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Biomass-Photovoltaic Hybrid Plant for Hydrogen Production via Steam Electrolysis

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Performance of a hybrid biomass photovoltaic plant has been studied. Electric energy from photovoltaic panels and biomass combustion steam cycle is utilized to produce hydrogen via steam electrolysis, and the electricity surplus is sent to the grid. Two different scenarios have been considered, varying the size of the solar plant, and annual performance of the plant has been analysed, studying the variation of the solar energy generated and biomass consumption as a function of the size of the solar plant. Results show the relationship between the solar plant size and the annual biomass consumption of the hybrid plant.

1. Introduction

Biomass and solar energy are expected to play a very important role in decreasing global CO_2 emissions. Carbon neutrality of biomass attracts a lot of scientific attention associated with the mitigation of climate change (Sebastián et al., 2011) and the depletion of fossil reserves (Paula et al., 2013). Its main advantages are the low cost of the fuel and the contribution towards the independence from fossil fuels. It is one of the main energy sources in many communities in the developing countries all over the world (Borges Neto et al., 2010) Disadvantages are problems related with combustion, the low ash melting temperature and the variation in the fuel properties (Gimelli and Luongo, 2014).

Photovoltaic cells are reliable and relatively easy to maintain, they do not have moving parts, they are easy to clean, and silent. They are also modular and flexible in size and applications. Photovoltaic panels are used broadly in remote applications (Meah et al., 2008). This technology is being deployed in a wide range of applications, such as power for consumer products, hydrogen production (Ghribi et al., 2013), water pumping and street lighting. Many big companies are turning towards photovoltaic energy to meet peak power demand and reduce the need of fossil fuels and other energy sources, such as hydroelectric (Maximo et al., 2013). However, conventional energy is needed to produce and assemble solar panels, and the conversion process is less efficient than fossil fuels. Additionally, this technology is still associated with a relatively high cost of manufacturing (Khatib et al., 2013).

Hybridization of biomass with photovoltaic energy can solve many of the problems that characterize each technology when it is used on its own (Nixon et al., 2012). Biomass and photovoltaic energy may be combined in a hybrid power plant, to co-generate electricity and hydrogen by electrolysis. This hydrogen produced by water electrolysis represents a highly clean energy source (Chennouf et al., 2012). The process includes direct combustion of biomass, which is the most common way to convert biomass to heat or electricity. The conversion of biomass through direct combustion is relatively simple and available commercially. Biomass combustion in a steam power plant is a common way to convert biomass to electricity and/or heat. Hybrid systems combining combustion and photovoltaic energy are useful in rural areas that have no access to the conventional electrical grid (Borges Neto et al., 2010). A variety of hybridization schemes for hydrogen and electricity production can be found in literature, including biomass-solar (Hashim et al., 2013), biogas-solar (Borges Neto et al., 2010), nuclear (Yan et al., 2014), solar-wind (Khalilnejad and Riahy, 2014) or wind-solar-fuel cells (Chávez-Ramírez et al., 2013). The goal of this work is the study of the feasibility of a hybrid power plant for hydrogen and electricity production from biomass and photovoltaic energy, and the influence of the solar plant size in biomass consumption.

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Table 1: Biomass composition

Element	Composition (% wt)
C	50.2
H	6.06
O	40.4
N	0.6
S	0.02
Cl	0.01
Ash	2.7

2. Process description and simulation

It has been assumed that the electrolyser will be incorporated into an already existing biomass power plant structure. Thus, the electrolyser unit will be adjusted accordingly to be coupled with already existing plant structures and will not require new plant configurations. All simulations presented have been performed using EbsilonProfessional (Version 10.0).

The biomass used in the power plant is hybrid poplar wood chips with the weight composition (dry) detailed in Table 1.

The biomass is combusted with air in a boiler, providing thermal energy to convert water to superheated steam. The high-pressure steam generated at 80 bar and 550 ºC is then expanded in the steam turbine of the plant. One reheat stage is included before the intermediate-pressure steam turbine in order to increase the power output and the efficiency of the plant. At the last level of the steam turbine, the steam is expanded to 0.05 bar and is led to the condenser of the plant. The saturated stream exiting the condenser is finally pumped back to the operating pressure of the boiler and enters the boiler at a temperature of 230 ºC to complete the cycle. The electrolyser works with air recirculation and a sweep gas stream.

