SOLAR THERMAL POWER PLANTS OPERATING ON PARABOLIC TROUGHS MIRRORS

VASIU I
Romanian National Committee of the World Energy Council
E-mail: termo_vasiu@yahoo.com

Abstract: Among the renewable energies, the Sun represents the most abundant, inexhaustible and clean primary energy source of our planet, which can partly solve in the future, the worldwide energy supply.

Sunlight has, at the terrestrial surface, low and variable intensity, largely depending on geographical latitude, seasons, weather and time of day, so that, with the view of obtaining high parameters of solar heat, useable in the power plants operation, concentrating and heat storage equipments are needed.

Under these circumstances, after reviewing the solar radiation properties and its availability at the ground level, the paper put into evidence the current design of parabolic trough collectors, as the most proven solar technology used in thermal power plants, able to achieve temperatures around 400°C, required for the thermodynamic cycle development.

To date, solar power plants capacities have recorded at global level low values, placed at almost 5 GW_e, especially due to the excessively costs needed by the solar field technologies, but promising achievements are expected in the near future, by increasing investmens in this area.

Keywords: solar energy, parabolic trough mirrors, solar thermal power plants.

1. INTRODUCTION

Economic and social achievements of any country requires increased and reliable energy supply. Energy has a strong influence about the development of the modern human society.

World energy consumption rose by more than one third in the last decades. Is well-known the relationship between energy consumption and economic growth. The size of energy used largely influence the technological achievements, everywhere around the world.

Electricity and heat are the most consumed final energy forms in industry and in daily human household activities, representing about 85% from the overall consumed final energy by mankind, [6].

.The limited resources of coal, oil and natural gas, unsecurity supply of liquid and gaseous hidrocarbons from regions marked by instability, in addition with some vulnerabilities of their use, mainly the significant pollutant emission released at the coal burning, that generate the global warming of the Earth, possible failures of the classical or nuclear power plants in adverse weather, including the infrastructure of oil, gas and energy transport, all together impose the requirement to find alternatively energies, safer, more available and friendly with the environment. Moreover, shortages or insufficient amounts of oil or natural gas in some countries, can initiate economic and political crises or conflicts at international level.

Renewables are energy sources resulted from the natural systems development, mainly the solar energy and its derivates, consisting of biomass energy, hidro and wind energy, seas and oceans waves and heat, are abundant and accesible primary energies, having together an imense energy potential, [6]. Renewable primary energies are of present interest, through their abundance and great potential, but especially from the environmental protection point of view.

Continously increased of energy needs, uncertainly and relatively high costs of oil or gas supply, depletion of these resources, dangers regarding to the nuclear waste storage management, have to raise in future the share of renewables energy to the global energy demand.

Although renewables are inexhaustible, with minimal environmental impact, at present these primary energies, excepting hidro, are none competitive with classical fuels from reability, performances and economically point of view, [6].

Amongst the renewable primary energies, the solar radiation is the greatest heat source of the Earth, far larger than all discovered classical and nuclear primary energy reserves. The sun provides as much energy to the Earth in one hour as the planet entirely use in one year, [2], [8].

The sunlight radiation represents an unlimited and clean energy source, but non-fully accurate predictability and availability, because of its low and variable intensity at the ground surface, lead to difficulties at the turning into electricity in thermal power plants.

Solar radiation has a dual corpuscular-wave character, which carries the energy to the ground surface in the form of a photon stream, on the support of electromagnetic waves, [4].

The distribution of solar radiation at the outer boundary of the Earth atmosphere is influenced by the planet revolution around the Sun, associated with the movement of the earth globe around its axis, but also by the tilting of this axis to the plane trajectory, described around the Sun.

The power of the sunlight radiation arriving at the top of the planet atmosphere on a surface placed in a right angle to the direct incident solar beam is about 1,367 W/m^2, so called „solar constant", [2-5], [8-10] .

The passage of solar radiation to the terrestrial surface is accompanied by reflection and absorption phenomena, followed by dispersion due to the interaction with clouds, water vapor, dust particles included in the atmosphere, [2-5], [8-10].

At the same time, environmental pollution with solid particles and various gases, coming from industrial and agricultural activities, reduce the share of solar radiation reaching the surface of the planet.

The components of direct beam radiation received at the terrestrial level, usable for heating purpposes, are shown in figure 1.

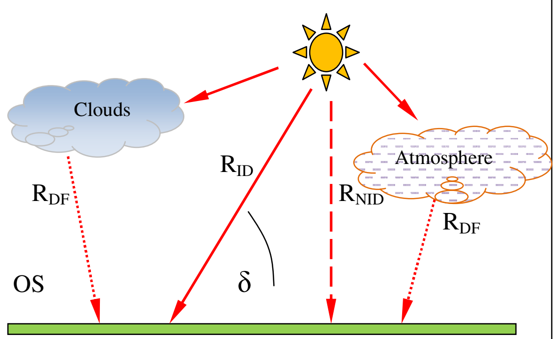

Fig. 1. Solar radiation available at the ground level on a horizontal surface.

R_{ID}-direct beam radiation; R_{NID}-normal component of direct beam radiation; δ-the angle of beam radiation with horizontal surface; R_{DF} – difuse component of sunlight coming from clouds and atmosphere.

For a certain Sun position on the sky, defined by the angle (δ) of solar beam with the horizontal of the place, the energy intensity of global radiation (E_G) depends on intensity of direct solar radiation (E_{ID}) and difused radiation (E_{DF}) flows, these being given by the relationship:

$$E_G = E_{NID} + E_{DF} \quad [W/m^2] \tag{1}$$

when:

$$E_{NID} = E_{ID} \cdot \sin\delta \quad [W/m^2] \tag{2}$$

represents the normal component of the direct beam to a horizontal surface mounted at the ground level.

