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GENERATION OF SOLAR COMBINED CYCLE POWER PLANTS WITH APPLICATION IN EGYPT

By

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Abstract:

Renewable energy sources (RESs) are used with the bulk power supply in many of the world countries and Egypt. Also, solar technology is available option of these RESs for Egypt, because the sunrise from 3000 to 4000 hours per year with average solar radiation of 2000 to 2400 kWh/m^2/year in many regions of Egypt.

Solar thermal power plants (STPPs) are the most economic form of solar technology for electricity generation. These STPPs are consisted of four elements. These are solar collector, receiver, transport-storage and energy conversion. Also, this power plant may be integrated with gas or/and steam turbine of a conventional power plant (CPP).The generation of a STPP depends on the efficiency of its elements, the meteorological data at the installation site, and the integrated combined cycle with CPPs. So, this paper aims to model the efficiency of the STPP elements and the generation of this power plant with an integrated solar combined cycle (ISCC) power plant. This model is applied numerically to compute the generation of the first STPP integrated with a gas power plant at El-Kuraymat, considering the design of this power plant and meteorological data at the aforementioned site in Egypt.

Keywords:

Solar Energy, Solar Thermal Power Plant, Integrated Solar Combined Cycle, Modeling, Generation, Egypt

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1. Introduction:

Renewable energy sources (RESs) are continue added to the electricity supply in many of the world countries as well as in Egypt. Solar electricity generation is available option of RES for Egypt because the high level of solar radiation with an annual sunrise more than 4000 hours in upper Egypt. Also, solar thermal power plants (STPPs) are the most economic form of the solar technology for electricity generation [1]. Currently the total installed capacity of STPPs in more than 600 MW world wide, and are planned these power plants in more than 10 countries [2].

The concentrating STPP technologies are relay on four basic key elements. These are concentrator, receiver, transport-storage and power generation. Also, These STPPs are characterized by its ability to be integrated with conventional thermal power plants (CTPPs) to produce electricity, either by gas turbine-Brayton cycle or/and steam turbine–Rankine cycle strongly affected the generation of these power plants. So, the overall efficiency of a STPP can be developed as a product of three efficiencies These are optical, receiver and power block efficiencies [3,4]. The optical efficiency depends on the type of concentrating solar thermal energy (CSTE) used. While, the solar receiver efficiency accounts for losses involved in the conversion of solar radiation to thermal power such as intercept (spillage), conversion and thermal emission. Finally, the efficiency of conversion from thermal to mechanical power and to electrical power in the power block depends on the selection of the thermodynamic cycle.

In reference [5], The design and cost of ISCC are studied for different concentrating solar thermal energy (CSTE) technologies. These are solar trough, linear Fresenal lens and solar tower. Also, nine STPPs had been built at California desert during the period 1984 and 1990 [6]. The integration of these power plants was initially proposed by Luz Solar Integration as a means of integrating parabolic trough solar plant with modern combined cycle power plants , Where several methods for transferring solar thermal energy (STE) into combined cycle are evaluated [7].

New and Renewable Energy Authority (NREA) of Egypt intends to implement an ISCC at EL kuraymat, 95 km South of Cairo, at altitude of 29° 16' N and longitude of 31° 15' E. This project had been implemented in three stages. These are solar island

and combined cycle island associated with the engineering of the complete ISCC. The solar island consists of a parabolic trough solar field, the heat transfer fluid (HTF) system up to the HTF inlet and outlet flanges of the solar heat exchanger, associated control systems and control and service buildings. While the combined cycle island consists of one gas turbine, one heat recovery steam generator (HRSG), one steam turbine solar heat exchanger plus all associated control and balance of plant equipment and installations [8,9]. This ISCC power plant had been complete operation in June 2011 and connected with 66 kV transmission system at El-kuraymat.

In this paper, a proposed generation model has been introduced. In this model, the efficiency of STPP elements and the generation of ISCC are modeled . The proposed generation model is applied numerically to asses the generation of ISCC El-Kuraymat in Egypt.

2.Proposed generation model:

Figure 1 shows two ISCC used for integrated STPP. Figure 1.a shows a solar combined cycle (SCC) comprises a Brayton cycle-gas turbine, while Figure 1.b illustrate a solar triple cycle (STC) using Rankine – cycle steam turbine. Solar energy is used as a heat source for these ISCCs. However, the STPP includes solar collector, receiver, transfer- storage and energy conversion, the efficiency of the entire STPP can be developed for both of these ISCCs as followings.