The electrolyser unit consists of 110 parallel stacks, each one of which requires 4.5 kW. As a result, the total amount of power required by each unit is 500 kW. In the simulations performed, 5 units of the electrolyser are utilized, and the total power input requirement is 2,500 kW. The operating temperature of the unit is 700 ºC. The simulation diagram for this process is shown in Figure 1.

Since steam used in steam cycles may present traces of harmful compounds and electrolyser demands high purity water, this is taken externally from a source independent from the biomass power system. In the simulation, low-pressure steam extracted from the biomass power plant at 2.2 bar and 238 ºC has only been used indirectly to generate the required steam for the electrolyser from a clean water source. The produced steam is mixed with recycled H_2 stream (part of the outlet gas of the electrolyser) and enters the electrolyser with a molar composition of 10 % H_2 and 90 % H_2O. Hydrogen is present to avoid oxidation processes inside the electrolyser. Additional electric heaters are used to increase the temperatures of the

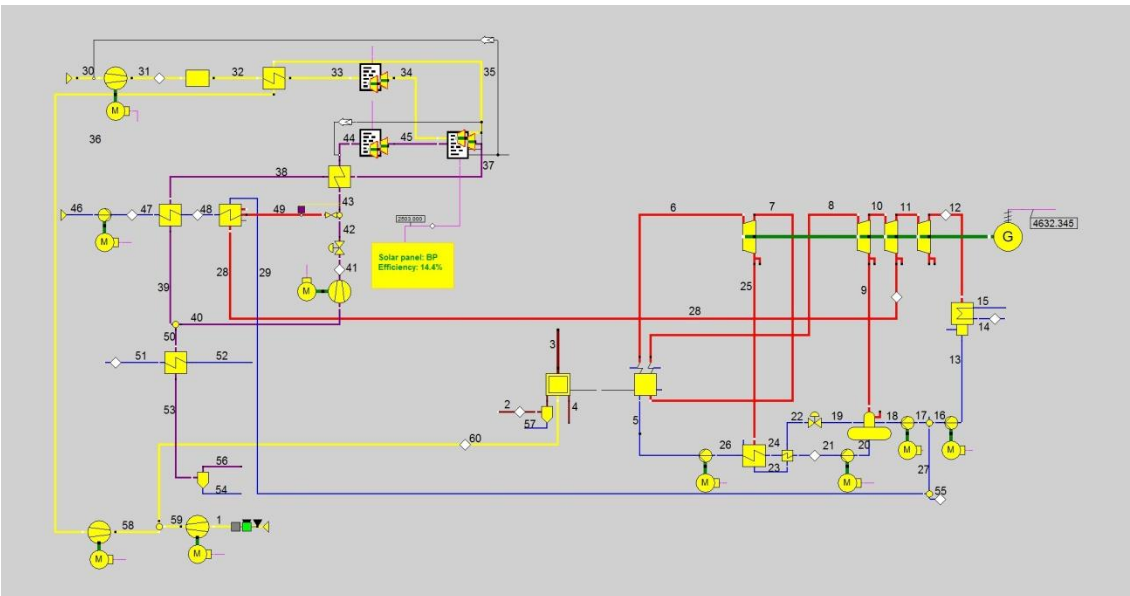

Figure 1: Simulation diagram for the hybrid plant

inlet streams to 700 ºC. The electricity input for these heaters is provided by the electricity generated in the biomass power plant. In the electrolyser, 61 % of the incoming H_2O is split into H_2 and O_2. Air enters the anode of the electrolyser, sweeps the separated O_2 and exits the electrolyser. The air reaches the desired conditions at the inlet of the electrolyser (temperature, pressure) after a compression step, filtering and two heat exchanges, one of which is electrical. The molar ratio between the air stream that enters the anode of the electrolyser and the steam stream that enters the cathode was selected to be 1:1.
The molar composition of the hydrogen-rich gas exiting the cathode of the electrolyser is 64 % H_2 and 36 % H_2O. The gas is then cooled to a temperature of 45 ºC and the condensated water is separated. It is then removed without any recirculation back to the electrolyser to not affect the quality of the water inlet. The extracted H_2 stream consists of 90.7 % H_2 and 9.3 % H_2O, molar composition.