Geophysical and meteorological factors have a great influence on the solar radiation that can be received at the ground surface. Among these can be mentioned the latitude of the capture site, weather, alternation day/night cycle, thickness of the cloud layer, composition of the atmosphere and its transparency or nebulosity, that are responsible in large part for mankind's access to the solar energy, [3-5], [8-10].

After entering in the upper layers of the atmosphere, the intensity of the solar radiation flow is gradually diminished, almost half (48 %) being absorbed/ dissipated/diffused/reflected by its components and only about 52 % effectively reaches the ground surface, in form of useable direct and diffuse radiation, [3-5], [8-10].

Thus, at the soil level, under a perfectly clear and unpolluted sky, around the moon, only about 1,000 W/m^2 may be registered, [4], [8-10].

A global map, showing the annual values of insolation on a horizontal surface placed al terrestrial level, is evidenced in figure 2, [8-10].

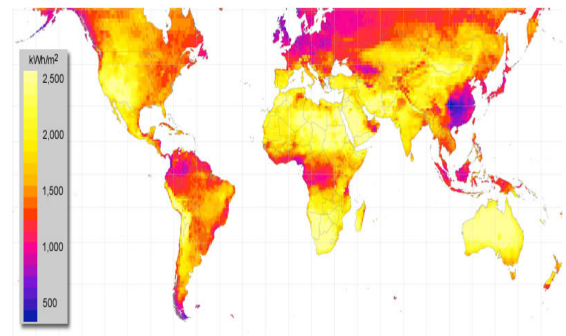

Fig. 2. Solar radiation map of the Earth.

The highest annual global irradiation, in the range of (1,800-2,500) kWh/m^2/year is recorded in the northern half and southern Africa, the Arabian Peninsula, Turkey, the Middle East and India, in most part of Asia, in Australia, in the south-west of the North American continent, on the west coast of South America, [8-10].

Lower solar radiation intensity at ground level, ranging from (1,000-1,800) kWh/m^2/year, are reported in much part of Europe and northern Asia, north and eastern North America, east Asia, Indonesia, northern and east of South America, (fig. 2), [8-10].

In order to obtain high thermal parameters of solar heat, in accordance with those of the thermodynamic cycle developed by the power plant, the sunlight energy intensity must be at the ground level above (1,800-2,000) kWh/m^2,year, which may achieve live steam temperatures of at least 400°C, [8-10].

2. ACTUAL STAGE OF PARABOLIC TROUGH SOLAR SYSTEMS

The low energy density of the sunlight reaching the Earth surface, the changes of its intensity during the day and with the seasons, in addition with its availability depending strongly on the geographical latitude, enclose the solar energy used for power generation.

Thus, solar thermal plants have to be placed only in areas with extended sunny periods during the year and increased intensity of the direct beam radiation.

At the same time, high energy density of the solar radiation, developing raised temperature levels at the sun energy conversion into heat, according with the values of the thermal cycles achieved in the power plants, can be obtained only through the direct sunlight concentration technologies.

The main components of this solar collector are the parabolic shape trough-mirror, named concentrator or reflector and the receiver including the absorber tube, passed by the heat transfer fluid. The absorber is protected by a cylindrical glazing to prevent heat losses by radiation and convection, [1], [4-5], [7-11], [14].

Concentrating solar power technologies require only direct solar beam radiation, which is focused along a line or in a point of the collector, [4-5], [7-11], [14].

As a rule, a parabolic trough collector system captures sunlight over a large aperture area and concentrates this energy onto a much small absorber area of the receiver, thus multiplying intensity of the incoming solar radiation by a concentration ratio comprised between (30–80), [4-5], [7-11], [14], (fig. 3).

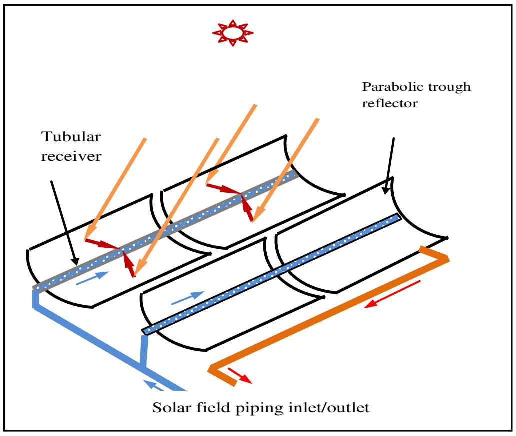

Fig. 3. Principle of the concentrating direct sunlight using parabolic trough mirrors.

For an efficient sunlight collection, the reflectors (mirrors) are equiped with mechanical devices, named tracking systems, in order to follow the sun throughout the day, to be sure that only the normal beam, coming in right angle on the aperture area of the reflectors, is captured and concentrated, [4-5], [7-11], [14].

Suitable locations for the solar concentrating projects are places between latitudes (15-35)°N, where the irradiance of the direct solar beam received at ground level is over (1,800-2,000) kWh /m^2, year, [4], [8-10],

The major concentrating solar technologies, commonly applied in the power plants achievements, are shown in the table 1, [1], [10-14].

Table 1. Concentrating solar technologies used in thermal power plants.

Concentrator type	Typical range of concentration ratio	Tempe-rature level provided	Heat transfer fluid
Parabolic trough-mirror system	30-80	250-400	Syntethic thermal oil, Water/Steam Molten salts
Linear Fresnnel reflector system	30-60	250-550	Water/Steam
Power tower system	300-1000	550-800 (1000)	Water/steam, Molten salts, Liquid natrium, Compressed air

There are several types of solar thermal collectors, all of them having the common principle of capturing solar radiation, converting it to useful heat and transferring it to a working fluid, having rised thermal capacity.