The overall efficiency (η_0) of an ISCC power plant is function of solar collector, receiver and power block efficiencies and given as [4] :

$$\eta_0 = \eta_{Opt} * \eta_{Re} * \eta_{PB} \qquad (1)$$

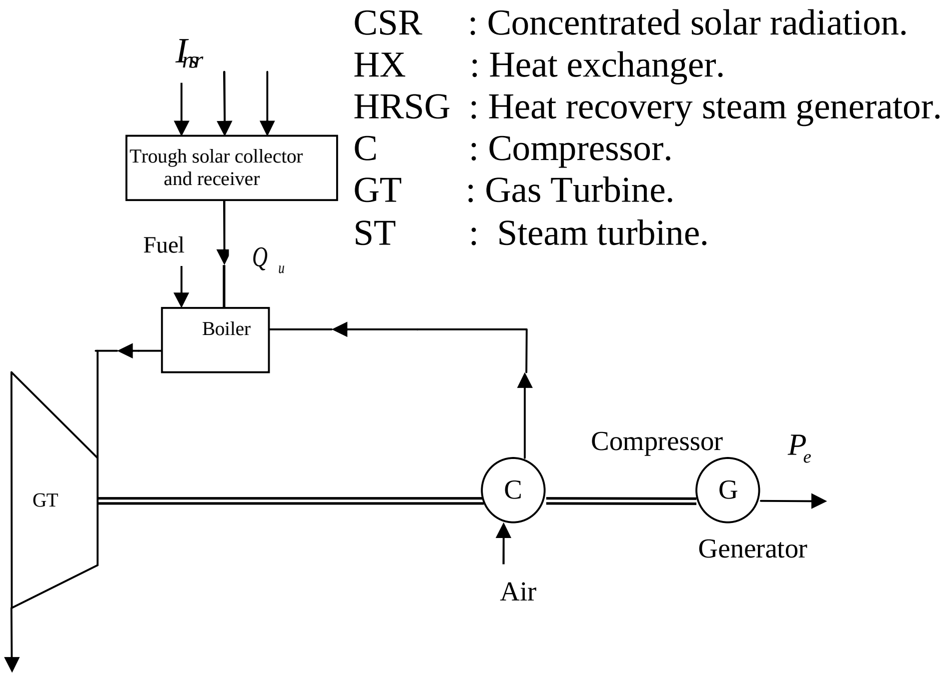
The solar collector efficiency (η_{Opt}) depends on the concentrating solar radiation (CSR) of the STPP and account due to the reflection of this device. For a parabolic trough solar collector have a field A_c, the incident solar energy (heat) is given by :

$$Q_{inc} = I_{si} * A_c \qquad (2)$$

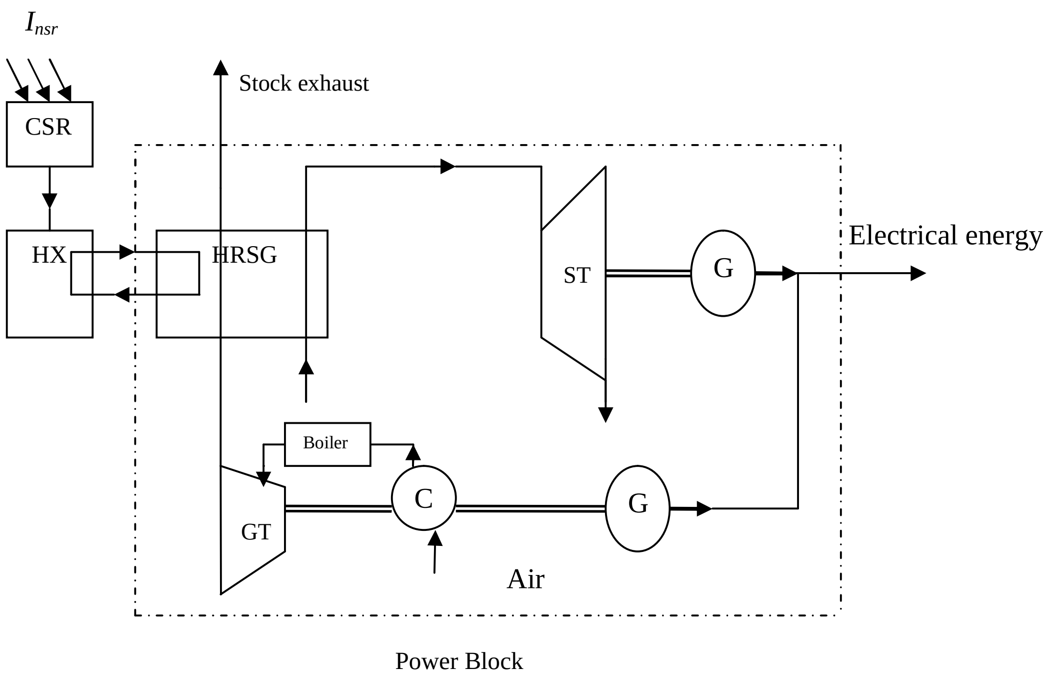
Where Q_{inc} is the incident heat and I_{si} is the incident solar radiation.

