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Performance Analysis of a Hybrid Solar/Biomass Power Plant for Different Operating Scenarios

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Abstract. Performances of a hybrid CPC/biomass system coupled to an ORC power block are investigated on a minute-by-minute basis for four representative days of the year under different operating modes. Furthermore, influence of the considered solar radiation threshold value for operating the solar field in the hybrid mode was investigated through an energy performances comparison of two alternatives. Research findings showed that the hybrid mode allow a significant improvement of the thermal and electrical output (143-446%) and efficiencies of the plant’s components (8,8-9,8 % for the solar field and 26-48% for the ORC) relatively to the solar mode, with a slight decrease of the thermal efficiency in comparison to the biomass mode (2,9-4,5 %). On the other hand, results showed that the choice of the solar radiation threshold for operating the solar field in the hybrid mode can have non-negligible impacts on the performances of the plant.

INTRODUCTION

Solar thermal technologies allow clean and sustainable energy production; however, solar energy is inherently intermittent. The use of a thermal energy storage can mitigate this issue, yet it will increase the investment cost [1] and the capacity factor of the plant will remain low [2]. Biomass energy allow flexible and dispatchable energy production, however, its use is limited by the seasonal availability of biomass resources, the logistic constraints and the cost [3]. Thus, hybridization of solar thermal and biomass energies is a promising solution to overcome their mutual drawbacks and combine their advantages to address energy supply challenges.

As part of the REELCOOP project [4], a novel hybrid solar/biomass system, representative of decentralized electricity production systems was designed and installed (Prototype 2) [5-7]. The plant is combining a solar field using compound parabolic collectors (CPC) and a biomass boiler to drive an Organic Rankine Cycle (ORC).

This study aims to investigate the impact of different operating scenarios on the performances of the hybrid plant and to assess to what extent the absorbed solar radiation considered threshold value for operating the solar field in the hybrid mode can influence the performances of the whole plant. Plant’s components were modeled in Ebsilon Professional and simulations were carried out for 4 days of the year considering a minute-by-minute step. Key indicators including solar field and biomass boiler thermal output, solar fraction, ORC electrical output, solar field, ORC and plant efficiencies were then compared for the different operating modes.
DESCRIPTION OF THE PLANT

Plant’s configuration consists on a solar thermal driven system hybridized with biomass and coupled to an ORC block (Fig. 1). The plant was designed and installed in Benguerir (Morocco) within the REELCOOP project.

The solar field includes 32 stationary (seasonally tracking) compound parabolic collectors (CPC) arranged in 8 loops, with a total aperture area of 146 m² (Fig. 2a). Olive waste residues, highly abundant in the region of Benguerir were chosen as biomass fuel for the boiler (Fig. 2b). The biomass has a calorific value of 17000 kJ/kg (LHV) and the biomass burner can operate within a range from 20 to 100 kW.

A buffer storage tank was installed in the downstream of the two heat sources to absorb temperature fluctuations of the heat transfer fluid (a mineral oil) at the inlet of the ORC block. The ORC block has a nominal power of 6 kW uses R245-fa as a working fluid and is air-cooled (Fig. 2c).

FIGURE 1. Schematic diagram of the plant

FIGURE 2. Main components of the plant, (a) Solar field, (b) Biomass boiler, (c) ORC block
SIMULATION MODEL AND OPERATING MODES

Model Description

To simulate the performances of the plant, model related to the considered operating modes of the plant (solar, biomass and hybrid) have been built in Ebsilon Professional (Fig. 3). Most of plant’s components (pump, heat exchangers, turbine) are included in the software’s component libraries. Table 1 summarizes the main model parameters in design conditions.

Since the CPC collectors are not available in Ebsilon’s database, the component 65 (programmable component) was used to simulate the performances of the collectors. Equation (1) was used to model the CPC collectors [8]:

\[ Q_u = F_R A_a \left[ S - A_r \frac{A_u}{A_a} U_L (T_i - T_a) \right] \]

Where \( Q_u \) is the useful gain energy (W), \( F_R \) is the collector heat removal factor, \( A_a \) and \( A_r \) are respectively the unshaded area of the concentrator and receiver tube area (m²), \( S \) is the absorbed solar radiation per unit of aperture area (W/m²), \( U_L \) is the loss coefficient of the receiver tube (W/m².K), \( T_i \) and \( T_a \) are respectively HTF inlet temperature and ambient temperature (K), with :

\[ F_R = \frac{m_f C_P}{A_a U_L} \left[ 1 - \exp \left( \frac{A_u}{m_f C_P} \right) \right] \]

Where \( m_f \) is the HTF mass flow (kg/s), \( C_P \) is the HTF specific heat (J/kg.K) and \( U_0 \) is the overall heat transfer coefficient between the surroundings and the fluid (W/m².K).

