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Yield Analysis of a Power Plant with Parabolic-Trough Collectors and Direct Steam Generation (DSG) using a Quasi-Dynamic Simulation Model in TRNSYS

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Abstract

After the construction of the first commercial solar power plant with direct steam generation in Thailand, a new horizon will be open for this technology. In this industrial application for electricity generation, financing directly depends on the expected electricity production and corresponding financial revenues. The development of a simulation model for this technology will help reduce costs and hence increase plant output. The simulation model applied in this study reproduces the thermal and hydraulic behaviour of the solar field, including parabolic-trough collectors and connecting pipes. This quasi-dynamic model is able to address transient conditions with low computational resources. In addition, a power block suitable for a 35 MW_e solar plant is defined and analysed, allowing its implementation into the whole solar plant model. An economic optimization of the solar field size has been performed considering standard economic parameters. The main results of thermal and electrical energy obtained from the annual simulation of the optimized plant are presented in this paper.

Keywords: *direct steam generation, parabolic-trough collector, yield analysis, simulation model*

1. Introduction

At this moment, electricity generation is the most extended application of solar heat in industrial processes. Parabolic-trough systems, central towers and Fresnel linear collectors are the main technologies used in industrial applications. Solar thermal power plants based on parabolic-trough collectors are nowadays a successful technology with more than 4,000 MW_e installed and in operation around the world. Most of them operate with synthetic oil as heat transfer medium in receiver tubes, but recently other working fluids, such as water, are being investigated in order to improve the performance of parabolic-trough technology and avoid the environmental issues of synthetic oils. In direct steam generation (DSG), water is heated and evaporated through the solar field to feed a steam Rankine cycle or an industrial process, such as cleaning, heating or distillation in the food and beverage sector (Fernández-García et al., 2010), avoiding the need for heat exchangers and hence increasing the efficiency of the whole system (Eck et al., 2003).

A 5 MW_e solar power plant (Krüger et al., 2012) built in Kanchanaburi (Thailand) and connected to the grid in 2012 is the only commercial plant with parabolic-trough collectors and DSG in the world. This is a first step in the commercialization of this technology. At this point, a flexible simulation model of this technical concept can help calculate the energy production and perform viability studies of solar power plants with DSG in different places, with different collectors and solar field configurations.

This work addresses the simulation of a hypothetical 35 MW_e solar thermal power plant using DSG in parabolic-trough collectors, including the definition of a suitable power block. The simulation applies a quasi-dynamic model able to calculate annual results of thermal and electrical energy with low computational resources. In addition, a brief economic analysis is performed to optimize the size of the solar

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field considering expected electricity costs.

2. Plant model

The simulation model reproduces the thermal and hydraulic behaviour of each component of the plant including the main elements of the solar field and the performance of the power block. The model has been developed with the TRNSYS software tool (Klein et al., 2007), a graphically-based environment used to simulate transient systems. Models are created by connecting different components, providing a flexible tool that allows different configurations and sizes of the plant and an easy modification of details such as collector type, location, etc.

The solar plant is composed of two main systems: the solar field with collectors' loops of 1,000 m of effective length (20 collectors of 50 m length per loop) with North-South orientation and the power block with a steam turbine of 35 MW_e. Each loop of the solar field works as a preheater, evaporator and super-heater of the feed water, using the solar energy as primary source of energy. In nominal conditions the feed water enters at 206 ºC and 70 bar in each loop to be preheated, evaporated and super-heated in once-through operation mode. The super-heated steam generated in the solar field (450 ºC) is led to the turbine to complete the Rankine cycle, which can operate either in nominal or part-load conditions.

The following sections describe the model of collectors' loop developed to simulate the solar field, the definition and modelling approach of the power block and, finally, the integration of these subsystems in the whole solar plant model.

2.2. Model of collectors' loop

The model of each loop is developed by joining components such as solar collectors, connecting pipes and accessories to compose a whole arrangement. The TRNSYS model of the proposed collectors' loop for the solar plant is shown in Fig. 1, including components for parabolic troughs (type218), connecting pipes (type214) and injector (type228) which have been implemented in the Fortran programming language.

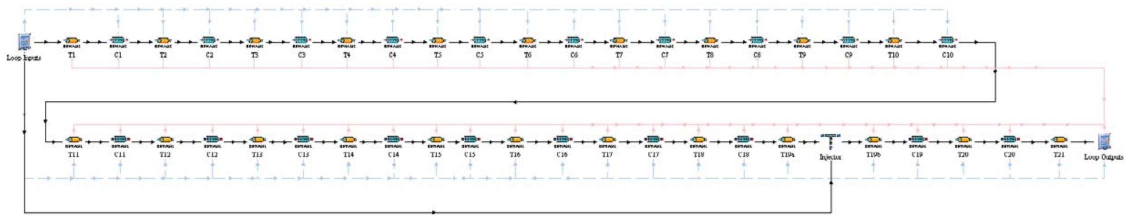

Fig. 1. Screenshot of the TRNSYS model for the collectors' loop

In general terms, the thermal model of parabolic-trough collectors is performed by evaluating the useful power gained by the fluid, $\dot{Q}_u$, with an energy balance between solar power absorbed by the system and thermal losses to the environment:

$$\dot{Q}_u = \eta_{opt,0^\circ}\, \eta_{clean}\, \eta_{sh}\, K(\theta)\, G_b\, cos(\theta)\, A_c - \dot{Q}_{loss} \qquad \text{(eq. 1)}$$

In this equation, G_b is the direct normal irradiance, A_c the net collector aperture area, θ the incidence angle, $K(\theta)$ the incidence angle modifier, $\eta_{opt,0^\circ}$ the peak optical efficiency, η_{clean} the cleanliness factor and η_{sh} the shadowing factor.