I_{si} is developed from the normal solar radiation (I_{sn}) measured at STPP installation site, considering the solar diluted filed ratio (ε_s) and ambient temperature (T_{amb})as :

$$I_{si} = \left(1 - \frac{\varepsilon_s * 20}{T_{amb}}\right) I_{sn} \qquad (3)$$



(a) Solar combined cycle (SCC).



(b) Solar triple cycle (STC).

Fig (1): *A schematic diagram of the ISCC solar thermal power plant.*

Q_{inc} propagates along the parabolic trough solar field and converted into absorbed heat (Q_{abs}). The difference between Q_{inc} and Q_{abs} represents the optical losses and η_{Opt} in this case is :

$$\eta_{Opt} = Q_{abs} / Q_{inc} \tag{4}$$

Q_{abs} is converted into useful thermal energy (Q_u) and thermal losses (Q_{loss}). To calculate Q_u the absorbed temperature (T_{abs}) is used to develop the dependent heat –loss coefficient (U_l) as following [10] :

$$U_l = dQ^{n}_{los} / dT_{abs} \tag{5}$$

The approximation heat loss per unit area ($\dot{Q}^{n}_{loss}$) is given by a quadratic function as [11] :

$$Q^{n}_{los} = U_0 * \Delta T + U_1 * (\Delta T)^2 \tag{6}$$

Where (U_0) and (U_1) are the characteristic constants of the solar collector used and ΔT is the difference between T_{abs} and the ambient temperature (T_{amb}). Thus, U_l can be expressed as a linear function as :

$$U_l = U_0 + 2 * U_1 * \Delta T \tag{7}$$

When U_l is non negligible temperature dependence, Eqn. [5] given as :

$$U_l = \dot{Q}^{n}_{los} / \Delta T \tag{8}$$

The total useful thermal power, integrated along the absorber, was developed as a function of the thermal fluid temperature at the entrance (T_1) and exit (T_4) of the collector as [12] :

$$Q_u = m_f * c_f (T_4 - T_1) \tag{9}$$

Where m_f is the mass flow rate of the thermal fluid and c_f is the specific heat of this thermal fluid.

Considering, T_1 and T_4 of the thermal fluid are always constants, the transfer of energy within the heat exchanger or HRSG can be given by :

$$m_f c_f (T_4 - T_1) = m_v (\Delta h_w + \Delta h_{ev} + \Delta h_v) \tag{10}$$

$$m_f c_f (T_4 - T_2) = m_v (\Delta h_{ev} + \Delta h_v) \tag{11}$$

Where; T_2 is the thermal temperature at pre-heater exit , m_v is the mass flow rate of water vapor (Kg/s), Δh_w is the enthalpy variation of water in pre-heating stage (J/Kg) , Δh_v is the enthalpy variation of vapor in super –heating stage (J/Kg) and Δh_{ev} is the liquid to vapor enthalpy variation (J/Kg).

Thus, $$\eta_{\mathrm{Res}} = Q_u / Q_{abs} \tag{12}$$

The conversion of the heat energy into electricity is through the power block of STPPs, This block include the heat exchange or HRSG, gas or/and steam turbine and the electric generator. The efficiency of this block (η_{PB}) is deduce for solar combined cycle (SCC) and solar triple cycle (STC). Figure 2 shows the temperature-entropy diagram of these integrated combined cycles. Figure 2.a shows SCC, Brayton cycle – gas turbine, used for the STPP.

Using the pressure ratio (r_p) and the constant K , the efficiency of this cycle (η_{Bc}) was stated as [13] :

$$\eta_{Bc} = 1 - \left(r_p\right)^{-(1-k)/k} \tag{13}$$

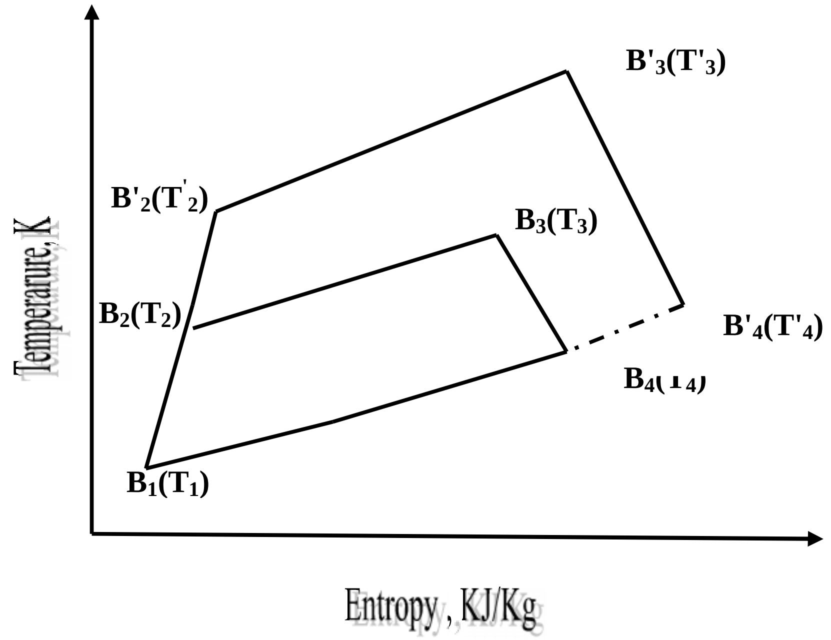
Thus, the solar thermal efficiency (η_{st})and η_{PB} are given as :

