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Solar Aided Power Generation (SAPG) System Using Parabolic Troughs: Techno-Economic Scenarios

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Abstract - Solar aided power generation system using parabolic solar collectors in Greece is described. Case studies from literature were selected and discussed. Various technical and economic perspectives are simulated and different scenarios are presented.

***Keywords*:** Solar energy, solar aided power generation system, parabolic trough solar collectors, hybrid energy systems.

1. Introduction

Nowadays, a very interesting research topic is the use of solar thermal energy into the existing thermal power plants in order to preheat the feedwater or to replace heat produced by fossil fuels. Solar thermal energy could be combined with lignite resources forming a Solar Aided Power Generation (SAPG) system, which constitutes a support strategy for the transition from coal power plants to environmentally friendly solar energy-based power plants.

In Mediterranean region, where solar radiation is quite strong, the SAPG systems constitute an interesting option for RES integration. In Greece some research projects were carried out regarding the integration of solar thermal plants into the existing conventional power plants. A research project was carried out in the area of *Megalopolis, Peloponnese* where a 50 MW natural gas power plant was combined with parabolic trough solar collectors field forming together an integrated solar combined cycle power plant [1]. Also, in the area of *Ptolemais, Northern Greece*, a 300MW lignite power plant was integrated with a solar field of parabolic trough collectors [2].

Power plant performance of the 300MW lignite power plant *Unit VI, Ptolemais* for power boosting mode of operation was investigated. Moreover, the economic analysis of various technical and economic scenarios was carried out.

2. Case Study

The 300 MW lignite power plant *Unit VI, Ptolemais* uses a typical Rankine steam cycle: combustion of coal takes place in the boiler, (Fig. 1), composed of heat exchangers, such as a superheater, an evaporator, an economizer and a reheater. The superheated steam from the boiler enters the high-pressure turbine and generates electric power. After the steam is reheated in the boiler, it expands further through intermediate and low-pressure stages, the final exhaust steam is condensed in the condenser. The unsaturated feedwater from the condenser enters the boiler after going through two low pressure feedwater heaters (FWH1, FWH2), three intermediate (FWH3, FWH5, FWH6), one deaerator and one high pressure heater (FWH7). There are seven stages of steam extraction: one stage in high pressure, four in intermediate pressure and two in low pressure. The extracted steam from turbine preheats feedwater and, increases efficiency.

The solar collectors are introduced to replace the bled off steam to the high-pressure heater FWH7, which, from previous study was found that is an efficient scenario [2]. The high temperature solar heat from parabolic trough collector at nearly 400 °C was introduced in the high-pressure feedwater heater FWH7 and an additional heat exchanger (thermal oil heater) was installed in parallel. The heat transfer fluid is heated gradually from direct normal insolation and then returns its heat to feedwater through heat exchanger for preheating the feedwater that enters the boiler in Rankine cycle.

Taking into consideration the results from [2] as a base for comparison, we continued the investigation with two more scenarios, which concern the introduction of the solar parabolic trough collectors to replace the low-pressure heater FWH2 and then the middle-pressure heater FWH6.

The system can operate either in power boosting mode (with constant fuel input) or in fuel saving mode (with reduced fuel input) depending on the contribution of the solar thermal field.

Rankine cycle model presented in Fig. 1, consists of three turbine stages with the reheating of the steam occurring between high, intermediate and low stages. Each turbine stage model is assembled using two generic submodules: one for a turbine stage and one for the steam extraction (purple line). The high-pressure turbine stage consists of one steam extraction, the middle-pressure stage of four steam extractions and the low-pressure stage of two steam extractions. The pressure is from 171 bar for high stage, 40 bar for middle stage and 4.5 bar for low stage. Low pressure stage is coupled with the electric generator.

The hot flue gases are the input to the system and come from the combustor of the boiler. These gases (red line) enter the heat exchangers, from the steam generator (evaporator), the superheater, the reheater and the economizer. The steam/water flows in the opposite direction. In the superheater model, the steam from the evaporator is superheated and then is driven to the high-pressure stage at 540 °C and 171 bar. The evaporator receives water heated by economizer and produces steam for the superheater. It also calculates the demanded water flow which acts as a control signal for the feedwater pump. Steam exiting low pressure turbine stage is passed on to the condenser where it is cooled down at 41.8 °C to form the feedwater supply for steam generation. Then the feedwater is passed on to the feedwater heaters and the deaerator and finally returns to economizer and closes the Rankine cycle, Fig. 1.