In this case, the expression applied to calculate the incidence angle modifier is based on the equation estimated for SkyFuel® concentrators (McMahan et al., 2010) from experimental data. However, SkyFuel® concentrators have 115 m length instead of the length of the foreseen collectors, 50 m. Hence, a correction with the ratio of end-losses factor for 115 m to end-losses factor for 50 m is applied. The resulting expression for incidence angle modifier is given by eq. 2, where θ is given in degrees.

$$K(\theta) = (1 - 2 \cdot 10^{-4} \cdot \theta + 3 \cdot 10^{-5} \cdot \theta^2) \cdot \frac{\eta_{end\ loss\ (50\ m)}}{\eta_{end\ loss\ (115\ m)}} \quad \text{(eq. 2)}$$

Regarding thermal losses in collectors, standard receiver tubes SCHOTT PTR®70 will be considered. The expression for thermal losses has been obtained (Valenzuela et al. 2014) from outdoor tests at PSA:

$$\dot{Q}_L = 0.342 \cdot \Delta T + 1.163 \cdot 10^{-8} \cdot \Delta T^4 \quad \text{(eq. 3)}$$

Where $\dot{Q}_L$ represents thermal power losses per unit length [W/m] and ΔT is the difference between average fluid temperature and ambient temperature [K]. Besides, the main parameters of the collectors and receiver tubes considered for the simulation are summarized in Table 1.

Tab. 1: Main parameters considered for solar collectors

Parameter	Value
Aperture length, m	6
Net collection area, m^2	272.7
Focal length, m	1.5
Peak optical efficiency, %	76.58
Cleanliness factor, %	97
Absorber tube length, m	48
Outer diameter of steel absorber tube, m	0.07
Inner diameter of steel absorber tube, m	0.0588
Inner roughness of absorber tube, m	$4 \cdot 10^{-5}$

During transient conditions, the model performs an energy balance taking into account the effect of thermal inertia due to the mass of fluid, m_{fluid}, and pipe, m_{pipe}, in a time step Δt. The useful energy absorbed by the fluid, $\dot{Q}_u \Delta t$, can be expressed as a sum of energy interchanged in each component. The specific enthalpy of the fluid at the collector's outlet, h_{out}, can be thus obtained knowing the rest of the elements in the following equation, where $\dot{m}$ is the mass flow rate, $\Delta\bar{T}_{pipe}$ and $\Delta\bar{h}$ the increase in average temperature of the pipe and average enthalpy of the fluid, respectively, since the previous time step, c_p the specific heat capacity of the pipe and h_{in} the specific enthalpy of the fluid at collector's inlet:

$$\dot{Q}_u \Delta t = m_{fluid} \Delta\bar{h} + m_{pipe}\, c_p \Delta\bar{T}_{pipe} + \dot{m}(h_{out} - h_{in})\Delta t \quad \text{(eq. 4)}$$

In steady-state conditions, the two first terms of this equation are neglected ($\Delta\bar{h} = 0$ and $\Delta\bar{T}_{pipe} = 0$) and hence this expression is simplified.

The calculation of the temperature difference between fluid and absorber tube requires the estimation of the heat transfer coefficient by convection, which depends on the fluid phase. For one-phase flow, either liquid water or steam, the heat transfer coefficient is calculated by means of the Dittus-Boelter equation; for two-phase flow the heat transfer coefficient is obtained by means of the Kandlikar (1990) correlation.

On the other hand, thermal losses in connecting pipes are calculated by means of a model of thermal nodes composed of metal pipe and thermal insulation whose properties are known. Then, an energy balance is applied to calculate thermal losses to the atmosphere due to convection and to the sky due to radiation.

The hydraulic model is basically the same for both receiver pipes and connecting pipes between collectors and is based on the calculation of pressure drop through each component of the circuit. If the contribution of pressure losses due to change in kinetic energy is neglected, the calculation can be expressed in terms of pressure losses due to differences in height and friction in straight pipes and accessories. The pressure drop of a two-phase flow of water through a straight section of pipe is estimated from the pressure drop of liquid water by applying the Friedel (1975) proportionality factor; and the pressure loss of liquid water flowing through this pipe is calculated using the Darcy-Weisbach equation.

A detailed description of the TRNSYS model of collectors' loop developed for direct steam generation, together with its validation using the configuration and real data of the DISS loop at PSA, can be found in a previous work (Biencinto et al., 2016).