Parabolic trough collector system is the most developed and proven of the all concentrating solar technologies, being accepted on a large scale in the solar thermal power plants designs. This type of collector operates based on principle of linear sunlight concentration. The incoming direct radiation is reflected and focused onto the tubular receiver by the parabolic reflector, located above trough, at the focal line of the mirrors, exposed to the concentrated sunlight (fig. 4), [1], [7-10], [12-14].

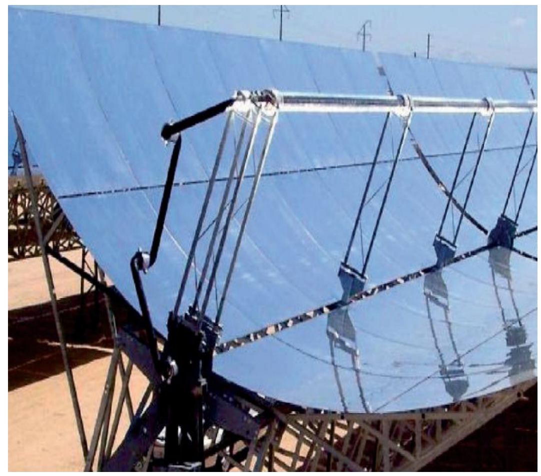

Fig. 4. A typical parabolic trough-mirror.

The tubular absorber, as part of the receiver, is crossed by the transfer fluid flowing inside the long line-pipes, accumulating the focused sunlight in form of heat

Because of its parabolic shape, the trough mirrors can focus the sunlight from 30 times to 100 times its normal intensity, on the absorber pipes, representing the concentration ratio, [4].

The surface of trough-mirror is made of a reflective layer, such as thin glass mirror, plastic films or thin metal foil, mostly polished aluminium or silver coated.

The solar collector field comprises a large number of parabolic trough-mirrors, aligned in parallel rows on a north-south orizontal axis, [1], [7-10], [12-14], (fig. 5).

Fig. 5. Solar field comprising of parabolic trough shaped mirrors arranged on rows.

The reflectors follow the movement of the sun along a single traking axis from east to west during the day, thus the concentrated sunlight is always directed on the linear receiver. Several receivers are assemblied in loops by side of heat transfer fluid, many loops being then connected to the power plant solar field pipe-line circuit.

The components of the parabolic trough solar mirrors collectors and the receivers, are installed on a steel support structure, attached on the ground, (fig. 5).

Usually, the heat transfer fluid flowed inside the tubular absorbers is a synthetic oil (for high temperatures an eutectic mixture of byphenyl $C_{12}H_{10}$ and dyphenyl oxide $C_{12}H_{10}O$ resisting at thermal degradation), sometimes molten salts (sodium and potassium nitrate NaNO3+KNO3) are used, according with the temperatures developed by the receivers, [4-5], [12-14].

3. MATHEMATICAL MODEL OF THE PARABOLIC TROUGH MIRRORS

The thermal efficiency calculation of the parabolic trough concentrating equipments takes place through the sizes involved, shown in figure 6, according to the mathematical relationships outlined below, [3-5].

The thermal flow of the direct solar radiation Φ_{in} incident on the aperture of the trough-mirror, is defined as, [3-5]:

$$\Phi_{in} = A_{in} \cdot E_{in} \ \ [\mathrm{kW}] \tag{3}$$

where: $A_{in}[m^2]$ – aperture area of the trough-mirror in right angle with the incident solar beam radiation;

$E_{in}[kW/m^2]$ – average energy density of the direct solar radiation.

The thermal flow of the concentrated solar radiation, sent by the reflector to the receiver Φ_{cr} is given by relation, [3-5]:

$$\Phi_{cr} = A_{in} \cdot \alpha \cdot C \cdot E_{in} \ \ [\mathrm{kW}] \tag{4}$$

in which : α – average absorptivity of the receiver;

C – concentration factor (ratio) of the trough-mirror.

The sunlight energy conversion into thermal energy is affected by significant heat losses, from the receiver to the environment.

Thermal flow Φ_{ls} lost especially by radiation and convection, may be written as follows, [3-5]:

$$\Phi_{ls} = A_{in}[\varepsilon \cdot \sigma \cdot T_{ab}^4 - k_{ls} \cdot (T_{ab} - T_{en})] \ \ [\mathrm{kW}] \tag{5}$$

wherein: ε – average emissivity of the absorber;

σ – Stefan-Boltzmann-constant;

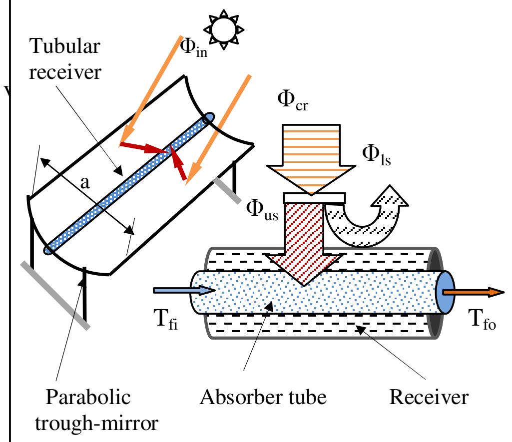

Fig. 6. Defining the main sizes of solar energy conversion into heat using parabolic trough mirrors.

Φ_{in}, Φ_{cr} - thermal flows of incoming sunlight and concentrated solar radiation; Φ_{ls} - thermal flow lost from the absorber surface; Φ_{us}-useful thermal flow; a-aperture (width) of the parabolic trough-mirror; T_{fi}, T_{fo} – inlet and outlet temperatures of the thermal transfer fluid associated to the absorber.

$(\sigma = 5{,}67 \cdot 10^{-8} \ W/m^2 \cdot K^4)$;

$k_{ls}[W/m^2 \cdot K]$ – coefficient of thermal loss due to convection and radiation;

$T_{ab}[K]$ – absorber surface temperature;

$T_{en}[K]$ – environmental temperature.