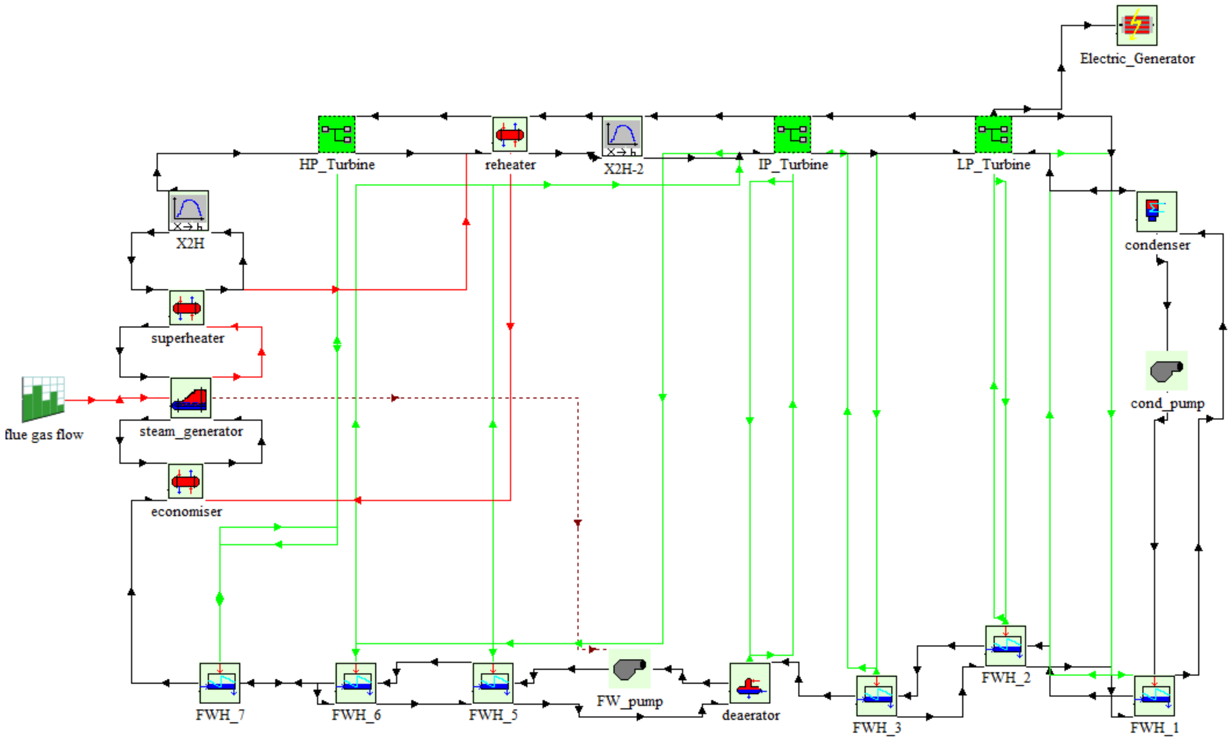

Fig.1. Rankine cycle TRNSYS model

Fig. 2 shows the solar field model which receives meteorological data, the thermal capacity modules and parameters of solar field area: weather data for one typical meteorological year with 1 hour step, including ambient temperature, wind speed and sun position.

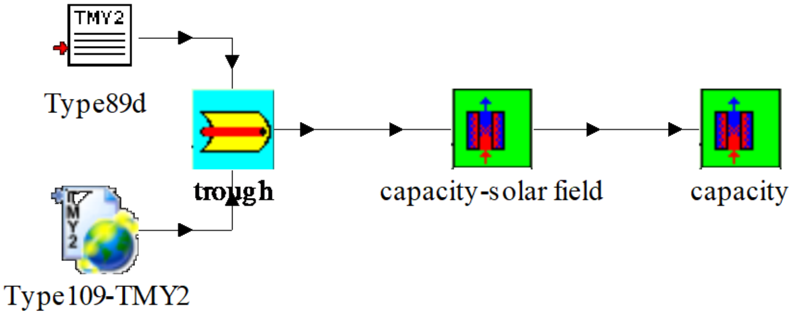

Fig.2. Solar field TRNSYS model

3. Results-Discussion

The solar collector field from Fig.2 is integrated in the low-pressure feedwater heater (FWH2), in the intermediate pressure feedwater heater FWH6, and in the higher-pressure feedwater heater (FWH7), from the thermal Rankine cycle system from Fig. 1. The power plant of 300 MW gives net electric power 275 MW and the 25 MW (around 8%) are for plant self-consumption, such as for powering of pumps, fans, lighting etc. Eight different simulation scenarios for power boosting operation mode were implemented, by changing the surface of the solar field areas, from 30.000 m^2 to 300.000 m^2. The solar field is composed of discrete modules of 12 solar collectors of 200mx5m=1000m^2. Between parallel adjacent rows is a gap of 12,5 m to avoid shadowing. Thus, 360 collectors in 30 rows constitute one solar field area of 30.000m^2.

The performance of the 300 MW power plant (Ptolemais Unit VI) was simulated in the TRNSYS shell [3], using the Solar Thermal Electric Component (STEC) library [4], [5]. The simulation is carried out for one-year time period with hourly time steps in power boosting mode. The fuel flow rate and the flue gas flow rate are held constant at full load conditions, the solar collectors' distribution does not affect it, and its electric power is added to the lignite generated electric power. The power output, plant efficiency and solar contribution for all scenarios in power boosting mode are summarized in Table 1.

