Feasibility of a Solar-Thermal Plant Hybridized with Biomass from Olive Oil Waste in Southern Spain

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ABSTRACT

This project analyzes the technical and economic feasibility of a solar thermal plant of 10MW of installed capacity. The plant is designed to operate a minimum of 2500 hours per year through the hybridization of biomass which is obtained from the wastes of the olive oil production, one of the most relevant agricultural products in the South of Spain. The plant is located in a strategic geographical zone with plentiful access to these wastes due to the large number of olive processing facilities and also with availability of water for refrigeration because of the nearby Guadalquivir river. A technical analysis of the project is performed to compare the different technological alternatives and the advantages of hybridization. The study is completed with an economic analysis in order to determine its economic feasibility under the current and projected regulations for this type of renewable energy installations.

Keywords: Solar thermal, Sustainable energy, Hybridization, Biomass, Economic analysis

1. INTRODUCTION

The object of this paper is to study the technical and economic feasibility of an electricity generation plant of 10 MW which uses solar thermoelectric technology hybridized with biomass. The plant will be located in Montoro (Córdoba) due to the excellent solar conditions, the availability of water from the Guadalquivir river and, as the main factor, the wide availability of alperujo from the plant of olive oil production located in the area (Los Predroches Mountains).

The power plant generates electricity using the Rankine power cycle. In order to improve performance (38%), the cycle features a reduction in the boiler´s pressure below atmospheric pressure, overheating and two extractions in the steam turbine. The contributed heat to the cycle comes from the field of parabolic trough solar collector and the combustion of orujo in the biomass boiler. The main peculiarity of this plant is that the two heat sources are placed in serie. The objective of this scheme is to guarantee that the turbine entry conditions are constant during the plant operation hours (2,500 hours per year) in order to ensure a steady supply of electrical power to the power supply. The acquisition of thermal energy in the collector field is due to the incidence of direct solar radiation (780 W/m2) on parabolic trough mirrors. These mirrors follow the position of the sun throughout the day reflecting the radiation on a pipe for circulating synthetic oil (therminol), which absorbs the heat and reaches to a temperature of 395 oC. This heat is transferred to the steam cycle in the heat exchangers. The field consists of 56 solar collectors on a total area of 30,520 m^2 wich produce 24.9 MWt at the point of optimum design. Due to the current generation system of the plant, the biomass boiler is oversized to 13.4 MWt in order to provide a greater amount of thermal energy along the hours where the field does not produce the solar maximum. The boiler fuel is orujo at 8% humidity. The orujo is the result of drying the alperujo, the waste of the olive after olive oil extraction. The plant design has been adapted to the amount of available biomass: 23.000 tons per year. To obtain the calorific value of the fuel, a set of tests were done in a calorimeter, having as result an average of 4075

Kcal/Kg. Once you know the values of the different points of the thermodynamic cycle, the next step is to calculate the main pieces oft he plant equipment.

The second part of this article is the economic viability study. The total required investment amounts to 20.268,035 €, which will be amortized over 10 years and financed at 85% (interests at a 4.3% rate). The costs are those arising from the purchase of biomass, the costs of labor and maintenance, administrative expenses and financial expenses. The revenues are for the sale of energy to the power supply. The cost-benefit analysis has been estimated for a plant life of 22 years, being the main parameters the variation of fuel, the selling price of energy to the electricity market and the consequent updating of the pool, the change CPI and interest rate. The profitability indicators obtained for the most likely scenario take these values: NPV = 30,539,554 € and IRR = 12.6% with an 8 years payback period. These results are completed withc an analysis of a pessimistic scenario due to the crisis. For an average interest rate of 4.3 %, the conclusion is that is feasible the existence of a power generation system based on clean technologies in order to ensure the supply capacity to the power supply.