3. Site selection

The hybrid power plant is planned to be built in Huelva, Andalusia (Spain). This area is characterized by mild winters and hot and dry summers. Huelva also has significant biomass resources, produced both as crop and as waste. The feasibility of such plant is also proven by the fact that ENCE, Spain's leading company in biomass-fuelled renewable energy generation, already operates a large biomass power plant in the area with an electricity production of 68 MW.
The plant is planned to be located in an area with various chemical and refinery installations, for which hydrogen availability is a very important factor. The electricity surplus generated in the power plant will be sent to the electrical grid.

4. Results

In nominal conditions, 40 % of the electricity needed in the electrolyser is provided by photovoltaic panels, while the remaining 60 % is generated by biomass combustion. Two scenarios have been considered in order to determine the nominal conditions for the hybrid plant:

- Solar radiation of 456.0 W/m^2, which has been calculated as the average value of data retrieved from Meteonorm (a software which incorporates a catalogue of meteorological data and calculation procedures for solar applications at any location in the world) for this area, taking into account only the daylight hours. Assuming a photovoltaic panel efficiency of 14.4 %, the area of panels required is 15,229 m^2.
- Solar radiation of 208.3 W/m^2, calculated as the average value of data retrieved from Meteonorm for this area, taking into account daylight hours and night hours. With a photovoltaic panel efficiency of 14.4 %, the same as in the previous scenario, the area of panels required is 33,333 m^2.

When the hybrid plant is out of nominal conditions, the electricity generated by photovoltaic panels may be higher or lower than 40 % of the electrolyser needs.
The efficiency of the plant has been calculated using the following equation:

$$\eta = \frac{\left(P_{elec\_grid}\right) + \left(LHV_{H2} \cdot m_{H2}\right)}{\left(LHV_B \cdot m_B\right) + \left(\dfrac{P_{elec\_electrolyser}}{\eta_{PV}}\right)} \qquad (1)$$

Where B: Biomass, PV: Photovoltaic, LHV: Lower heating value, m: mass flow, η: energetic efficiency, P: power output.
The power output of the hybrid power plant at nominal conditions is 10 MW. The plant may operate out of nominal conditions due to the variation in the solar radiation received by photovoltaic panels. This radiation changes continuously during the day, and there is also a daily variation along the year due to the season change.
A performance analysis of the hybrid power plant has been carried out taking into account two scenarios, as detailed above.

4.1 Scenario 1. Average solar radiation taking into account only daylight hours.

The annual performance of the hybrid power plant has been studied via process simulation. Figure 2 shows the simulation results for 24 h in a typical sunny day, and Figure 3 for a typical cloudy day, when solar radiation is not so continuous due to the presence of clouds.