$$\eta_{st} = \eta_{Bc} \tag{14}$$

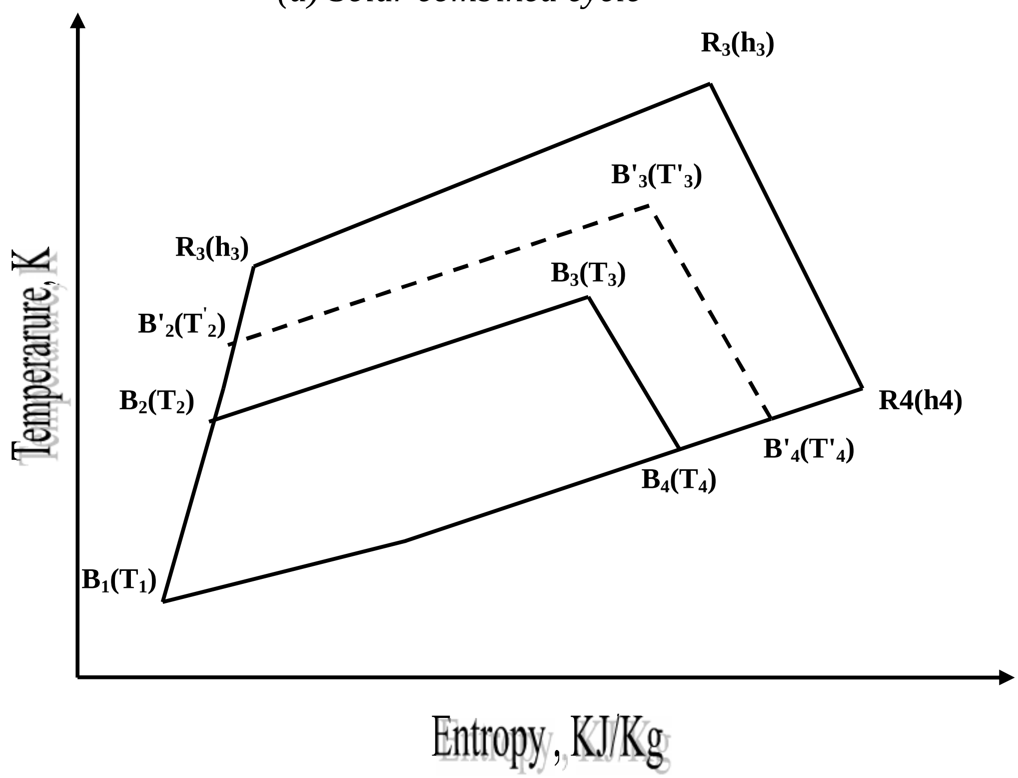
$$\eta_{PB} = \eta_{st} * \eta_T * \eta_G \tag{15}$$

When STC, Rankine cycle – steam turbine is used for the STPP, the boiler temperature(T_3) and intermediate pressures, and the exchanger exit temperature (T_1) are used to develop the entropy h_2, h_3, h_4. Then ,the efficiency of Rankine cycle (η_{Rc}) is given as :

$$\eta_{Rc} = \frac{h_3 - h_4}{h_3 - h_2} \tag{16}$$



(a) Solar combined cycle



(b) Solar triple cycle

Fig (2) : *The temperature – entropy diagram of an ISCC solar thermal power plant.*

Thus , η_{st} equals η_{Rc} and η_{PB} is given as in Equation (15).

η_{st} , η_T and η_G are the efficiencies of the solar combined or triple cycle ,the gas or steam turbine and the electric generator. These efficiencies are represented η_{PB} of the solar thermal power plant study; and the output power (P) of this STPP is given as :

$$P = \eta_0 * Q_{inc} = \eta_{Opt} * \eta_{\mathrm{Res}} * \eta_{PB} * Q_{inc} \qquad (17)$$

3.Case study:

The electric power generation system at El-Kuraymat incorporates gas, steam and combined cycle power stations and interconnecting with 66, 220 and 400 kV transmission systems. NREA of Egypt had been installed the first STPP, 2008-2012, at EL Kuraymat (29º 16´ N) with the cooperation of Fichtner solar Gmbh. This STPP integrated with a certain gas turbine type and interconnecting with 66 kV since June 2011. The technical parameters of this ISCC power plant is given in Appendix (I).Also, the ISCC of El. Kuraymat power plant is shown in Figure 3.