The objectives to be covered with the installation are:

- Generate electricity using solar thermal energy and biomass energy. Two renewable energies with big growth opportunities in the coming years.
- Study the feasibility of renewable energy hybridization.
- Use agricultural wastes as a source of energy.
- Reduce the dependence on fossil fuels in Spain.
- Large electric power from renewable energy installed for reaching the goals set in the country for 2013.

2. TECHNICAL STUDY

The purpose of this installation consists of three parts clearly differentiated: a solar collector field which uses parabolic trough, a facility using biomass, and the power block.

2.1 SOLAR FIELD

The solar collector field consists of cylindrical-parabolic concentrators (CPC's). The solar collectors used in the project plant will be the LS-3 shape or similar (Figure 1), which have the following features: solar tracking accuracy 0.10^o, maximum wind speed 56 Km/h, spatial structure, absorbent surface Cermet, 18% emissivity at 350 ^{o}C, 95% transmissivity, absorptivity of 96%, 94% reflectivity, concentrator focal length 1.71 m, the opening angle of 80^o, parable width 5.76 m, length 99 m, aperture area of 545 m^2, distance between supports 12 m, distance between parallel rows 17 m, maximum working temperature of 400 ^{o}C, intercept factor 93%, fouling factor of 95%.

Figure 1: Cylindrical-parabolic solar collector

The mission of the receptor is to absorb the concentrated radiation, and in this case, using the selector sensor LS-3 which should have the following characteristics: diameter 70 mm, length 4060 mm, weight 25 Kg, maximum operation temperature 400°C.

The heat transfer fluid used will be VP-1, which through an oil-water exchanger will help us to produce superheated steam (Rankine cycle). It must have the following characteristics: density, 767 kg/m3; viscosity, 1.81·10 - 4 kg/m·s; optimum temperature range, 12-400°C, vapor pressure at 395°C, 10 bar; Cp, 2.44 KJ/Kg·K. The CPC's are oriented in the north/south axis, and thanks to the solar tracking system it should always have the best possible position towards the solar azimuth, oriented east at dawn, and describing an arc as the hours pass by, to finish facing west at sunset. The maximum performance of the system takes place between the two hours after sunrise and two hours before sunset.

The positioning system of the CPC's is done by a range of elements which should be reviewed: Weather Station, angular encoder, communications bus, central PC for the plant control and hydraulic systems for the CPC's displacement. The CPC's are sustained on the ground by a steel frame, to which they are joined by an articulated spatial structure. The thermal receiver is a suck tube by the one circulates heat transfer fluid, in this case the fluid is heated to aproximately 395°C by the concentrated sun rays. The selected model is the Solel tube. 1.770 units of 4m each will be installed.

The HTF (Heat Transfer Fluid) system moves the heat transfer fluid through the solar collector system, ensuring its adequate flow rate. Two units will be installed at 100% capacity, this will allow to remain operating the system in case of failure. The pumps inlet pressure must be enough to ensure that no cavitation effects take place.

The heat exchange system between the primary circuit of fluid heat transfer and the secondary circuit of steam is done by exchangers. These elements are positioned in the primary flow direction: overheating exchanger and evaporator exchanger.

The hottest fluid flows through the plate heat exchanger in order to rise the steam temperature up to 373°C. Two heat exchangers are used in this process. Afterwards, the oil flow passes through the evaporator plate heat exchanger, where water is heated until it transforms into low temperature steam. In this process are used two exchangers of 300 plates, being the selected model the SPW-55 Tranter, or similar.

2.2 INSTALLATION FOR BIOMASS UTILIZATION

The biomass installation includes:

- Fuel storage, unprepared
- Transport system
- Dryer band or trommel type
- Store fuel
- Dosing biomass
- Boiler equipped with economizer, electrofilter and boiler ash

Fuel storage is done in a large pond located in the plant where alperujo is stored. The transport system consists of 30 meters conveyor belts distributed among the storage pond and the drying trommel where, taking advantage of the temperature of the leaving gases of the boiler, the alperujo is dried until it transforms into orujo 8% moisture. Then the biomass passes to the storage area. Afterwards it will be sent to the dispenser, which allows the combustion to be always accurate and regular. The boiler is a heat generator for thermal fluid (it can heat up to 430°C) and operates in different modes along the year, always according to the needs of the steam cycle.