2.2. Description and model of the power block

A 35 MW_e power block suitable for the proposed DSG solar plant has been defined. This section describes and analyses the behaviour of this power block both at nominal and part-load conditions.

The power block proposed is based on a non-reheat Rankine cycle and includes a steam turbine with three extractions, a wet-cooling condenser, a deaerator, two surface heat exchangers for feed-water preheating and two water pumps. In nominal conditions, the steam produced by the solar field is driven to the turbine inlet at 450 ^oC of temperature and $6{\cdot}10^6$ Pa. The condenser pressure will be $6.6{\cdot}10^3$ Pa. Besides, standard values have been selected for the rest of parameters of the power block.

The analysis of the behaviour of the power block at nominal conditions has been performed with the IPSEpro (2016) software. Fig. 2 shows the basic diagram of the system obtained from this software tool including fluid conditions in relevant points of the system.

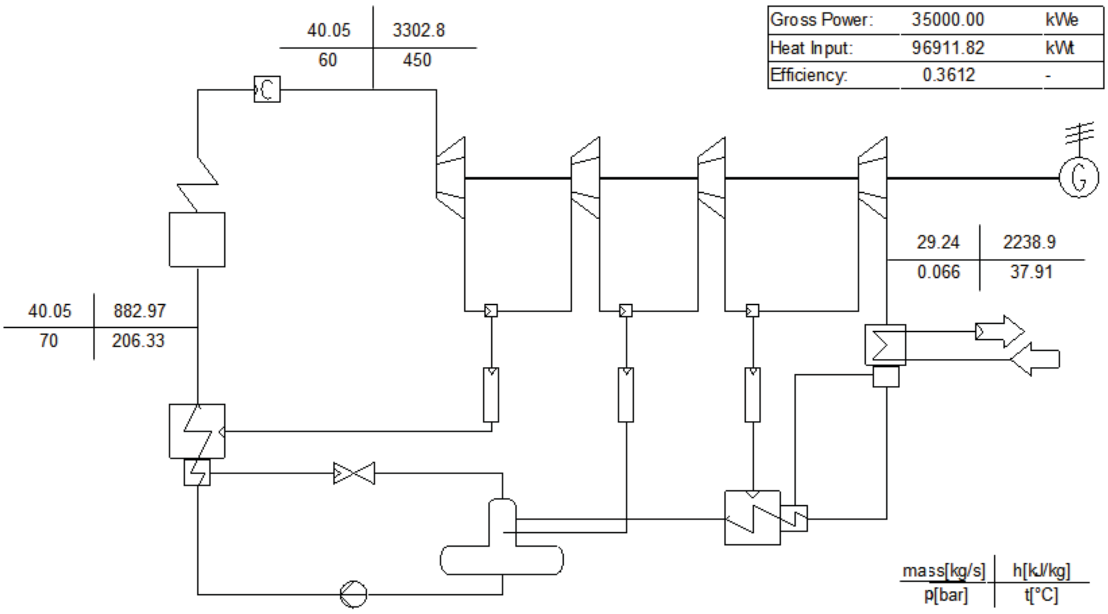

Fig. 2. Diagram of the power block design at nominal conditions in IPSEpro

Equal-enthalpy steps have been assumed for the selection of extraction pressures because this strategy is supposed to lead to an optimum efficiency (Kostyuk and Frolov, 1988). The analysis at nominal conditions in IPSEpro has been applied to determine the most relevant results of the power block that will be useful for the modelling, summarized in Table 2.

Tab. 2: Main results of the power block analysis at nominal conditions

Parameter	Value
Inlet water temperature for the solar field, °C	206.3

Inlet water pressure for the solar field, MPa	7
Steam quality at turbine outlet, %	86.3
Gross efficiency of the power block, %	36.12
Mass flow rate required from solar field, kg/s	40.05
Thermal power required from solar field, MWth	97
Parasitic consumption for water pumping, kWe	416.9

The methodology applied for part-load analysis is based on similar studies for typical Rankine cycles used in solar thermal plants (Montes et al., 2009). However, given the uncertainties associated to the regulation of the working pressure of the solar field in DSG, the control strategy will be based on fixed pressure instead of sliding pressure. Nevertheless, the regulation of part-load behaviour with fixed inlet steam pressure of the turbine by nozzle section control implies an efficiency reduction related to valves throttling and aerodynamic losses. In this way, an additional efficiency losses factor, taken from previous studies (Eck et al., 2008), has been applied for part-load regulation. The resulting isentropic efficiencies at part-load conditions including both conventional reduction and fixed-pressure regulation is shown in Fig. 3 for each turbine stage.