Taking into acount the heat losses, useful thermal flow Φ_{us} available at the absorber surface, results as:

$$\Phi_{us} = \Phi_{cr} - \Phi_{ls} \ \ [\mathrm{kW}] \tag{6}$$

$$\Phi_{us} = A_{in}[\alpha \cdot C \cdot E_{in} - \varepsilon \cdot \sigma \cdot T_{ab}^4 - k_{ls} \cdot (T_{ab} - T_{en})] \ \ [\mathrm{kW}] \tag{7}$$

The absorber converts the concentrated sunlight energy into heat at high temperature and then is transferred to the fluid flowing inside. The useful heat defined in relation (7) above mentioned, can be expressed in another form, depending on the absorber parameters.

Thus, the thermal flow Φ_{ab} transmitted to the absorber surface, will be, [3-5]:

$$\Phi_{ab} = A_{ab} \cdot k_{tr} \cdot (T_{ab} - T_{wf}) \ \ [\mathrm{kW}] \tag{8}$$

where: $A_{ab}[m^2]$ – absorber surface area;

$k_{tr}[W/m^2 \cdot K]$ – heat transfer coefficient from the absorber surface to the working fluid;

$T_{wf}[K]$ – average temperature of the working fluid.

The average temperature of the working fluid, can be calculated as:

$$T_{wf} = \frac{T_{fo} - T_{fi}}{2} \ \ [\mathrm{K}] \tag{9}$$

where T_{fo}, T_{fi} represent the temperatures at the outlet and inlet of the absorber tube.

The thermal flow Φ_{wf} collected by the heat transfer fluid, passed through the absorber tube, is expressed as:

$$\Phi_{wf} = M_{wf} \cdot c_{wf} \cdot (T_{fo} - T_{fi}) \ \text{[kW]} \qquad (10)$$

in which : M_{wf} [kg/s] – working fluid mass flow;
c_{wf} [kJ/kg·K] – average thermal capacity (specific heat) of the working fluid.

The thermal efficiency of solar radiation capture by the receiver η_{cap} is defined as the ratio of useful solar heat flow Φ_{us} (without thermal losses), that reaches the absorber surface, to the incoming solar thermal flow on the aperture of the mirror Φ_{in} , [3-5].

Thus:

$$\eta_{cap} = \frac{\Phi_{us}}{\Phi_{in}} \cdot 100[\%] = = \frac{A_{in}[\alpha \cdot C \cdot E_{in} - \varepsilon \cdot \sigma \cdot T_{ab}^4 - k_{ls} \cdot (T_{ab} - T_{en})]}{A_{in} \cdot E_{in}} \cdot 100[\%] \qquad (11)$$

or in final form:

$$\eta_{cap} = \alpha \cdot C - \frac{1}{E_{in}}\left[\varepsilon \cdot \sigma \cdot T_{ab}^4 + k_{ls} \cdot (T_{ab} - T_{en})\right] \cdot 100[\%] \qquad (12)$$

The thermal efficiency of parabolic trough solar collector η_{thc} , representig the ratio between solar heat flow taken over by the transfer fluid Φ_{wf} and the heat flow of the direct solar radiation incident on the aperture of the trough-mirror Φ_{in} , can be expressed as, [3-5]:

$$\eta_{thc} = \frac{\Phi_{wf}}{\Phi_{in}} \cdot 100[\%] = \frac{M_{wf} \cdot c_{wf} \cdot (T_{fo} - T_{fi})}{A_{in} \cdot E_{in}} \cdot 100[\%] \qquad (13)$$

To evaluate the thermal efficiency of solar energy systems, a standard flux of E_{in}=1,000 W/m^2 is used, which is approximately the solar radiation incident on a surface directly facing the sun on a clear day around noon, [3-5].

There are some ways to increase the thermal efficiency of the concentrating parabolic trough equipments, such as improvements of the optical systems, lowering the heat losses depending on high temperature components and better solar heat storage facilities.

4. SOLAR THERMAL POWER PLANTS SUPPLIED BY PARABOLIC TROUGHS SYSTEMS

Increasing energy demand, as a result of the planet population growth, concerns about the continuous lowering amounts of the mineral primary resources, in association with their significant pollutant emision released in the burning processes, energy security supply and the threat of global warming, lead to the requirement to develop cleaner and more affordable power sources.

Solar thermal power plants provide a clean energy, friendly with the environment, using an inexhaustible and free primary source, easily accessible on a wide area of the Earth.

Electricity generation in the solar power plants faces with issues related to the specific properties of the solar beam radiation, such as low irradiance, intermittent nature and variable intensity, largely depending on weather and day-night cycle, recorded at the terrestrial level. Thus, the achievement of high temperatures required by the power plant operation, is possible only through solar focusing technologies, in addition with thermal storage.

The energy of solar radiation can be used for power generation, as alone thermal source, suppling so named „solar-only thermal" power plants, or as an additional source of heat, intregrated in an existing conventional thermal plant, so called „solar-thermal hybrid" power plant, which usually operate on fuels burning (natural gas, coal or wooden biomass), [7-9], [14].

For electricity production, heat transfer fluid circuit powered by the solar field of the power plant is coupled with conventional electricity generation equipments, including rotary thermal engines directly coupled with electrical generators, which turn the solar heat into electricity, as is shown in the figure 7.

