, tube length and diameter as well as other surface properties affecting heat transfer have also been taken from the SOLUGAS project. This is why the rated performance of the receivers considered in this work and in the SOLUGAS project are very similar when considering the same rated conditions, see Table 1. It is noted by the authors that a complete description of the governing equations of the model is beyond the scope of this paper, due to the obvious length constraints.

The aforedescribed model calculates the heat absorbed by the working fluid based on the environmental/meteorological conditions, the inlet air pressure and temperature and the incoming thermal power in the solar field. Given that the outlet temperature is kept at the rated value of 800ºC, the air flow rate changes according to the said dataset.

**Power Cycle**

The power range considered in this analysis is at the upper end of typical aeroderivative engines (40-60 MWe) and below the characteristic values of frame gas turbines (>150 MWe). Therefore, a twin shaft engine has been considered (gas generator and power turbine), modified to incorporate a low temperature (LT) combustor in parallel with the receiver and a high temperature (HT) combustor downstream of these elements. This HT combustor is of the lean premixed type to avoid excessive NOx formation. The LT combustor backs up the receiver to ensure that the inlet temperature to the HT combustor remains at the rated value (800ºC). Also, for operational reasons, a pilot flame is always sustained in the LT combustor in order to enable fast response of this component if needed. This implies that even if the solar heat input were enough to run the engine at full capacity, a minor fraction of the air delivered by the compressor would still be bypassed through the LT combustor. The power block model is implemented in Thermoflex environment as shown in the schematic layout in Figure 4.

**ECONOMIC MODEL**

In a Concentrated Solar Power plant, the project cycle comprises several stages whose duration and cost must be considered in order to make an informed decision: development and permitting, construction, operation and maintenance and dismantlement. To such aim, the economic model in this work is
Cost Model

The cost analysis tool comprises the costs incurred in all the aforelisted stages of the Project. It yields an accurate estimate of the cost of the components and of the total cost as a function of several design parameters of the plant: solar field size, gas turbine output or thermal power of the receiver amongst others. The model incorporates a cost database of real power plants provided by Abengoa. This database includes costs of CSP power plants in operation worldwide as well as economic information used in a large number of bids, hence covering a very wide range of boundary conditions, sizes and technologies. The following correction factors are used to harmonize the information:

- An inflation-based correction is used to take into account the time value of money.
- The regional influence is corrected through an index for the labour cost of local workforce and also the cost of local supply of industrial goods and services.

The corrected/harmonized database is then transformed into a set of analytical cost functions, each one of which corresponds to an item of the detailed budget. The complete list of items whose costs are calculated by the economic model is presented in Table 3. Two of these items are illustrated here. Figure 5 presents the relative cost index of the tower, considering two different diameters, whereas Figure 6 resents the same information for the gas turbine [24]1. The information in these figures is expressed analytically as follows:

\[ C_T = C_0 \left( \frac{H_{0}}{H} \right) \left( \frac{D}{D_0} \right)^2 \]  
(1)

\[ C_{GT} = W_{GT} \left( a \cdot \ln W_{GT} + b \right) \]  
(2)

where \( a \) and \( b \) are coefficients of the fitting line, \( D \) and \( H \) are the diameter and height of the tower and the subscript 0 stands for the reference values. \( C_T \) and \( C_{GT} \) are the costs of the solar tower and gas turbine respectively.

Financial Model

The financial model is used to calculate the figures of merit that enable making informed decisions about the investment, both technically and economically. In this case, given the early stage of development of the process and the lack of definite market conditions, it is decided to base the financial analysis on monetary figures of merit that exclude the income coming from the sale of electricity. The financial model produces the cash-flow balance over the life of the project based on the results provided by the cost model (development, construction, O&M and dismantlement costs), and this information is then integrated with the results from the technical performance model. The following decision variables are considered2:

- Levelized Cost of Electricity (LCoE), Eq. (3).
- Breakeven Electricity Cost (BEC), Eq. (4).