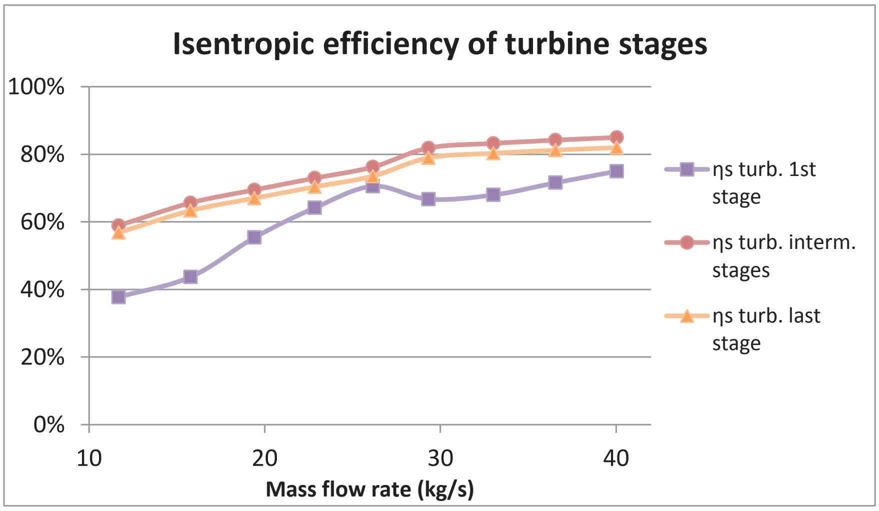

Fig. 3. Isentropic efficiencies for each stage of the turbine obtained at part-load behaviour

An efficiency-load curve has been obtained taking into account the above-mentioned assumptions and methodology. As a result, the evolution of gross efficiency of the power block at part load is shown in Fig. 4.

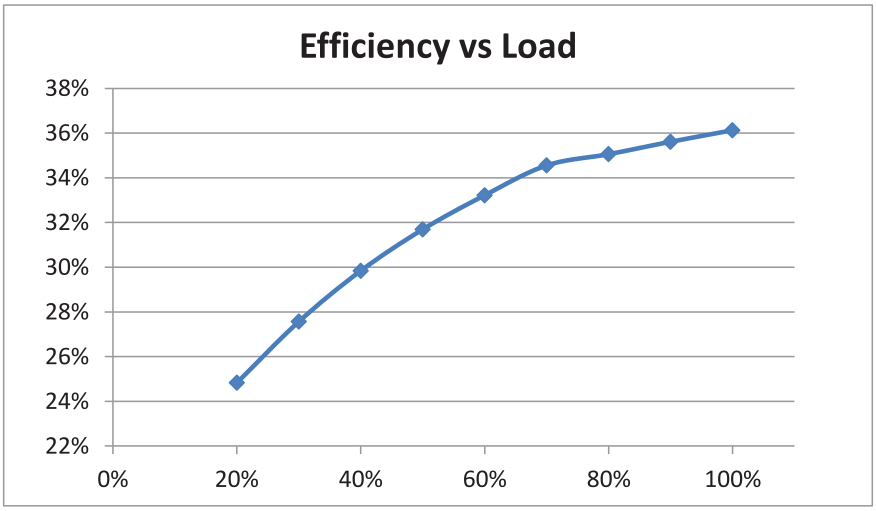

Fig. 4. Gross efficiency vs load curve obtained for the power block

Based on previous works (Eck et al., 2008), 10% overload will be allowed for the power block, leading to a maximum power of 38.5 MW_e. In this case, the nominal gross efficiency will be also applied.

Analogous curves have been obtained for inlet water temperature of the solar field and pumping consumptions. As a result, polynomic expressions relating gross efficiency, inlet temperature of the solar field and electrical losses with mass flow rate have been inferred. In addition, a quadratic curve has been included to simulate the start-up & preheating process of the turbine taking into account metal temperatures.

Finally, the approach explained in this section has been applied to implement a suitable model for the power block at part-load behaviour to be integrated with the proposed DSG solar field.

2.2. Solar plant model in TRNSYS

The general layout of the TRNSYS model for the whole solar plant is shown in Fig. 5, including equation editors, components from the TRNSYS standard library to read input data (Type9a) and determine solar angles (Type16g) and components specifically developed to retain values from the previous time step (type293) and to obtain thermo-physical properties of water/steam (type221). This overall model also includes macro-components that represent several subsystems of the plant: 'Collectors Loop', 'Distribution Pipes' and 'Solar Field Control'.

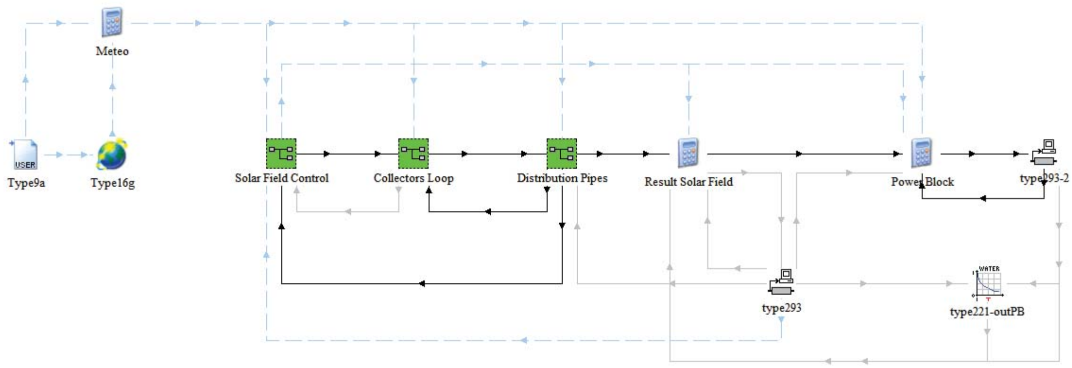

Fig. 5: Screenshot of the TRNSYS model for the solar power plant

The 'Collectors Loop' subsystem (seen in Fig. 1) simulates the behaviour of one loop with 20 collectors. Since all loops in the solar field are equal and they receive the same solar irradiance, the values of mass flow rate and thermal power of one loop are multiplied by the total number of loops to obtain the total results of the solar field.