In order to ensure continuous supply of the power plants, at a steady heat input during solar transients,

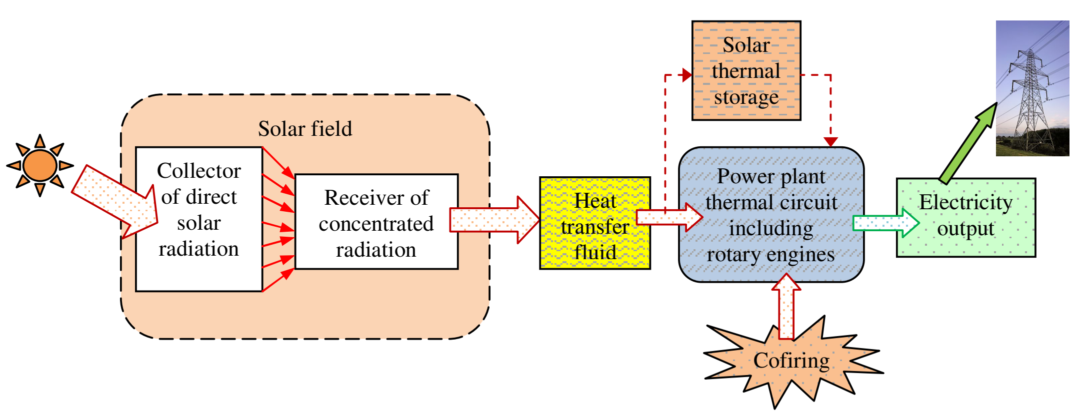

Fig. 7. Principle flow diagram of the solar energy conversion into electricity related to a power generating system operating on thermal rotary machines.

resulted from cloud cover or night periods, storage facilities of thermal energy have to be included in the main thermal scheme, in both „solar-only thermal"and „solar-thermal hybrid" configurations, with a view of later solar heat delivery, [7-14].

Currently, the solar thermal storage systems assure the power plants operation at full load over an average time of (6-8) hours, in periods without availability of the direct beam radiation. If the cloudy days are registered for a long time, the thermal demand of the power plant can be covered by fuels burning, (fig. 7).

The main requirements for siting a solar-only thermal power plants are: available annual insolation, land area needed especially for the solar field placement and mostly, the water resources in suficient amounts, to cover all demands, taking into account the difficult running conditions, usually in desert areas, [7-14].

The first criterion in order of a site selection for a solar power system is the available annual insolation, defined as the integration over the year of the ground-level solar radiation, at the chosen location. The solar radiant energy incident on a surface per unit area and per unit time is called irradiance or insolation, measured in kWh per square metre per year (kWh/m^2, year). It is commonly accepted that the minimum direct normal insolation at which it becomes economically viable to build a concentrating solar power plant is around 2,000 kWh/m^2, year. Higher insolation values mean better thermal performances, [7-14].

Concentrating solar-only thermal power plants need a significant stretches of land, which typically cannot be put to other uses simultaneously. Average values of the land area requirement for installing the parabolic trough mirrors field of an solar plant, are in range of (3,000-6,000) m^2/MW, [7-14].

The increased demand of water in a solar power plant is mainly on account of significant evaporative losses in cooling towers recorded in areas with high irradiation, where the solar plants are sited, that have to be replaced by the make-up water in the main thermal circuit. In addition, water is needed for cleaning the reflectors surface. Minimum water demand of an solar thermal plant, equipped with parabolic mirrors, has values between (3,0-3,5) m^3/MW$_e$, [7-14]

4.1. Solar- only thermal power plants

The „solar-thermal only" power plants, harnessing the sunlight energy by means of parabolic trough mirrors, generally, provide electricity through a thermodynamic conversion process of a working fluid, usually water/steam, sometimes organic fluids, achieved between high and low temperatures/pressures, named Rankine thermal cycle, [7-14].

A typical diagram of a solar-thermal only power plant, with heat storage, operating on a solar field comprising of parabolic trough mirror system, arranged in a large number of rows, is shown in the figure 8, [14].

The heat generated by the solar field (SF) is taken over through the transfer fluid, flowing inside the absorber long-line pipes, as part of the parabolic trough mirrors equipments, being transferred to the thermal circuit of the power plant via a series of shell-in tube heat exchangers (SP, SB, SSH). The preheater (SP), steam boiler (SB) composed of economizer, vaporizer and superheater (SSH), together convert the feed-water into live steam at high temperatures, using solar energy. Hence, the heat transfer fluid is cooled and then is sent back across the solar field network, by means of the circulating pump (HTCF), [7-14].