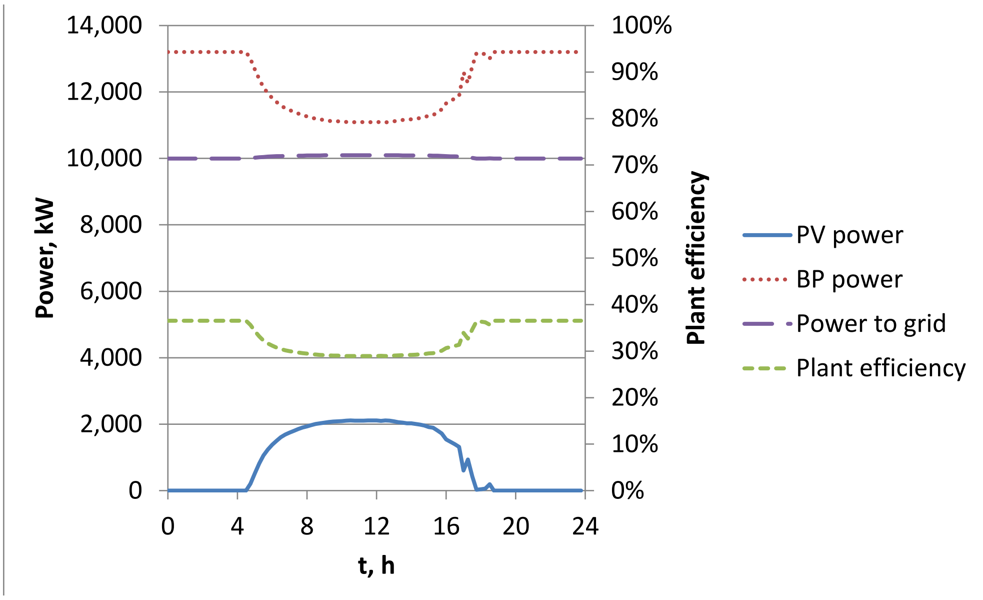

Figure 2: Sunny day, scenario 1

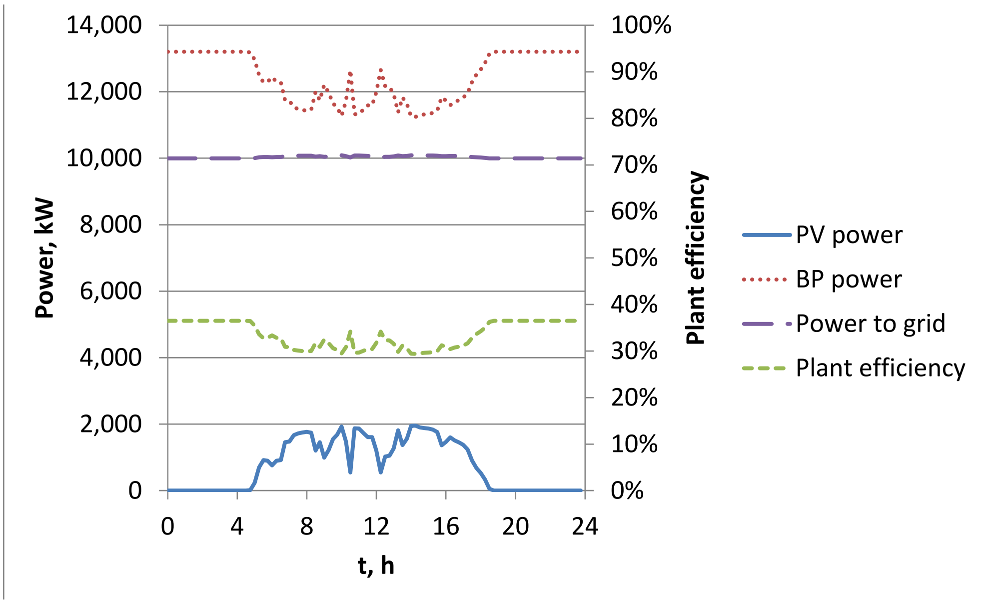

Figure 3: Cloudy day, scenario 1

4.2 Scenario 2. Average solar radiation taking into account all hours of the day.
The annual performance of the hybrid power plant for this scenario has been carried out in the same way as for scenario 1. Figure 4 shows the simulation results for a sunny day, and Figure 5 for a cloudy day.

4.3 Annual yield analysis.
The performance of the hybrid power plant has been shown above in a typical sunny day and in a typical cloudy day. Broadening the analysis to the whole year for both scenarios considered leads to the results detailed in next Table.

The total amount of biomass needed depends on the scenario considered. As shown in Table 2, an increase in the photovoltaic panels area from 15229 to 33333 m^2 (118 %) leads to a decrease in biomass consumption of 4.6 % (from 84070 t/y to 80165 t/y). Thus, the size of the solar plant could be further optimized, taking into account economic and environmental concerns.