On the hourly basis, the daily, monthly and annual generations of this STPP are determined using the generation model in section 2. The hourly normal solar radiation (I_{nsr}) at the aforementioned installation site is recorded by Meteorological Authority of Egypt (MAOE) through a day of different months of the year and given in Appendix(II). Also, the average ambient temperature had been recorded by MAOE through five years and given in Appendix (II). Concentrating solar radiation (CSR) on the receiver of this STPP includes the heliostats and the trough solar collector. A maximum _density heliostat field is used for the CSR corresponding to an area coverage ratio (heliostat area to ground area). This ratio is developed as 0.14 when the solar thermal energy (STE) is of 4.4 MW/m^2/yr [14].

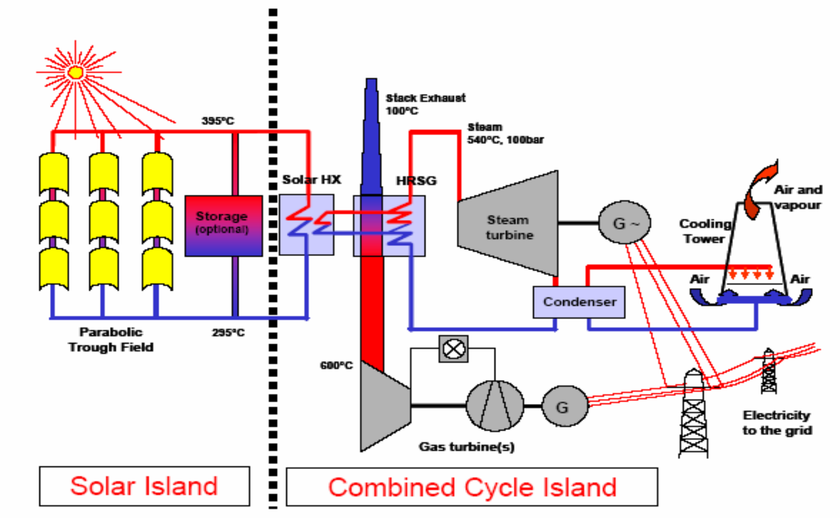


***Fig (3) :** Schematic diagram of The ISCC El-Kuraymat power plant [9].*

Considering this ratio, the recorded I_{nsr} at EL-kuraymat is used to determine the incident solar radiation (I_{isr}) on the through collector and shown in Figure 4. This figure shows the hourly I_{isr} through a day of different year months..

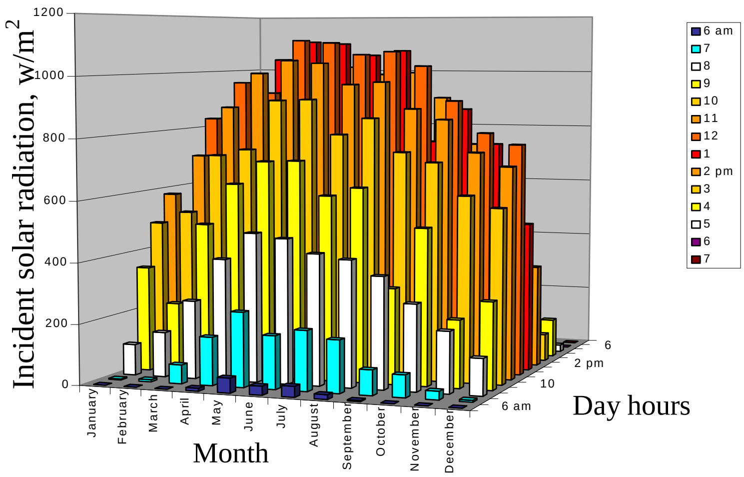


Fig (4) : *The average hourly incident solar radiation on the solar trough at El-Kuraymat site through a day of the year months.*

Using the matlab program, the results of this figure are used with the design parameters of El-kuraymat STPP to evaluate the incident STE (Q_{inc}), the absorbed STE (Q_{abs}) and the useful STE (Q_u) used in this STPP. Figure 5, gives the incident STE on the receiver of the STPP study through a day of different year months.