Besides, the 'Solar Field Control' subsystem implements the corresponding control strategies to determine mass flow rates (loop and injection) and pressure, based on ideal schemes for once-through mode (Valenzuela et al., 2005). This subsystem also handles strategies for plant operation, such as mass flow rate assignment during start-up process, shutdown mechanisms, etc.

The 'Distribution Pipes' subsystem simulates the behaviour of the piping circuit (both hot and cold) between collectors' loop and power block for a solar field composed of two subfields with East-West orientation by means of the pipe component. Since the geometry of distribution pipes may strongly vary throughout the solar field, average diameters for pipe and insulation are applied to allow a simplified approach.

Finally, an equation editor is used to implement the power block model described in section 2.2, both at nominal and part-load conditions, giving as outputs the gross and net electric power generated, pumping consumptions and parasitic losses.

3. Solar field optimization and annual yield analysis

The solar plant model described in section 2 has been applied to perform annual simulations aimed at both optimizing the number of loops in the solar field and obtaining the electricity production of the optimized plant. The location selected for the plant is Plataforma Solar de Almería, Spain (37º05'30" N, 2º21'19" W), and the input data used for the simulation is a typical meteorological year (TMY). This TMY file contains the record of direct normal irradiation (DNI) and ambient temperature every five minutes from the same site, yielding a yearly DNI balance of 2,071.46 kWh/m^2 and 3,658 hours of sunlight. The time step of every simulation is the same as the time step of input data, 5 min.

3.1. Economic optimization of solar field size

The solar field size needed to match the nominal thermal power required by the power block (97 MWth) will be given by the thermal power gained by the fluid in a collectors' loop at the design point, which is expected to be around 3.3 MWth. The resulting calculation leads to 30 loops in the solar field.

Besides, an important figure to assess the solar field size is the Solar Multiple (SM) of the plant, which is the ratio of thermal power gained by the fluid in the solar field at nominal conditions to nominal thermal power required by the power block. Hence, a number of loops of 30 will represent a SM = 1. However, a Solar Multiple of 1 may involve a limited production, mainly in winter, because low solar irradiances imply that the power block works at part-load condition and therefore at reduced efficiency. In this way, it is recommended to oversize the solar field to avoid part-load operation as much as possible. Nevertheless, the oversizing of the solar field will imply that in certain conditions with high solar radiation the thermal power that is able to produce the solar field will be higher than the maximum thermal power allowed by the power block. These situations will require a partial defocusing of the solar field, thus causing energy dumping.

To assess the effect of solar field oversizing, annual simulations for several solar multiples have been performed using the DSG solar plant model described in section 2. Fig. 6 shows the annual results of net electricity production and thermal energy dumped for the proposed plant, using solar multiples from 1 to 1.47. This range of solar multiples represents 30 to 44 collectors' loops in the solar field, respectively.

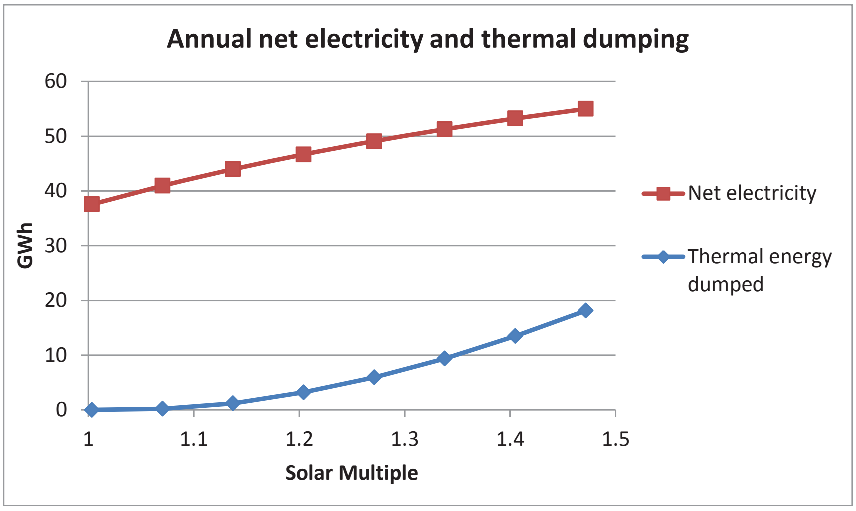

Fig. 6. Annual results of net electricity production and thermal energy dumped as function of the solar multiple for the DSG solar plant considered

In order to obtain the optimum value of the solar multiple (and therefore the number of loops in the solar field), a basic economic analysis has been performed taking into account a rough estimation of electricity costs. According to current definitions (AENOR, 2013), levelized electricity cost is given by the following expression:

$$LEC = \frac{CRF \cdot K_{invest} + K_{O\&M} + K_{fuel}}{W_{net}} \qquad \text{(eq. 5)}$$

Where K_{invest} is the total investment cost of the plant, $K_{O\&M}$ the annual cost of operation and maintenance, K_{fuel} the annual cost of fuel, W_{net} the annual net electricity production and CRF the capital recovery factor.