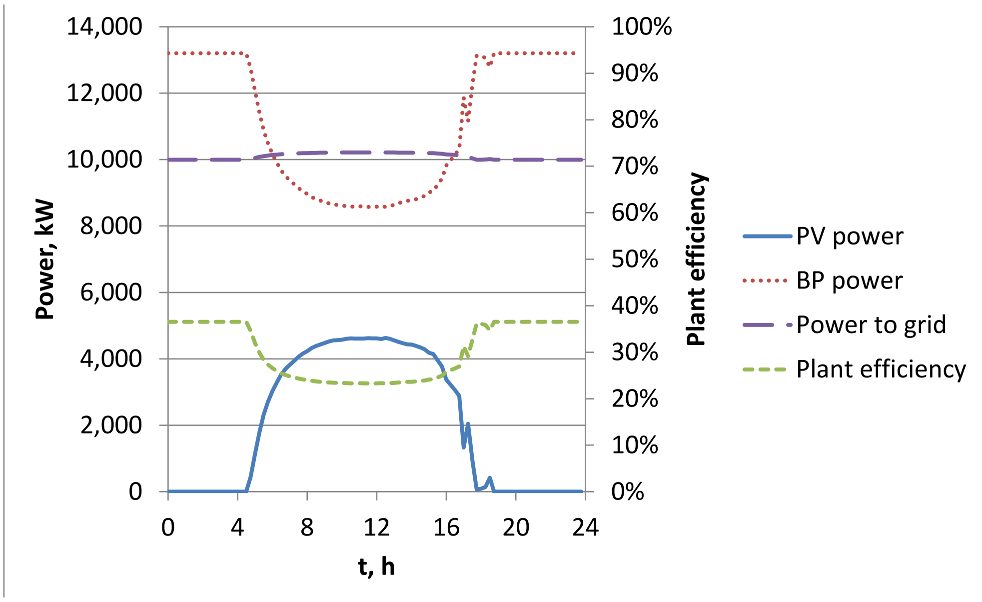

Figure 4: Sunny day, scenario 2

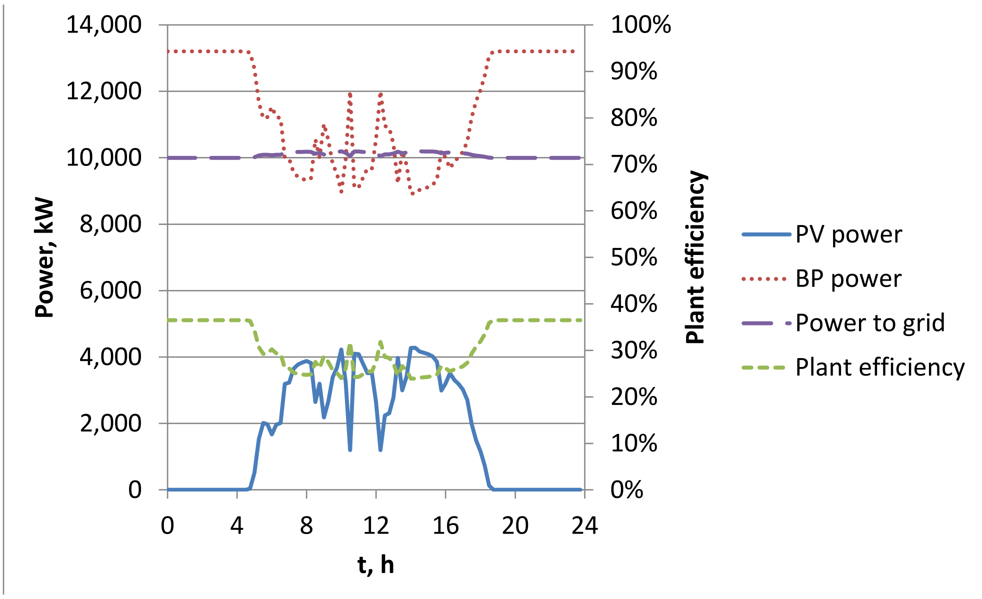

Figure 5: Cloudy day, scenario 2

Table 2: Annual simulation results.

	Scenario 1	Scenario 2
PV panels area	15,229	33,333
Radiation in nominal conditions (W/m^2)	456.0	208.3
Biomass consumption (t/y)	84,070	80,165
Energy from biomass (MWh/y)	286,600	273,300
Energy from PV (MWh/y)	4,359	9,540
Electrical heater duty (air) (kW)	12.1	12.1
Electrical heater duty (water)(kW)	52.7	52.7

5. Conclusions

Hybridization of biomass with photovoltaic energy can supply the requested hydrogen for a continuous demand on the bases on the simulation carried out.

The technologies involved for supplying the energy to the electrolyser are relatively simple and available commercially.

A big increase in the solar plant size (from 15,229 to 33,333 m^2) produces a slighty decrease in biomass consumption. Hybridization of both technologies is a feasible pathway to produce hydrogen and electricity, but further studies are necessary to select the most appropriate solar plant size.

6. Acknowledgement

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