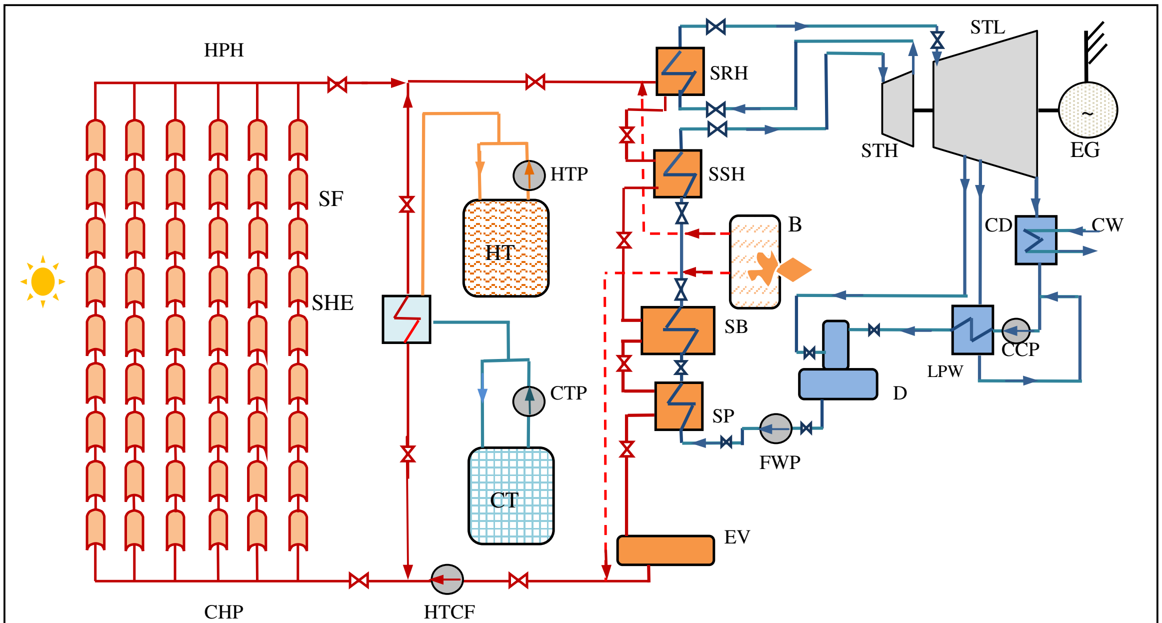

Fig. 8. Flowsheet of a solar-thermal only power plant operating on parabolic trough mirrors.
SF-solar field; CPH-cold header; HPH-hot header; SHE-storage heat exchanger; HTCP-heat transfer fluid circulating pump; HT-hot tank; CT-cold tank; HTP-hot tank pump; CTP-cold tank pump; SSH-solar steam superheater; B-boiler for transfer fluid heating on natural gas; SRH-solar steam reheater; FWP-feed water pump; D-deaerator; CCP-condensate circulating pump; SP-solar water preheater; SB-solar steam boiler; STH-high stage steam turbine; STL-low pressure steam turbine; EG-electrical generator; LWP-low pressure water preheater; CD-steam condenser; CW-cooling water.

In order to produce mechanical energy, the live steam passes the two-stage turbine (STH-STL). After the inlet into the high pressure stage of turbine (STH), the live steam is expanded, converting its thermal energy into mechanical shaft work, to drive an electrical generator (EG), which generates electricity, based on the electromagnetic induction law.

The steam leaving STH is reheated passing a solar heat exchanger, named reheater (SRH) and then is led to the low stage turbine (STL). Subsequently, at the outlet of the last stage (STL), the steam lowers its temperature and pressure, being routed to the condenser, operating under slight vacuum, where is turned into liquid state and finaly is circulated back along the solar heat exchangers, by the feed water pump (FWT), repeating the thermal cycle, (fig. 8), [7-14].

A general view of a „solar-only thermal power plant", having an installed capacity of 50 MW_e is put into evidence in the figure 9, [9-10]. The considerable extent of the solar field can be observed, in the middle of which are placed the buildings for electricity generating equipments.

Fig. 9. An overview of a „solar-only thermal" power plant having 50 MW_e achieved with parabolic trough mirrors.

Due to the factors depending on the weather conditions (sunny-cloudy periods) and day-night cycles, the direct beam radiation is intermittent and dificult to predict, having limitted availability. Therefore, the heat resulted from solar energy conversion must be strored, with a view of later delivery, when the direct solar radiation is not useable.

This smoothing obtained through the storage equipments helps, on the one hand, to extend the operation time of power plant in unfavorable solar radiation and, on the other hand, to maintain the power generation cycle running at or near its nominal point, [7-10]

For the solar heat storage with a view of its later delivering, fluids with rised thermal capacity, such as water under presure or molten salts, are recomanded.

A proven form of storage system operates with two tanks, hot (HT) and cold tank (CT), additionaly with pumping equipments (HTP and CTP). The fluid medium for high-temperature heat storage is molten salt. The excess heat of the solar collector field heats up the molten salt, which is pumped from the cold to the hot tank. If the solar collector field cannot produce enough heat to drive the turbine, the molten salt is pumped back from the hot tank to the cold tank, through solar heat exchanger (SHE), heating up the heat transfer fluid, [7-14], (fig. 8).

In periods with low intensity direct sun radiation (cloudy days for a long time) or during the nights, constant thermal load of the solar-only plant is assured primarily from storage system and then by fuels burning (commonly natural gas), using a boiler (B).

Usually, solar thermal storage systems assure the solar plants operation at full load for 3-6 hours, in periods without availability of the direct beam radiation.

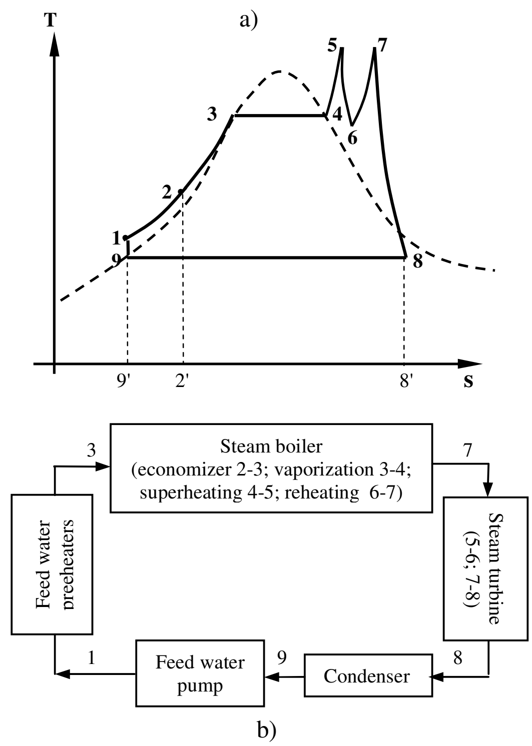

Fig. 10. Reheated steam power Rankine cycle
a)-Rankine cycle represented in T-s diagram; b)-Equipments taking part to the thermal circuit of the power plant.

The temperature level of the working fluid can be controlled by the velocity of thermal transfer fluid through the solar field piping, flowing inside the tubular absorbers of the parabolic mirrors. In this manner is possible to match the captured solar energy to the load requirements of power plant, according to the amount of needed heat and temperature level.