The economic parameters and specific costs considered for the *LEC* calculation are summarized in Table 3.

Tab. 3: Economic parameters and specific costs considered for the LEC analysis

Parameter	Value
Specific cost of solar field, €/m^2	190
Specific cost of power block, €/kW	350
Land specific cost, €/m^2	2
Engineering & building, % of K_{invest}	20
Annual O&M specific cost, €/(kW·SM)	56
CRF (Capital Recovery Factor), %	10.37

Fig. 7 represents the *LEC* values calculated for the above-mentioned range of solar multiples, together with the dumping factor. For this analysis, we define dumping factor F_{dump} as the ratio of thermal energy dumped to useful thermal energy to the power block.

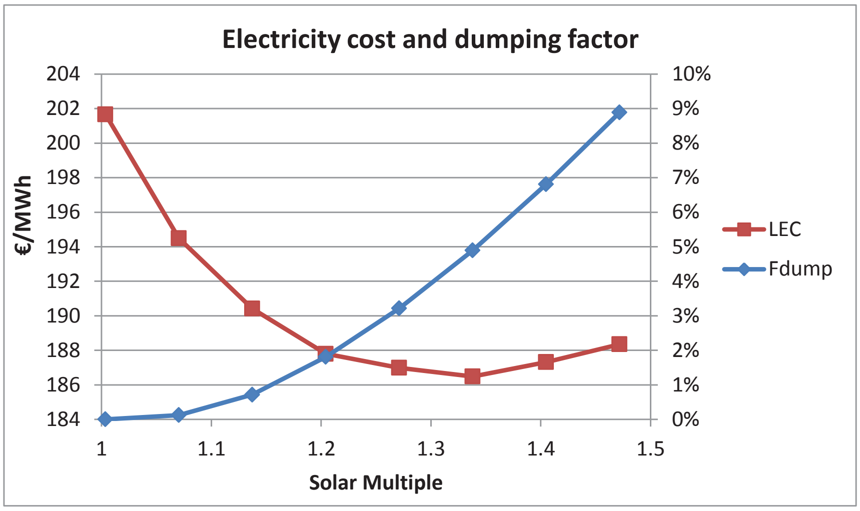

Fig. 7. Results of levelized electricity cost (*LEC*) and dumping factor (F_{dump}) as function of the solar multiple for the DSG solar plant considered

As seen in Fig. 7, the solar multiple that provides a lowest electricity cost is 1.338, which corresponds to a solar field with 40 loops of collectors, leading to a net collection area of 217,760 m^2. The resulting solar field lay-out proposed for this plant is shown in Fig. 8, with the power block in central location and 40 collector loops distributed in two subfields, West and East. Considering an extra space for access and maintenance purposes, the land area required for this arrangement would be around 1,100,000 m^2.

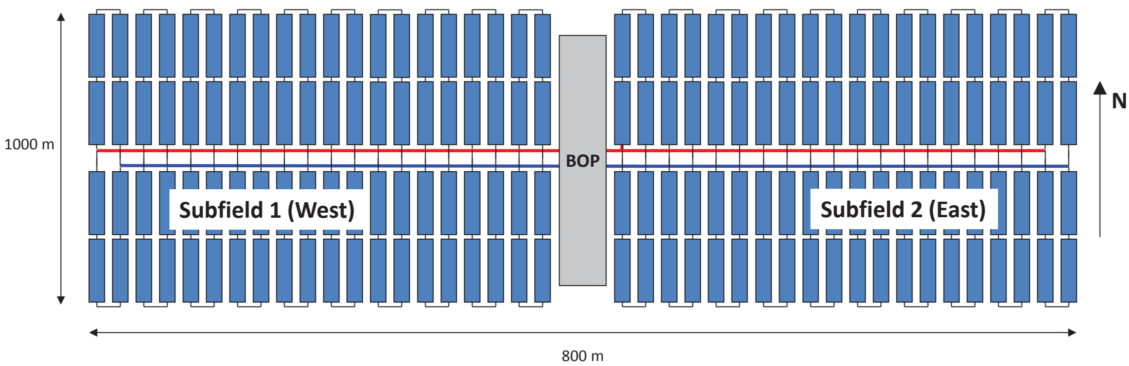

Fig. 8. Solar field lay-out proposed for the DSG solar plant

3.2 Annual yield results

Once defined the optimum solar field size and plant lay-out, an annual simulation has been performed to obtain either the thermal or electrical energy involved through each subsystem. As a result, Fig. 9 shows the monthly values of thermal energy gained by the fluid in the solar field and thermal energy useful to the power block.