1 The information in Figure 5 is expressed in relative terms due to confidentiality restrictions imposed by the company.

2 Due to length constraints, the discussion in this paper is based on LCoE only. The complete financial analysis is available in Manuel Martín’s PhD.
• Total Life Cycle Cost (TLCC), Eq. (5).
• The rate of return is calculated according to the weighted average capital cost (WACC), Eq. (6).

\[
LCoE = \left( \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t} \right) / \left( \sum_{t=1}^{n} \frac{E_t}{(1+r)^t} \right)
\]

(3)

\[
0 = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t} + \sum_{t=1}^{n} \frac{E_t \times BEC_t}{(1+r)^t}
\]

(4)

\[
TLCC = \sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}
\]

(5)

\[
WACC = \frac{Eq}{DT} \times r_{eq} + \frac{DF}{DT} \times r_{DF} \times (1 - T_j)
\]

(6)

where:
• \(I_t, M_t\) and \(F_t\) are the capital, O&M, and fuel costs and \(E_t\) is the annual yield in year \(t\).
• \(r\) is the rate of return.
• \(DT\) is the total debt, \(E\) is the equity, \(DF\) is the bank loan, \(T_j\) is the tax rate, \(r_{eq}\) is the cost of equity (usually equal to the rate of return) and \(r_{DF}\) is the interest rate on the bank loan.

LCoE and BEC are used to compare different options for the same investment opportunity whereas TLCC is used to rank these alternatives according to the capital that is required. It is thus assumed that these figures of merit provide the investor with the necessary information to make an informed selection [25].

RESULTS

Selection of reference case

The rated ISO output of the reference power plant in this work is set to 50 MWe (with an allowance of +5%). This is the output of virtually all power plants in Spain and it also stems from a compromise between the strong economies of scale of CSP technology and the techno-economic feasibility of installing the turbine atop the tower. Additional assumptions are the cost of fuel (8 €/MBTU) and the site of the plant (Ouarzazate, Morocco).

For these conditions, the design space comprises eight cases with turbine inlet temperatures (TIT) ranging from 800 to 1400°C. Two pressure ratios are considered for each TIT, corresponding to peak specific work and simple cycle efficiency respectively. Table 3 shows this information along with the corresponding cycle efficiency and solar field aperture area.

The performance of the configurations in Table 3 are modelled for both operating modes, base-load and daily operation, and the corresponding solar-share (SS) and cost of electricity are presented in Figure 7 and Figure 8. It is easily observed that raising TIT increases cycle efficiency and reduces LCoE but this is at the expense of a much lower contribution of the solar heat input (higher fuel consumption in the HT combustor). In other words, increasing the amount of electricity produced from fossil fuel has a diluting effect on the very high cost of the solar subsystem (solar field and receiver).

Table 3. Cases of Design Space

<table>
<thead>
<tr>
<th>Case</th>
<th>TIT (°C)</th>
<th>PIT (bar)</th>
<th>Cycle efficiency (%)</th>
<th>SF Surface (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>800</td>
<td>8</td>
<td>28.03</td>
<td>382,288</td>
</tr>
<tr>
<td>#2</td>
<td>800</td>
<td>12</td>
<td>29.85</td>
<td>363,181</td>
</tr>
<tr>
<td>#3</td>
<td>1000</td>
<td>10</td>
<td>31.79</td>
<td>216,413</td>
</tr>
<tr>
<td>#4</td>
<td>1000</td>
<td>20</td>
<td>35.39</td>
<td>170,029</td>
</tr>
<tr>
<td>#5</td>
<td>1250</td>
<td>12</td>
<td>34.44</td>
<td>123,922</td>
</tr>
<tr>
<td>#6</td>
<td>1250</td>
<td>30</td>
<td>39.59</td>
<td>65,769</td>
</tr>
<tr>
<td>#7</td>
<td>1400</td>
<td>18</td>
<td>38.06</td>
<td>74,630</td>
</tr>
<tr>
<td>#8</td>
<td>1400</td>
<td>28</td>
<td>40.38</td>
<td>50,123</td>
</tr>
</tbody>
</table>

Figure 7. Solar share and LCoE (daily operation)

Figure 8. Solar share and LCoE (base load)