For smaller applications, from 100 kW_e to 10 MW_e and live steam temperature around 250°C, an organic Rankine cycle is preferable. Instead of water, organic fluids, such as butane or pentane, allow for lower temperatures and pressures. Organic components also have the advantage of condensing at or above atmospheric pressures, eliminating the need for a vacuum in the condenser, [4-7], [9-14].

Solar thermal power plants generate electricity, frequently based on a reheated steam Rankine cycle. The main conversion processes of the working fluid heat into mechanical energy, represented in T-s diagram, associated with the equipments that make possible a reheted steam Rankine cycle development, can be observed in figure 10.

Generally, the working fluid undergoes a series of thermodynamic conversions, turning from water into superheated/reheated steam (meaning in the T-s diagram: pressure rising 9-1; preheating 1-2; superheated and reheated steam generation 2-3-4-5/6-7). Farther, the live steam expands along a two stage turbine (processes 5-6/7-8), and finaly sent to the condenser (process 8-9), which converts the steam back to water, thus closing the thermal cycle at the feedwater pump (9-1).

The thermal efficiency of a solar-only power plant is under influence of the operating performances of its main components (sunlight collectors, solar field and power steam-cycle). Efficiency of the collectors depends on the angle of the sunlight incidence and on the temperature accumulated by the heat transfer fluid running inside the absorber tube, that can reach values above 75 %. Solar field thermal losses are usually below 10%. Steam-cycle efficiency reaches average values in range of (30-35) %, having the most significant influence on the entire power plant efficiency. Thus, the maximum overall efficiency of solar thermal plants, equipped with parabolic trough mirrors, takes values between (20-22) % (solar radiation to net electric output) and annual efficiencies of about (14-15)%, [7-14].

The thermal initial parameters of the Rankine cycle, supplied by solar heat collected through of parabolic mirrors systems, are generally set at (370-390)°C/100 bar, [7-14].

4.2. Solar-coal thermal power plants

Today, the electricity generated worldwide is obtained in the thermal power plants by fuels burning, in a great share of 68 %, which are responsible for the global warming phenomenon, dangerous for the environment, [6].

The regions of the globe having available direct sunlight radiation at the ground level, above than 2,000 kWh/m^2, for long periods over the year, can benefit from the facility of its integration in the conventional thermal plants operating on fossil fuels. Thus, so called „solar-thermal hybrid" power plants were promoted in the last decade, [14].

Among the organic fuels used in the conventional thermal plants, the coal is often preferred due to its affordable and stable supplying cost, but also to the efficient power generation technologies that have been applied, [6].

On the other hand, knowing that the burning process of the coal release in the atmosphere an increased level of pollutant emissions, the solar energy additional input, is applied especially to the existing power plants based on this fuel, thus offering more advantages for environment in comparison with the use of natural gas or oil- fuels.

A suitable application of the solar energy integration into the conventional coal firing power plants, working on superheated/reheated steam Rankine cycle is considered to be the feed water preheating, before the steam boiler inlet, [14].

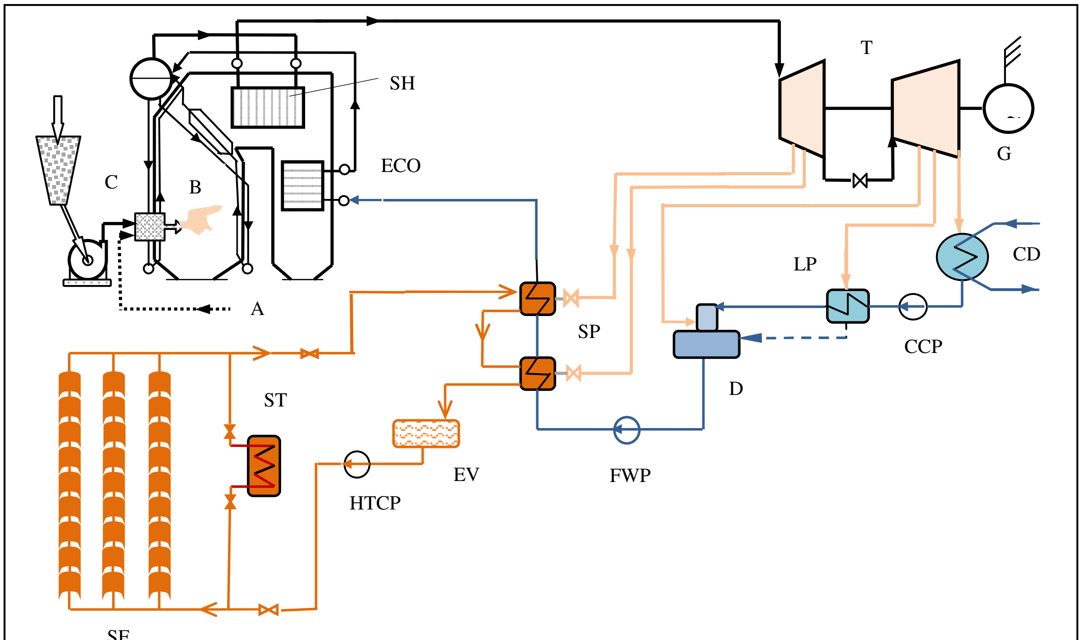

Fig. 11. Flow diagram of a coal fired thermal power plant operating with an additional solar heat input collected by parabolic trough mirrors.
C-coal preparing and burning system; A-preheated combustion air; B-pulverized coal firing power steam boiler; ECO-economizer; SH-steam superheater; SP-high pressure feed water solar preheaters; ST-solar thermal storage system; SF-solar field composed of parabolic trough-mirrors; EV-expansion vessel; T-steam turbine; G-electrical generator; D-dezaerator; LP-low pressure water preheater; CD-condenser; CCP-condensate circullating pumps; LP-low pressure feed water preheater; FWT-feed water pump; HTCP-heat transfer fluid circulating pump.