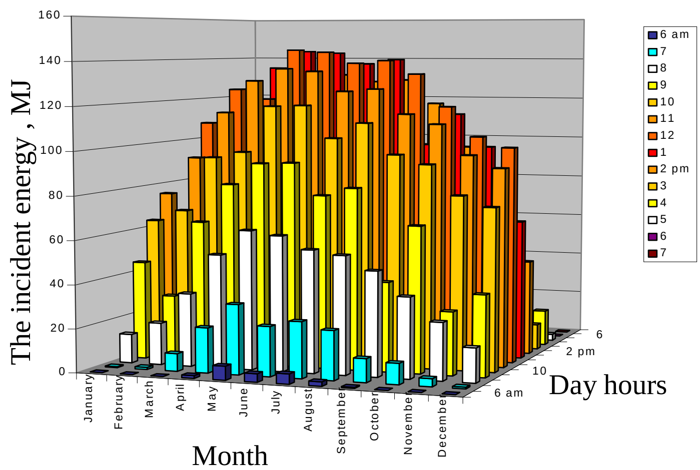


Fig (5) : *The hourly incident STE (Q_{inc}) at El-Kuraymat STPP through a day of the year months.*

The optical efficiency (η_{opt}) of the concentrating solar thermal energy (CSTE) of EL kuraymat STPP had been determined and given as 0.72 [15]. With a thermal losses in the pipe of receiver of 0.05, the STE absorbed by the heat transfer fluid (HTF) is development and given in Figure 6. This figure gives the absorbed STE by the HTF (Q_{abs}) through a day of different year months. The result of this figure is used with the receiver efficiency (η_{Rec}) of 0.93 [14] to estimate the useful STE (Q_u) and given in Figure 7. This figure gives the energy inlets the heat recovery steam generator (HRSG) of the ISCC power plant of EL kuraymat, Figure 3. The power block of this ISCC incorporates the HRSG gas turbine, steam turbine and electric generators. Figure 8 shows temperature_ entropy diagram of ISCC El-kuraymat power plant at the base case (50MJ/s or 700W/m^2). The temperature at different points on this ISCC are developed as [9] :

HTF inlet temperature ,^{o}C	: 395
HTF exit temperature ,^{o}C	: 295
GAS turbine exit temperature ,^{o}C	: 680
Stack exhaust temperature , ^{o}C	: 100
HRSG exit temperature ,^{o}C	: 540

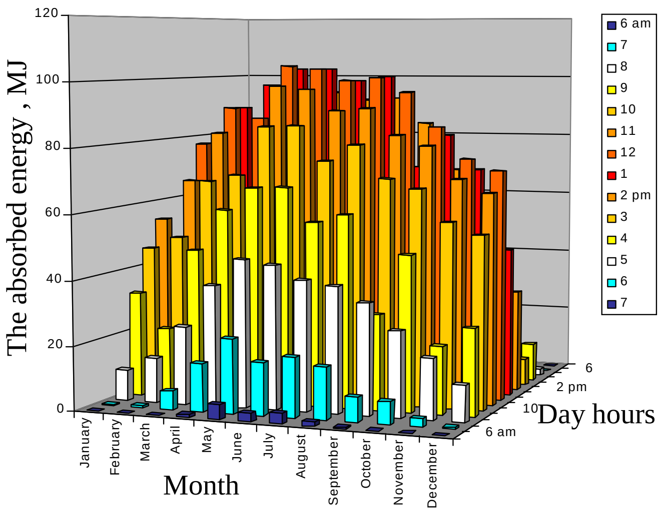


Fig (6) : *The hourly absorbed STE (Q_{abs})at El-Kuraymat STPP through a day of the year months.*

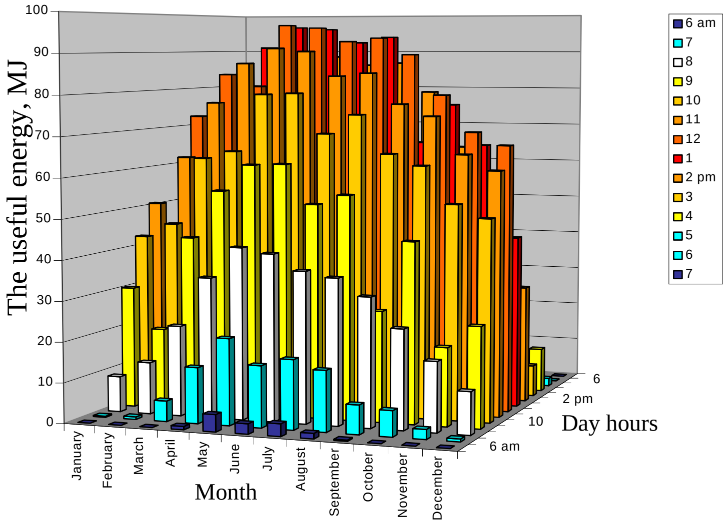


Fig (7) :*The hourly useful STE (Q_u) at El-Kuraymat STPP through a day of the year months.*

Also the efficiency of power block parameters are determined and given as:

Expansion polytrophic efficiency : 0.58
Steam cycle isentropic efficiency : 0.95
Electric generator efficiency : 0.98
Power block efficiency : 0.39