Table 1. Performance of Hybrid Solar-Thermal System: Integration of Solar Field to Feedwaters in Power Boosting Mode. The rated net electric power from coal is 275 MW.

	Total Power Output	Solar Power Contribution			Thermal Efficiency Rankine Cycle	Thermal Efficiency SAPG System
	MW	MW		%	%	%
Low-Pressure Feedwater FWH2	281	> 4	6	2,14	34,0	59
Middle-Pressure Feedwater FWH6	285	> 8	10	3,50	34,2	60
High-Pressure Feedwater FWH7	287	> 8	12	4,18	34,2	60

An economic analysis of the proposed SAPG power plant was also performed using RETScreen software. The parameters used were retrieved from [2] and summarized in Tables 2 and 3. The cost for land is neglected and the capital cost of the lignite fired power plant is considered equal to zero, as the infrastructure already exists.

Table 2. Parameters of economic analysis.

Inflation rate (%)	2
Discount rate (%)	12
Project life (years)	25
Incentives and grants (€)	0
Debt ratio (%)	70
Equity ratio (%)	30
Debt interest rate (%)	9
Debt term (years)	10
Fuel cost (€/ton)	18
Fuel cost escalation rate (%)	3
Income tax rate (%)	20
Electricity export rate (€/MWh)	80
Electricity export escalation rate (%)	2,4

Table 3. Cost data for economic evaluation

Initial costs	
Cost for solar collectors (€/m^2)	260
Cost for land arrangement (€/m^2)	15
Cost for heat transfer fluid (€/m^2)	37,34
Engineering, procurement, construction (%)	10
Project, land and management cost (%)	1,2
Contingencies (%)	10
Annual costs	
Operation and maintenance cost (%)	2,5
Insurance cost (%)	1
Fuel cost (€/ton)	18
Rankine cycle cost (€/kW)	400
CO_2 emissions cost (€/ton)	8

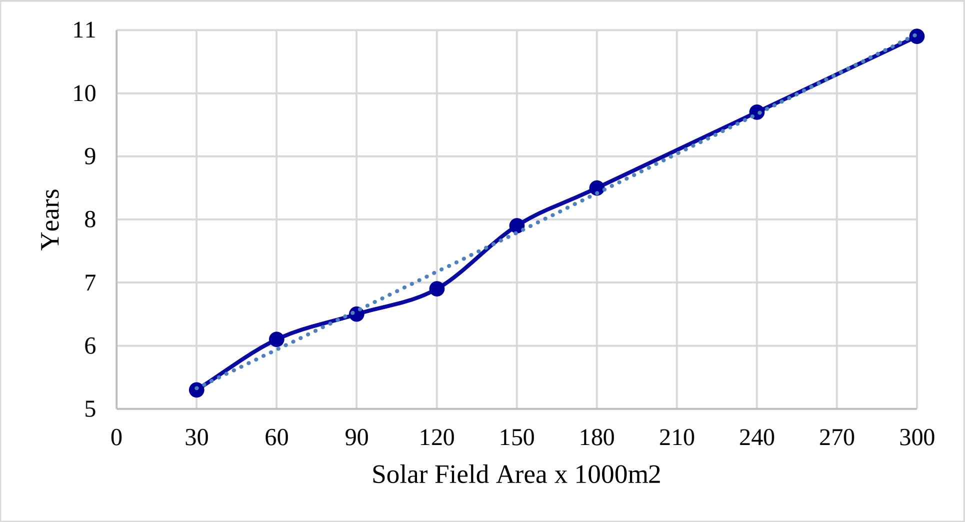

Fig. 3. Return of Investment in years for different sizes of solar field area
The dotted line is the moving average approximation

The solar system is economically efficient for the size of solar area of 30.000 m^2. Solar fields higher than this size give non-viable investment and increase the time of return of investment. With a solar field of 30.000 m^2, the duration of return of investment is almost at 5,5 years. With the increase of size of solar field, the obtained duration for the return of investment is according to Figure 3.

4. Conclusions

The developed TRNSYS model can be used for parabolic troughs based SAPG power plants located in different geographical areas with various meteorological data.

The main conclusions concern the increased thermal efficiency and economic viability of parabolic troughs based SAPG power plants. On the other hand, the benefit of investment decreases with the increase of size of solar field, while the duration for the return of investment is increased.

The economic analysis, taking into account various economic indexes, shows that the integration of parabolic trough solar thermal power plant into existing conventional thermal power plant, under certain conditions, could be an attractive RES integration option in Mediterranean region and elsewhere.

We propose to implement such an installation on a pilot base, in one of existing lignite units in Northern Greece, with the necessary retrofit of the power plant, with the limited size of solar field and adding thermal storage for the periods without high sun radiation, or during night time. Depending on the available capital for investment, the SAPG can be flexibly implemented, in yearly stages, beginning with a solar field of 30.000 m^2 and continuing with similar modules in next years.

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