In the figure 11 is presented a principle diagram of a coal fired thermal power plant running with a solar energy input, delivered by the parabolic trough mirrors system, as the most developed concentrating solar technology, able to provide heat at about (300-400)° C.

The heat transfer fluid, usually a thermal syntetic oil, circulated by pumps (HTCP) over the solar field (SF) pipe-lines, is heated at the passing inside the tubular receivers and then is sent to the high pressure heat exchangers (SP), where the heat is transferred to the feed water circuit, with the aim of rising its temperature at about (260-270)°C, before the economizer (ECO) inlet.

Because of the solar beam limited availability, in order to ensure the continuous supply of solar heat, it must be stored in the storage heat exchanger (ST), with a view of later providing, [14].

The cooled thermal oil is recirculated through the solar field network, thus the solar heat is continuosly supplied to the conventional electricity generation system, based on coal burning.

If the solar heat is used to preheat the feed water, it displace partly or even completly the steam taken from the turbine intakes delivered to the high pressure solar water heat exchangers (SP), leading to the electrical output increasing.

Also, the boiler thermal load of conventional plant lowers, as a result of reduced amount of coal burnt in its furnace. Finally, on these ways, improved performances of the whole power plant will be obtained, including environmental benefits, [14].

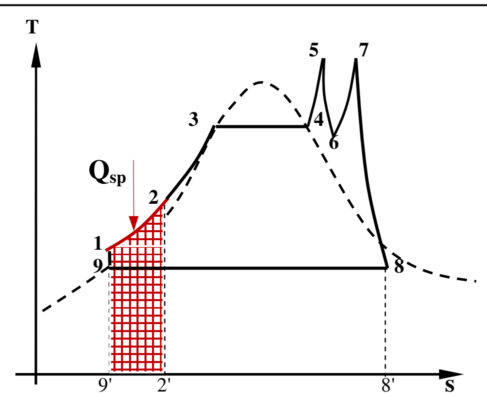

Fig. 12. Solar energy preheating feed water highlighted in the steam Rankine T-s diagram.

Qsp-solar thermal energy input preaheating the feed water (in proportion to surface area $S_{1\text{-}2\text{-}2'\text{-}9'\text{-}9\text{-}1}$).

The share of solar energy in the overall energy output of the coal-fired power plants reaches average value of (10-15) %, even 18%.

Figure 12 presents the Rankine cycle of a conventional power plant, running on coal combustion, drawn in T-s diagram, having a share of solar energy input. It can be remarked the area of the Rankine cycle where the solar heat (Q_{sp}) enters in the main thermal circuit, in order to rise the feed water temperature.

Scientific research has shown that the most suitable point of the conventional power plant circuit for the solar heat input to preheat the working fluid is after the high pressure feed water pump (FWP) discharge, (fig. 11). Displacing significant amounts of burnt coal in thermal plants for feed water preheating, solar energy, as a suplementary energy source of the conventional thermal plant, can provide cleaner electricity, due to the lower pollutant emissions released to the environment. At the same time, an improved overall efficiency of thermal plant, in range of (12-15) %, will be obtained, [14].

5. CONCLUSIONS

Solar radiation is one of the most promising energy source, which can partly cover the power demand at global level, under an environmental sustainability, without warming phenomenon.

Although the solar electricity generation faces some difficulties due to the unpredictable nature of solar radiation, mainly discontinuity and variability caused by meteorological and geophysical phenomena, which entail high costs for the heat capturing, converting and storing, however, over the last decade, can be observed a fast increasing of thermosolar plants built worldwide, obviously in regions with available solar radiation.

Solar energy can be promoted in the field of electricity generation on two main directions, currently identified: as a single heat source in so named „solar-only thermal" power plants and as a supplementary heat input helping the conventional technologies, in so called „solar-thermal hybrid" power plants. In both cases, the solar radiation capture and focusing is performed using parabolic trough mirrors, which have demonstrated their operational maturity. These operations associated with the storage of solar heat involve at present, high financial costs, unbearable for countries belonging to certain regions of the globe, precisely by those who enjoy large solar radiation.

Solar power plants usually operate according to superheated/reheated steam Rankine cycle, either from the „solar-only thermal" category or from that of „solar-thermal hybrid" power plants.

The size of the turbogenerator groups in the „solar-only thermal" power plants with a solar field consisting of parabolic mirrors reaches the maximum installed power of 300 MW_e/unit by now, corresponding to maximum initial steam parameters of 370° C and 100 bar. The overall thermal efficiency of these plants is at only (20-22) % sometimes reaching 25%, while annual values do not exceed 15%, which are reasonable values, knowing that solar energy is inexhaustible and free accessible.

„Solar-thermal hybrid" power plants use a supplement of heat coming from solar radiation to rise the temperature of working fluid (water) in the thermal circuit at level of (260-270)°C, displacing partly the coal amounts, that otherwise would be burnt, thus diminishing environmental pollution being obtained. Higher investments needed for solar heat conversion and storage equipments is balanced by lower coal consumption or increased electricity output. Hence, it is obvious the thermal efficiency improvement of the entire power plant, which rises by (12-15) %, [14].

In the last years, there are significants achievements in the field of solar thermal power plants. Over the period 2011- 2017, was recorded at the global level an increased solar electricity production of almost 3 times, from 1,7 GW_e to 4,9 GW_e. In 2017, the largest share of 84 % from the annual worldwide solar electricity generation was recorded by Spain (2.4 GW_e) and USA (1.7 GW_e), while 0.8 GW_e are mainly attributable to North Africa countries, to India, Australia and South Africa. In the year 2017, new capacities of about 2.0 GW_e were installed in solar thermal plants operating in China, Middle East and North America, [14]

Having said all that, with the aim of solar power plants further developments, more financial support is required by the governments of states, especially of those located in areas of the planet where high-intensity solar radiation is associated with an extended period of sunny days during the year.

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