At this point, it is worth drafting some preliminary conclusions about the economics of producing electricity with a solarized gas turbine in a tower plant:
• Technical specifications enabling solar shares higher than 50% yield LCoEs in the order of 14.5 c€/kWh.
• Gas turbines with intermediate turbine inlet temperature (Cases #3 to 5 in Table 3) yield similar or even higher LCoE than engines without fuel combustion downstream of the solar receiver (Cases #1 and 2 in Table 3). This is because the higher yield implies burning fuel at a modest efficiency which does not compensate for the additional operating costs.
• Nonetheless, if turbine inlet temperature is increased further, the higher yield is achieved by burning fuel at an efficiency which does compensate for the additional operating costs (Cases #1 and 2 in Table 3).
With this information in mind, cases with low solar share are discarded in the understanding that they do not offer any significant advantage over combined cycle power plants or conventional simple cycle gas turbines. Therefore, a lower solar share limit is set to 50%, which reduces the feasible TIT to 800°C. Amongst the two options in Table 3, case #2 is selected for its superior performance. In this case, the HT combustor is not needed since the receiver outlet is already at the target TIT.

**Sensitivity to fuel costs**

One of the usual discussions when it comes to hybridization in Concentrated Solar Power plants is the impact of higher fuel costs on the economics of the technology. In order to explore this potential risk (fluctuation of fuel costs), a sensitivity analysis is presented in Figure 9 and Figure 10 where the LCoE resulting from different fuel costs is shown. Two aspects are worthy of note.

![Figure 9. LCoE sensitivity to fuel costs (daily operation)](image)

**Figure 9. LCoE sensitivity to fuel costs (daily operation)**

In a scenario with lower fuel prices, increasing the fraction of electricity that is produced with fossil fuels brings about lower LCoEs, irrespective of the operating strategy, daily or base load operation. Amongst the two cases, the lowest cost of electricity is obtained in base load operation (as expected) since LCoE is dominated by capital costs (which are actually the same for both cases).

This pattern is different if fuel prices are high. In this case, increasing the fraction of electricity that comes from fossil energy (higher TIT) brings about higher LCoEs if the plant is in operation during the day only whilst LCoE decreases if the plant is run in base load.

The foregoing discussion confirms that in future scenario with higher fuel costs, gas turbines with modest turbine inlet temperatures being used to harvest solar energy when this is available (i.e., daily operation) will arguably yield lower LCoE than engines with advanced specifications. This is further confirmed by the plot in Figure 11 where the markers for each case have been removed for clarity (i.e., lines show trends for each case and not necessarily the exact value).

![Figure 10. LCoE sensitivity to fuel costs (base load)](image)

**Figure 10. LCoE sensitivity to fuel costs (base load)**

**Sensitivity to boundary conditions**

Concentrated Solar Power plants are usually exposed to warm environments and to irregular energy supply, with low frequency oscillations in the former parameter and both high and low frequency oscillations in the latter. The sensitivity of the proposed technology to these boundary conditions is analyzed in this section where the following effects are studied: (1) ambient temperature change at constant solar heat input, and (2) changes in solar heat input at constant ambient temperature.

![Figure 11. LCoE sensitivity to fuel costs (comparison)](image)

**Figure 11. LCoE sensitivity to fuel costs (comparison)**

![Figure 12. Sensitivity to solar heat input at 25°C (I)](image)

**Figure 12. Sensitivity to solar heat input at 25°C (I)**

Figure 12 shows the impact of reducing the solar heat input to the receiver. A reduction of air flow rate through the receiver...
is observed in order to keep the outlet temperature constant whilst, at the same time, the flow of air through the LT combustor increases. This brings about a lower pressure drop in the former stream and a higher one in the latter, Figure 13. Overall, the effect is a lower combined pressure drop in the heat addition process which increases the output of the engine for the same total heat input. It is nevertheless interesting to see a change in this pattern when the solar heat input drops below a certain value (~90 MWt). At this point, the air flow rate through the LT combustor is so high that the pressure drop in this stream becomes dominant, outweighing the lower pressure drop across the solar receiver.

Figure 13. Sensitivity to solar heat input at 25ºC (II)

Figure 14 and Figure 15 present the impact of changing the ambient temperature. It is to note that the analysis is performed with the solar receiver operating in part load; i.e., the solar heat input (120 MWt) is below the rated value (~165 MWt).