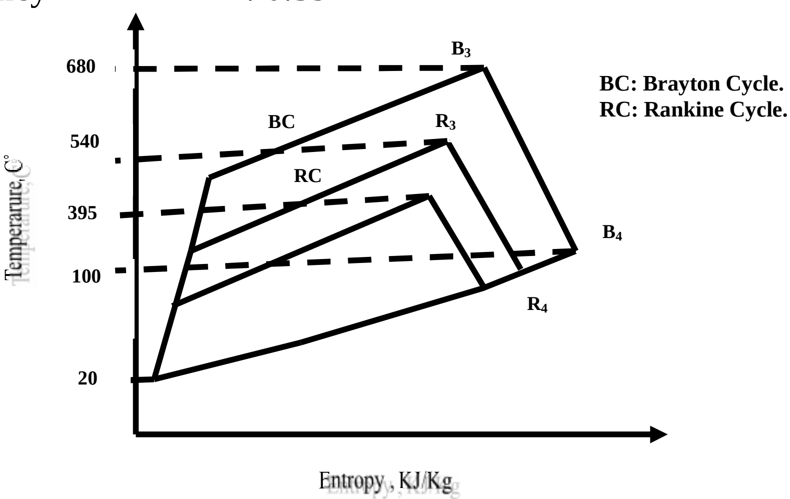


Fig (8) : *Entropy – Temperature diagram of the ISCC El-Kuraymat power plant.*

Thus, the overall efficiency of the study STPP is developed as a function of η_{Opt}, $\eta_{Re\,c}$ and η_{PB} given as 0.268 .This efficiency is used with the result of Figure 5 to estimate the hourly generation of the ISCC El kuraymat power plant and given in Figure 9. This figure shows the generation of power plants study through a day of the different year months and concluded that the maximum generation is at 12 o'clock on may 15th. While, the minimum generation is at 7am o'clock on January 17th. The results of Figure 9 are used to determine the daily and monthly generation of this power plant and shown in Figure 10. The results of this figure concluded that the annual energy output of EL kuraymat solar thermal power plants is 835.23 GWh.

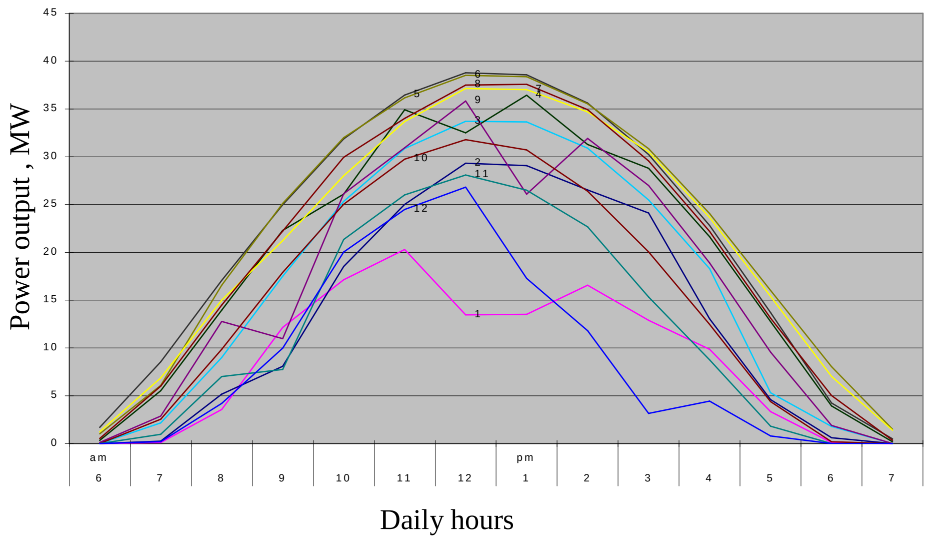


Fig (9) : *The hourly generation curve of El-Kuraymat STPP through a day of different months.*

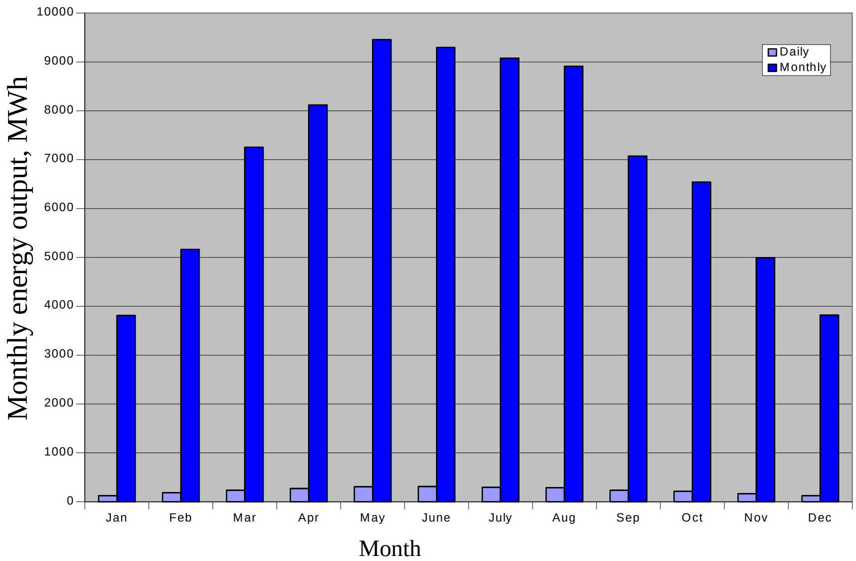


Fig (10) : *The daily and monthly energy output of El-Kuraymat STPP through the year months.*