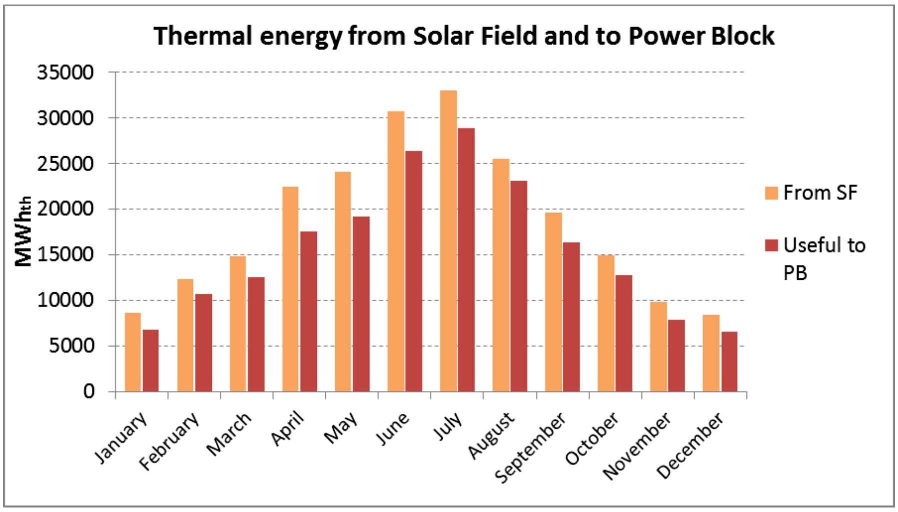

Fig. 9. Monthly results of thermal energy obtained from the solar field and useful to the power block for the DSG solar plant considered

As seen in Fig. 9, thermal energy results show a strong variation between summer and winter months, both from solar field and to the power block. The thermal energy obtained from the solar field in the worst month, December, is 25.6% of the result for the best month, July. In terms of thermal energy useful to the power block, this ratio is 22.6%.

The differences between both magnitudes are related to two main effects. On the one hand, some of the thermal energy obtained from the solar field cannot be used by the power block because the steam has not the required conditions of temperature, pressure or mass flow to feed the turbine. On the other hand, when thermal power produced by the solar field exceeds the maximum thermal power allowed by the power block, the remaining thermal energy is discarded as energy dumping. The monthly breakdown of these two effects is represented in Fig. 10. From this figure, we can point out that energy dumping becomes relevant from April to July.

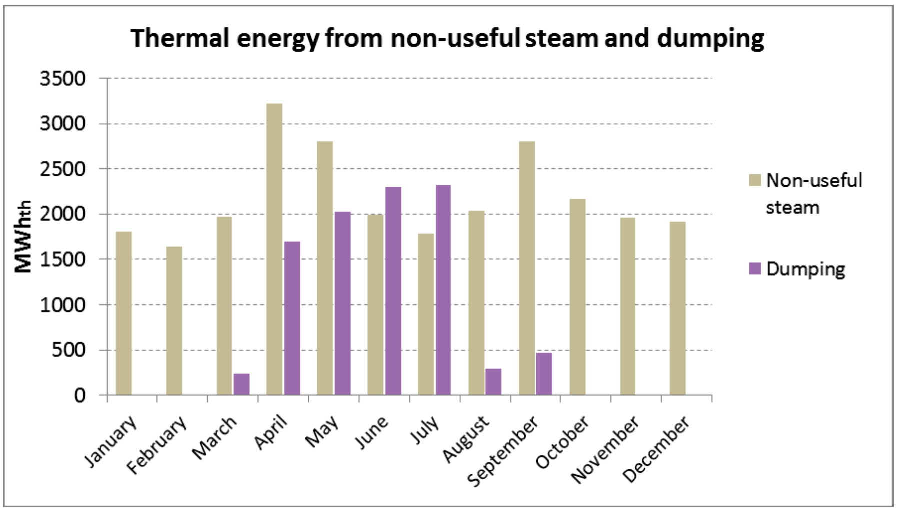

Fig. 10. Monthly results of thermal energy from non-useful steam and thermal energy dumping for the DSG solar plant considered

Fig. 11 shows the monthly results of gross and net electricity produced by the plant.

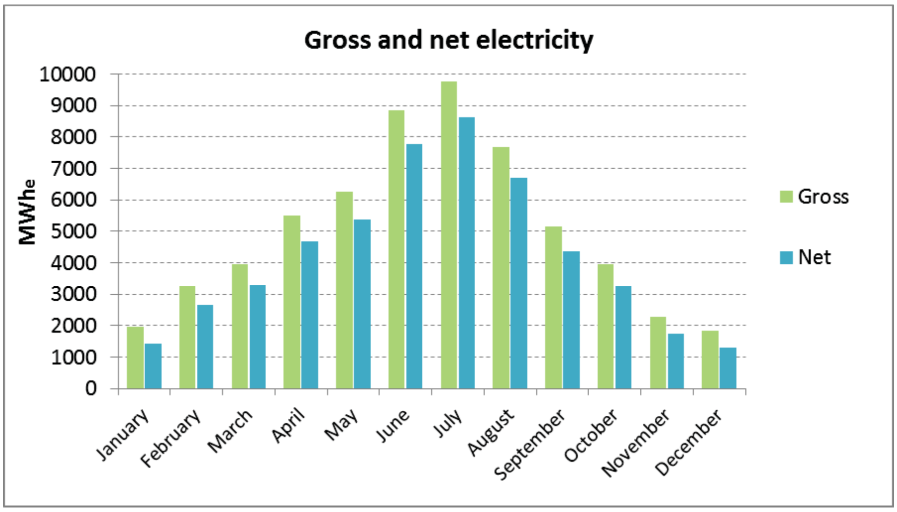

Fig. 11. Monthly results of gross and net electricity production for the DSG solar plant considered