Figure 14. Sensitivity to ambient temperature at 120 MWt (I)

Overall, higher temperatures lead to higher solar shares thanks to the lower throughput of the engine. Indeed, density at compressor inlet is lower but remains somewhat constant at the inlet to the receiver, meaning that this component is now absorbing a larger fraction of the total amount of air through the engine, thus reducing the amount of fuel burnt in the LT combustor. This is the only positive effect of a higher temperature since, as it is common to all gas turbines, higher ambient temperatures lead to lower outputs and efficiencies.

Figure 15. Sensitivity to ambient temperature at 120 MWt (II)

Daily performance

Figure 16 and Figure 17 show the operation of the engine running in daily operation mode in a clear winter day. The plot shows that a fraction of the available solar energy is dumped off the system between 12.30 and 16.30 in spite of which the engine still runs at full capacity. This is thanks to the lower than rated ($T_{am, rated} = 20ºC$) ambient temperature.

Figure 16. Daily performance in a clear winter day (I)

The consumption of natural gas during start-up and shutdown maneuvers is also worthy of note. Indeed, a fraction of fuel is burnt early in the morning to speed up the start-up process and allow for the warm-up of the receiver with the available solar energy. In the evening, fuel is against burnt to keep the engine in operation whilst there is still some solar energy supply. A pilot flame is also sustained during the day in the combustor to reduce the response time of the engine in case of a sudden loss in solar energy supply. The information in Figure 17 confirms that this operating mode enables a very high solar share.

Figure 18 and Figure 19 show the performance of the engine in a cloudy day when a sudden loss of solar energy supply takes place between 12.30 and 14.30. After an operating sequence
similar to the previous case (Figure 16), a cloud covers the solar field, bringing about a temporary shutdown of the plant. When solar energy is supplied again, there is a steep ramp-up of the plant enabled by the back-up fuel burnt in the LT combustor. The amount of fuel burnt is not very high, Figure 19, and it is further increased near the end of the day to facilitate the shutdown sequence.

**Annual performance**

Table 4 shows the hourly average output at generator terminals for the reference meteorological year. Each cell provides the average output at generator terminals in each hour, showing also a colour code where red corresponds to the highest output (rated output is 50 MW with a +5% overcapacity allowed) and dark green indicates that the plant is not in operation.

The expected higher yield in the central months of the year, May to September, is confirmed in Table 4. Nevertheless, it is interesting to note that the peak production is obtained at different times in each month. This is due to the change in the DNI pattern of the representative clear day in each month but, most importantly, to the different daily pattern of clouds whose effect is then averaged monthly. This highlights the need to average the output data of the performance model rather than the input dataset as it is often done in this type of analysis. Accordingly, the importance of performing hourly simulations in lieu of calculations based on monthly or even weekly averaged values is confirmed by the results in Table 4.
CONCLUSIONS

The detailed analysis in this article has presented a discussion on the technical and economic features of gas turbines installed in Concentrated Solar Power plants of the central receiver type. In addition to the inherent virtues of gas turbines (virtually null water consumption, short lead time to installation, small footprint and flexibility), a specific integration layout able to cope with the irregularities of solar energy supply has been proposed.

From a technical standpoint, the main conclusion drawn from the analysis is the ability of the proposed layout to:

- Enable annual solar shares higher than 60% when modest turbine inlet temperatures are selected.
- Sustain the engine running at full capacity regardless of the available solar energy.
- Enable constant operating conditions of the higher temperature combustion process, thus ensuring compliance with the environmental regulations in place.
- Enhance the flexibility of the system in terms of fast start-up and shutdown maneuvers and operation in markedly transient conditions.

With regards to the economics of the system, the main conclusions are:

- Costs of electricity (LCoE) in the order of 14.5 €/kWh seem possible with annual solar shares higher than 60%.
- High fuel prices favour a business case based on engines with low turbine inlet temperature run on a daily start/stop basis. This case exhibits a very high solar share.
- Low fuel prices favour a business case based on engines with high turbine inlet temperature run base load. Unfortunately, the solar heat input is marginal in this case, which cannot really be considered a solar thermal power plant but, rather, a system based on natural gas where fuel savings are enabled by a small fraction of solar energy input.
- Exceptionally, having engines with low TIT run base load in a scenario with very low fuel prices has the potential to yield LCoEs in the order of 8.5 €/kWh and solar shares higher than 60%. This is a promising result for countries with cheap natural gas.

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