4. Conclusion:

Generation model is presented in this paper to evaluate the generation of integrated solar combined cycle power plants. Two combined cycles of integrated STPP are considered here. These are integration of the STPP with gas turbine-Brayton cycle or/and steam cycle- Rankine cycle of conventional thermal power plants (CTPPs). However , STPP includes four elements (solar collector, receiver , transport-storage and energy conversion), the efficiency of these elements are modeled for the proposed generation model. Then, the efficiency of the entire STPP is modeled for two cycles of integrated STPP with CTPPs. The proposed model is applied numerically to assess the hourly, daily, monthly and annual generation of the ISCC El-Kuraymat power plan in Egypt and concluded that :

1. The overall efficiency of the STPP is 0.268.
2. The hourly generation varies from 0.11256 to 38.79 MW through the sunshine hours of the year.
3. The daily and monthly generation varies from 122.9691 to 309.8696 MWh and from 3812.043 to 9457.661 MWh respectively. These variations are depended on the meteorological data at the installation site.
4. The annual generation of ISCC El-Kuraymat power plant is 835.231 GWh.

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Nomenclatures:	
η_0	Overall efficiency
η_{Opt}	Solar collector efficiency.
η_{PB}	Power block efficiency.
η_{Rec}	Receiver efficiency.
A_c	Filed area.
I_{si}	Incident solar radiation.
I_{sn}	Normal solar radiation.
Q_{inc}	Incident heat.
ε_s	Solar diluted filed ratio.
T_{amb}	Ambient temperature.
Q_{abs}	Absorbed heat.

Q_u	Useful thermal energy.
Q_{loss}	Thermal losses.
T_{abs}	Absorbed temperature.
U_l	Heat – loss coefficient.
$Q^{\cdot n}_{loss}$	Heat loss per unit area.
U_0, U_1	Characteristic constants of the solar collector.
ΔT	The difference between absorbed temperature and the ambient temperature.
T_1	Thermal fluid temperature at the entrance.
T_4	Thermal fluid temperature at the exit.
m_f	The mass flow rate of the thermal fluid.
c_f	Specific heat of the thermal fluid.
T_2	Thermal temperature at pre-heater exit.
T_3	Boiler temperature.
η_{Rc}	Efficiency of Rankine cycle.
η_{Bc}	Efficiency of Brayton cycle.
η_{st}	Solar thermal efficiency.
P	Output power.

Appendix(I) :

Technical data of ISCC EL kuraymat power plant [9].

TECHNICAL DATA	UNIT	VALUE
Solar field total Aperture Area	m^2	130000

Number of Collectors	N°	160
Number of Collector Loops	N°	40
Design Irradiation	W/m^2	700
Solar Field Design Thermal Power at Reference Conditions	MJ/s	50
Hot Leg HTF Temperature	°C	393
Cold Leg HTF Temperature	°C	293
Gas Turbine Generator Rated Power Output	MWe	74.4
Steam Turbine Generator Rated Power Output	MWe	59.5

Appendix(II) :

Normal radiation (Isn) and ambient temperature (T_{amb}) recorded at El-Kuraymat site (29˚ 16˝) [16].

Month	Day	Day hours														T_{amb} ˚C
		6 am	7	8	9	10	11	12	1 pm	2	3	4	5	6	7	
Jan	17	0	3	125	427	602	714	473	475	583	453	346	117	3	0	15
Feb	16	0	8	175	274	628	848	995	986	903	818	443	155	20	0	18
Mar	16	0	71	297	578	837	1020	1114	1112	1021	842	604	175	59	0	21
Apr	15	10	178	450	719	842	1127	1049	1176	1009	929	698	412	126	6	25
May	15	54	274	548	802	1023	1171	1246	1239	1144	971	733	440	136	15	26
June	11	32	193	527	800	1019	1151	1227	1222	1132	982	766	510	256	47	28
July	17	38	216	472	669	883	1062	1170	1167	1093	962	745	485	221	43	31
Aug	16	16	189	457	703	947	1075	1186	1188	1104	935	701	415	158	10	30
Sep	15	3	91	407	349	832	985	1141	854	1017	860	602	304	60	0	28
Oct	15	0	81	315	572	800	951	1016	982	844	641	399	140	6	0	27
Nov	14	0	31	230	254	700	854	922	875	744	503	287	59	0	0	22
Dec	10	0	6	141	336	676	826	905	583	398	106	150	26	0	0	18