The main components of the boiler are:

- Combustion chamber
- Ash collectioning tray
- Ashtray
- Economizer

- Electro-filter

The combustion chamber is located in the lower part of the hearth, above the ash collecting tray. A combustion with oxygen excess and hearth overpressure will take place. The ash collecting tray works automatically and drains out the wastes to the ashtray. The economizer is a smoke/fluid heat exchanger. Its mission is to recover some of the heat contained in the combustion smokes, cooling them and reheating the water steam up to 430°C. The electro-filter is placed in the vent and its objective is to keep the small unburned particles that could originate fires in the nearby olive groves, especially in summer time.

2.3 POWER BLOCK

The electricity production set of equipment is composed of a steam turbine, which engages in its shaft an AC electricity generator at 50 Hz, 20 KV and produces 10 MW. Afterwards the substation transforms the voltage to adapt it to the network. Counter and control interlocking network equipments will be installed. The design of an electrical substation is not needed because there is another one already existing nearby the plant that can be used. The turbine-generator set used is the model Siemens SST-200 (Figure 2), which is a single casing turbine with direct adapter to drive the generator. It has a compact and flexible design with a high level of standardization and it is used for power generation applications.

Figure 2: Turbine-generator Siemens SST-200

After leaving the turbine, the steam is condensed and the resulting water is pumped to the preheater where it absorbs heat from the second extraction of the turbine. The installation requires plate capacitors, Alfa model or similar. The cooling tower evacuates the heat from the condenser, and water from the river is used for this. A tower with a heat dissipating capacity of 20 MW will enough for this facility. Water is forced from the condenser to the preheater at the working pressure of the degasser. The inlet pressure into the pumps will be the required to prevent cavitation.

When water comes out from the preheater, it reaches the degasser (Figure 3), where it heats thanks to the steam that comes from the first turbine extraction. Steam then becomes into liquid phase, so when it enters the set of exchangers not too much energy is needed to reach the operating temperature. The degasser fulfills another two functions: remove the dissolved oxygen and store power water to supply any loss that might take place along the cycle.

Figure 3: Degasser

The power water is sucked up from the degasser and is propelled towards the heat exchangers. The main function of the feed pump is to supply previously heated water to the high pressure steam generation system.

2.4 CALCULATIONS

The steam cycle is the Rankine cycle, where the minimum pressure is limited by the cooling media and the work contribution is done in liquid phase, so it is very small. To increase the cycle performance, some changes have been done:

- Reduction of the condenser pressure, so a wider expansion is generated in the turbine. Due to the vacuum effect, air comes in and it becomes necessary to install a degasser.
- Overheating at high temperature, so expansion can be extended by reducing humidity at the turbine´s outflow.
- Reheating which increases the average temperature of heat addition.
- Regeneration with closed heater, to raise the inlet temperature to the heat supply systems.

The performance of the cycle is optimized through the turbine´s extraction pressures, which are 30, 20, 2 and 0.1 bar, so that the performance ends at 38%.

The steam´s mass flows which circulate through each of the cycle zones are calculated so that the flow rate of the first extraction is 1.21 Kg/s, for the second extraction is 0.97 Kg/s, for the turbine output is 6Kg/s and for the main flow is 8.18 Kg/s. Then we calculate the performance that each of the equipments that form part of the generation plan must have, according to this and considering the minimum costs criteria, the same equipments are chosen.

The turbine is defined by the design conditions, with 10 MW power, with two high and low pressure zones where the extractions are done. The condenser has a flow rate of 6 Kg/s and its power to dissipate is 13.01 MW, this determines its dimensions and the dimensions of the cooling towers. The extraction pumps of the condensed steam have a flow rate of 6 Kg/s, and the suction and discharge pressures are 0.1 and 20 bar respectively, so that the pump power consumption is 14.7 KW.