In the same way as for thermal energy, a strong variation can be observed between summer and winter months. The ratio of worst month (December) to best month (July) production is 18.8% in the case of gross electricity and 15% in the case of net electricity. As inferred from these figures, this ratio decreases with each subsystem due to either thermal or electrical losses. In order to illustrate the evolution of energy losses, including optical losses in the solar field, the monthly results of available and useful radiant solar energy, thermal energy from solar field and useful to power block, gross and net electricity production is depicted in Fig. 12.

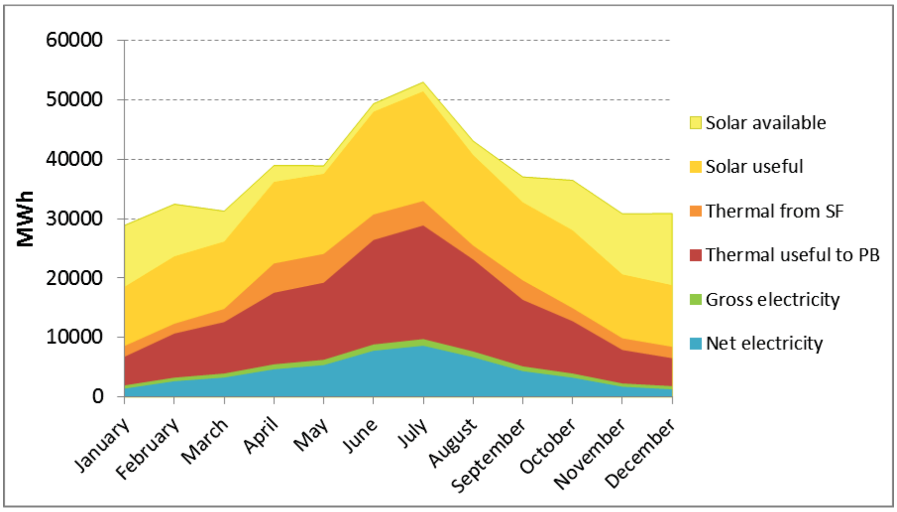

Fig. 12. Monthly results of available and useful radiant solar energy, thermal energy from solar field and useful to power block, gross and net electricity production for the DSG solar plant considered

Finally, Table 4 summarizes the main results obtained from the annual simulation of the plant. The efficiency values included in this table are obtained by dividing thermal or electrical energy results by available radiant solar energy (for plant and solar field efficiencies) or thermal energy useful to power block (for power block efficiencies). Besides, the equivalent operating hours are obtained as the ratio of net electricity production to nominal power (35 MW_e); and the annual capacity factor is the equivalent operating hours divided by the annual total hours (8,760 h).

Tab. 4: Main annual results obtained from the simulation of the DSG solar thermal power plant

Result	Value
Available radiant solar energy, MWh	451,081.56
Useful radiant solar energy, MWh	382,811.24
Thermal energy from solar field, MWh_{th}	224,330.91
Thermal energy dumped, MWh_{th}	9,357.30
Thermal energy in non-useful steam, MWh_{th}	26,107.33
Thermal energy useful to power block, MWh_{th}	188,866.28
Gross electricity production, MWh_e	60,469.84
Net electricity production, MWh_e	51,172.67
Solar field efficiency, %	49.73
Gross power block efficiency, %	32.02
Net power block efficiency, %	27.09
Gross plant efficiency, %	13.41
Net plant efficiency, %	11.34
Dumping factor, %	4.95
Equivalent operating hours, h	1,462.08
Annual plant capacity factor, %	16.69
LEC (Levelized Electricity Cost), €/MWh	186.5

4. Conclusions

Direct steam generation in parabolic-trough collectors may be an interesting solar technology both for industrial applications and electricity production. In this way, this work describes and analyses a 35 MW_e solar thermal power plant with DSG in parabolic troughs using a quasi-dynamic simulation model developed in TRNSYS. A solar field with North-South oriented loops of 1,000 m with 20 collectors of 50 m length, together with a suitable power block based on a steam Rankine cycle, has been defined for this plant. An economic optimization of the solar field size leads to a solar multiple of 1.338, which represent 40 collector loops. The annual simulation of this plant yields a net electricity production of 51,173 MWh_e and a capacity factor of 16.7%. Additionally, a brief economic analysis for this plant gives a levelized electricity cost of 186.5 €/MWh.

5. Acknowledgements

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