\( S \) is expressed as:

\[ S = (G_{bc} + G_{dc}) \eta_0 K_{at} = G_{eff} \eta_0 K_{at} \]

Where \( \eta_0 \) is the peak optical efficiency of the collector, \( K_{at} \) is the incidence angle modifier of the collector, \( G_{bc} \) and \( G_{dc} \) represents respectively the contribution of the beam and the diffuse radiation. They are calculated using the following equations:

\[ G_{bc} = G_{bn} \cos(\theta) \]

\[ G_{dc} = \begin{cases} \frac{G_d}{C} & \text{if } (\beta + \theta_c) < 90^\circ \\ \frac{G_d}{2} \left( \frac{1}{C} + \cos(\beta) \right) & \text{if } (\beta + \theta_c) > 90^\circ \end{cases} \]

Where \( G_{bn} \) is the beam normal irradiation (W/m²), \( \theta \) is the incidence angle (°), \( \theta_c \) the collector half acceptance angle (°), \( G_d \) is the diffuse radiation (W/m²), \( C \) is the concentration ratio of the collector and \( \beta \) is the collector slope angle from the horizontal (°).

### TABLE 1. Model parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar field aperture area A</td>
<td>123 m²</td>
</tr>
<tr>
<td>Peak optical efficiency ( \eta_0 )</td>
<td>0.623</td>
</tr>
<tr>
<td>HTF inlet/outlet temperature</td>
<td>140 / 180°C</td>
</tr>
<tr>
<td>Biomass boiler efficiency ( \eta_b )</td>
<td>75 %</td>
</tr>
<tr>
<td>R245-fa high/low pressure</td>
<td>14/2.5 bars</td>
</tr>
<tr>
<td>R245-fa superheating degrees</td>
<td>5 K</td>
</tr>
<tr>
<td>Turbine isentropic efficiency</td>
<td>50 %</td>
</tr>
</tbody>
</table>
Operating Scenarios and Control Strategies

Simulations were conducted on a minute-by-minute basis from 08:00 h to 18:00 h in four representative days (Fig. 4) (March 21st, June 21st, September 21st and December 21st) using the time-series function. Initial temperature of the buffer tank was assumed to be 120°C. The three following operating scenarios (modes) were investigated:

- **Solar mode:** the HTF start its recirculation in the solar field once $S$ reach a value of 100 W/m²; when the buffer storage reaches 158°C, the ORC block starts electricity production until the storage temperature is cooled down to 158°C. HTF mass flow is varied in the thermal circuit to reach a temperature of 180°C at the outlet of the solar field. Organic fluid mass flow is varied to allow cooling of the HTF to 140°C at the outlet of the heat exchanger. A sliding pressure control strategy is adopted for the operation of the ORC block in off-design conditions.

- **Hybrid modes 100/200:** the HTF start its recirculation in the biomass boiler until $S$ reach a value of 100 (resp. 200) W/m²; from that moment, the HTF starts to be preheated in the solar field and the boiler provide sequentially the complementary energy to heat the HTF up to 180 °C. HTF circulation in the solar field is interrupted when $S$ decreases to 100 (resp. 200) W/m². HTF mass flow is set to its nominal value and the ORC block is operated on its nominal conditions (mass flow and high pressure).

Besides, a reference case of a biomass power plant was assessed and compared to the investigated scenarios.
Performance Indicators

Numerical simulations were conducted in Ebsilon Professional for the considered operating scenarios. In addition to the solar field thermal output ($P_{\text{sol}}$), boiler thermal output ($P_b$) and ORC electrical output ($W_{\text{ORC}}$), performances of the plant under the different scenarios were evaluated using the following indicators:

- **Solar field efficiency:**
  \[ \eta_{\text{sf}} = \frac{P_{\text{sol}}}{G_{\text{eff}} A} \]  

- **Solar fraction:**
  \[ SF = \frac{P_{\text{sol}}}{P_{\text{sol}} + P_b} \]  

- **Boiler efficiency:**
  \[ \eta_b = \frac{P_b}{LHV m_b} \]  

Where $m_b$ is the biomass mass flow (kg/s).

- **Dumped heat:**
  \[ P_{\text{dump}} = P_{\text{sol}} + P_b - P_{\text{ORC}}^0 \]  

Where $P_{\text{ORC}}^0$ is the ORC nominal thermal input (W).

- **ORC efficiency:**
  \[ \eta_{\text{ORC}} = \frac{W_{\text{ORC}}}{P_{\text{ORC}}} \]  

Where $P_{\text{ORC}}$ is the ORC thermal input (W).

- **Plant efficiency:**
  \[ \eta_p = \eta_{\text{ORC}} \eta_{\text{th}} \]  

Where $\eta_{\text{th}}$ is the thermal efficiency defined as: \[ \eta_{\text{th}} = (SF \eta_{\text{sf}} + (1-SF) \eta_b) \]

RESULTS AND DISCUSSION

Solar, Hybrid and Biomass Scenarios

Simulation results for the considered days are illustrated in Fig. 5. For the sake of clarity only the results of one hybrid scenario (hybrid 100) were represented in the figure.