The preheater is a countercurrent cross-flow heat exchanger, where the extracted steam from the turbine flows through the outside of a chamber, where the water flow pipe is located too. The transfer area, considering the input and output temperatures of the fluid and the overall heat transfer coefficient, is 7.2 m2. To dimension the degasser, we start with an operating pressure of 20 bar and with water and steam flow rates of 6.97 Kg/s and 1.21 Kg/s, being the provided water flow rate of 0.35 Kg/s in order to supply the water losses that might take place along the cycle. The storage capacity of the tank is 8.5 m3.

In the water pump which feeds the degreaser the flow rate is 0.35 Kg/s, and the suction and discharge pressures are 1 and 20 bar respectively, so the pump consumed power is 0.728 KW. The feed pumps of the heat exchangers and the biomass boiler, for a rate flow of 8.18 Kg/s, consume 94.69 KW power. The heat transfer between the heat transfer fluid, which absorbs the heat energy from the sun, and the steam cycle is through the plate exchanger. This transfer is done in two stages: in the first one saturated steam is obtained and in the second one the steam overheating is done. The exchanged heat in the evaporator (Figure 4) is 16.32 MW, so that the required are for the heat exchange is 359.53 m^2.

Figure 4: GEA plate evaporator

The exchanged heat in the superheater is 1489 KW, so that the required exchange area is 73.39 m2. Then we calculate the number of sensors needed in a row of solar field and the number of rows needed to achieve the pressure and temperature conditions of the fluid at the exit of the field. The temperature changes of the fluid between the entrance and exit determine the number of collectors per row, while thermal power that the entire plant must supply determine the number of rows in the solar field. The net thermal power will be of 22.4 MWt that will give a 10% higher gross thermal power (24.9 MWt). As we are working with a solar power plant for producing electricity, the collectors must be north-south orientated to obtain the maximum utilization. The design point corresponds to the noon of 15th June, and we have to take into account that in winter the thermal power supply of the plant will be around the 50% of the power provided in summer. The oil temperatures at the entrance and exit of the field are 295 and 395 ^{o}C respectively. It is known that the average sun radiation in the area potential of the plant is 780 W/m^2, the incidence angle is 17^{o} and the average temperature of at the design point is 30 ^{o}C. Considering the type of collector used, LS-3, and that the achieved temperature increase in each collector is of 45 ^{o}C, the decision is to arrange them in series of two so there will be a central feed with symmetry for the pipes. 56 collectors will be needed with a total area of 30.520 m^2. At this time stage, the diameter of all the required pipes can be calculated. The collectors feed pumps has a flow rate of 20.9 Kg/s, which results in a power consumption of 256.4 KW. Finally, the cooling tower is dimensioned, as well as the necessary pump for its performance.

3. ECONOMIC STUDY

The investment has been detached in the following items: civil works; development of biomass system; development licences and contracts; electric system; HTF system and others; insurances, commissions and unforeseen expenses; power block and spare parts; project direction; solar field and integration. After asking for catalogs and budgets to different suppliers, about equipments and facilities detailed in the technical study, the final budget is 20.268.035 € (Table 1).

Table 1: Budget [€]

Power block and spares	**Solar field & integra-tion**	**Develop-ment, licences and contracts**	**Project direction**	**Civil works**	**Insurances, commissions, unforeseen expenses**	**Develop-ment of biomass system**	**Electric system**	**HTF system and others**
4836413	5101283	1242356	1065294	3083511	824095	2278887	395114	1441082
Total budget: 20268035 €								

In this kind of projects the incomes depend on the “Real Decreto 661/07” which regulates the energy production activities in special regime generation and ensures the sale of electricity at a minimum price for different renewable energy plants. In addition, each quarter the fees and premiums for group c.2. facilities must be updated. Moreover, the Decree IET/3586/2011 establishes access tariffs, rates and premiums for special regime facilities since 1st January 2012. It also reviews the costs for 2012 and sets the access fares to the electric energy transport and distribution networks since 1st January 2012. The Decree IET/843/2012 establishes access tariffs, rates and premiums for special regime facilities since 1st April 2012. Also the April 25, 2012 Resolution from the “Dirección de Política Energética y Minas” establishes last resort tariffs that must be applied during the period between 1st October and 22nd December 2011 and during the first quarter of 2012 and establishes the electric energy production costs and the last resort tariffs that must be applied since 1st April 1, 2012.