Results showed a significant difference between the thermal output of the solar mode on the one hand (177,79 – 244,44 kWh/day) and the thermal output of the biomass and hybrid modes on the other hand (~ 596 kWh/day). Moreover, since the sequential combination of the solar field and the biomass boiler in the hybrid mode allow the operation of the solar field at a lower temperature in comparison to the solar mode, results reported an improvement of the solar field efficiency (8,8 – 9,8 %). However, due to the limited operating range of the biomass boiler, a fraction of the boiler thermal output in the hybrid mode is dumped due to energy excess (2,4 – 13,8 %). For the different days, solar fraction value is varying between 37,7 and 49,6 % and is highly dependent on the effective solar radiation on the aperture of the CPC collectors $G_{\text{eff}}$ (Fig. 4a).

Figure 5b illustrates that the thermal output findings are directly affecting the electrical performances of the operating scenarios. Hence, electricity production is correspondingly lower in the solar mode (7,5 – 12,8 kWh/day) in comparison to the biomass and hybrid modes (38,2 – 46,9 kWh/day). Moreover, the flexible and stable running of the biomass boiler in the hybrid and biomass modes allow operating the ORC closer to its nominal conditions, thus reaching optimized ORC efficiency values. Impact of ambient temperature (Fig. 4b) on the performances of the ORC can be clearly assessed through the variation of electricity production and ORC efficiency between the considered days. Thus, electricity production and ORC efficiency are maximized (respectively 46,9 kWh and 8,41%) on December 21st, whereas the 21st of June is the less effective day (38,2 kWh and 6,93%). Overall plant efficiency results showed that the hybrid mode performances are slightly penalized by the lower solar field efficiency in comparison to the biomass boiler, nevertheless its performances remain significantly higher relatively to the solar mode.

Figure 6 represent simulation results of the hybrid mode for the summer solstice (21st June). After the start-up phase, the plant is running using the boiler as a single heat source allowing a stable operation of the system. The solar field is coupled to the plant at around 08h:40 and contribute to a noticeable reduction of the boiler thermal output.
leading to its operation at the minimum power between 10:20 and 15:00. Nonetheless, solar field operation is restricted to about eight hours, despite the presence of sunlight due to the limited optical performances of the non-tracking CPC collectors (incidence angle modifiers).

FIGURE 5. Performance comparison of the operating scenarios for the considered days, (a) Solar field output, solar field output, solar field efficiency, boiler useful output, boiler dumped heat and solar fraction (hybrid mode), (b) ORC electrical output, ORC and plant mean efficiencies

FIGURE 6. Simulation results of the hybrid mode for the 21st of June
Hybrid Mode: Threshold Value for Solar Field Operation

The aim of this section is to assess the impact of the considered absorbed solar radiation (S) threshold value for operating the solar field, on the performances of the plant for two alternatives of the hybrid mode, hybrid 100 and hybrid 200 considering respectively 100 and 200 W/m² as threshold values for S.

As illustrated in Fig.7a, results showed that the hybrid 100 option allow an increase of the solar field thermal output up to 6.6 % (21st of September) in comparison to the hybrid 200 option due to the extension of solar field operation time. This led to an increase of the solar fraction (1.2 – 6.6%) and a reduction of biomass consumption between 1.1 and 3.7 % relatively to the second alternative.

On the other hand, Fig. 7b, report higher thermal efficiency values of the hybrid 200 option in comparison to the hybrid 100 option due to the lower solar fraction in the former mode, resulting in a corresponding increase of the overall plant efficiency of the second alternative. Thus, maximum plant efficiency difference between the two alternatives is reached during the 21st of December (4.5%) when the solar fraction is respectively 42.42 and 41.36 % for the two alternatives, whereas the minimum difference (2.89%) is obtained during the 21st of June when the solar fraction is respectively 49.56 and 49.04 %.

![FIGURE 7. Comparative results of the hybrid 100 and hybrid 200 options, (a) Solar field output, biomass consumption and solar fraction, (b) Thermal efficiency and plant efficiencies](image-url)
CONCLUSION

In this study, a hybrid CPC/biomass plant coupled to an ORC block is simulated in four representative days under different operating scenarios. Findings report that the performances of the solar mode are penalized by the optical performances of the CPC collectors, thus reducing the operation of the plant under this mode to few hours at lower efficiencies in comparison to the other modes. In contrast, the biomass mode allows a continuous and stable running of the plant against a daily biomass consumption rate of ~ 151 kg (10 h operation). The hybrid mode is considered as the alternative scenario to the two reference cases: on the one hand it enables the flexible and continuous operation of the plant at comparable performances relatively to the biomass mode and on the other hand it contributes to a noticeable reduction of biomass consumption (up to 46%) in comparison to the biomass mode. Finally, the investigated two hybrid options showed that the considered solar radiation threshold value can have a non-negligible impact on the performances of the plant, however, the choice of the optimized value should consider additional aspects not addressed in this study such as electricity selling price and biomass cost and availability.

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REFERENCES