Between the different alternatives, the most profitable option is to sell the energy in the market because the sell at the regulated tariff is only profitable when the electricity value is below 14.09 €/MWh. After the year 15 of the plant operation, the electricity from biomass can be sold at regulated rate: 121.6 €/MWh. The price of solar energy will be the market price while it is above 22.01€/MWh.

The costs are distributed as follows: fuel costs, due to the purchase of alperujo to the plants in the nearby area; labor costs and maintenance, for the 15 employees 432.000€ are needed during the first year; administrative expenses, estimated at 5% of the incomes but deducting labor, fuel and maintenance expenses; financial expenses, due to the interests that have to be paid for the investment loan, taking into account the EURIBOR data and the CPI variation; corporate tax, which represents 30% of the incomes but deducting the spending and the amortization. One of the main factors that affect the price of biomass is the olive production. The biomass prices are estimated between 30 and 50 €/ton. The electricity price is influenced by the oil price, we can estimate that the first one will increase in about 40 €/MWh annually due to the evolution of the second one.

The cost-benefit analysis has been estimated for a 22 years plant life, being the main parameters to consider: the variation of fuel, the energy selling price to the electricity market and the consequent updating of the pool, the variations in the CPI and the interest rate.

Assuming that we are in the most likely scenario, the value of the studied parameters will be: 40 €/ton for the biomass price, 40 €/MWh for the electricity starting price, 4% for the annual increase in the electricity pool renovation due to the tariff deficit, 4.3% for the annual interest rate historic low levels, 2.5% for the CPI (lower than the historical average due to the crisis). The profitability indicators obtained for the most likely scenario take values: Net Present Value, NPV = 30.539.554 € and Internal Rate of Return, IRR = 12.6% with a payback period of eight years.

These results are completed by an analysis of a pessimistic scenario due to the crisis. Assuming that the unfavorable values for the studied parameters are: 50 €/ton for the biomass price, 25.4 €/MWh for the starting electricity price (it is the historic minimum value), 4% for the annual increase in the electricity pool update, 9.8% for the interest rate with the Euribor in its historic maximum value, 1% for the Consumer Price Index in a long duration crisis situation. The profitability indicators obtained for the pesimistic scenario take values: NPV = 21.424.660 € and IRR = 7.2% with a payback period of twelve years.

4. CONCLUSIONS

This paper has demonstrated the technical and economic feasibility of an electricity generation plant of 10 MW which uses solar thermoelectric technology hybridized with biomass. This value of 10 MW is on the lowest side of the power where is useful to apply this hybrid technology, achieving perfect utilization of biomass in electricity generation. Another facts that make it interesting are the save on fossil fuels and the reduction in carbon dioxide emissions.

The two operating parameters that influence the most in the investment return are the selling price of the electric power and the purchase price of the fuel. We analyzed the variations of NPV, IRR and payback according to both parameters, and the conclusion was that the worst scenarios appear in situations of lower electricity price and with higher raw material costs.

If the IRR is evaluated, we can see that the plant profitability exceeds, at any situation, the 5% required profitability limit. The NPV never approaches to zero, breakeven. Bacause of this, we can conclude that this type of plant, in a likely scenario, will be attractive regardless the electricity and biomass prices. The investment will not be attractive only in a very pessimistic scenario: if there are high interest rates (higher than 6.6%), combined with high costs and low selling prices.

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