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On the use of integrated solar-combined cycle with desalting units in Qatar

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ABSTRACT

Qatar declared that by 2020, at least 2% of its electrical power generation should be by solar energy. This means that solar power plants (SPPs) of at least 640 MW capacity should be added, and be operational by 2020. Among the SPP alternatives to be built are: stand-alone solar Rankine cycle operated by parabolic trough collectors, photovoltaic power stations, and integrated solar combined cycle (CC). In this paper, the main characteristics and equipment of CC operating in Qatar and other Gulf area are illustrated. Then, the integration of the CC with solar field to become ISCC is introduced, and its merits are given. Then the ISCC is integrated with multi-stage flash desalting units to produce both electric power and desalted seawater. The addition of solar increases the solar steam, and thus, the capacity of both the steam turbine and desalination units. The additional cost of adding 55 MW capacity to the CC by solar energy is less than the 60% of stand-alone SPP with Rankine cycle having the same capacity.

Keywords: Combined gas/steam combined cycle (CC); Desalination; Electric power; Solar energy; Cogeneration power desalting plants (CPDP); Dispatchability; Concentrated solar power; Parabolic trough collectors

1. Introduction

Qatar has abundant solar energy (SE) and natural gas (NG) that can be used as prime energy for electric power (EP) generation. While the NG is used to meet all its EP generation needs, the SE contribution is nil. All utility power plants (PPs) in Qatar are using gas turbines (GT) and gas/steam turbines (STs) combined cycle (CC) driven by NG. The use of CC's plants is due to their high efficiency and relatively low capital cost, and NG availability. Burning NG contributes heavily to the emission of CO_2 and NO_x, both are greenhouse gases (GHG) causing global warming. Although the NG is considered cheaper and more abundant than oil, the other sometimes used fossil fuel (FF), its consumption in the country are continuously on the rise (Fig. 1). This has to be reduced as its cost is continuously increasing (Fig. 2). Besides, Qatar has the highest CO_2 emission per capita in the world (44 ton/y/cap in 2009), [3], and its FF consumption should be reduced.

So, Qatar mandated that 2% of EP generation must be from SE by 2020. Since Qatar receives high levels of SE, about 2,100 kWh/(m^2 year), the use of SE to generate EP is a viable real option.

Typical solar power plant (SPP) using concentrated solar power (CSP) and Rankine steam cycle can be installed with easy implemented gas burner, similar to that shown in Fig. 3 [4].

The problems of stand-alone SPP are: high cost and non-dispatchability. These can be solved by using

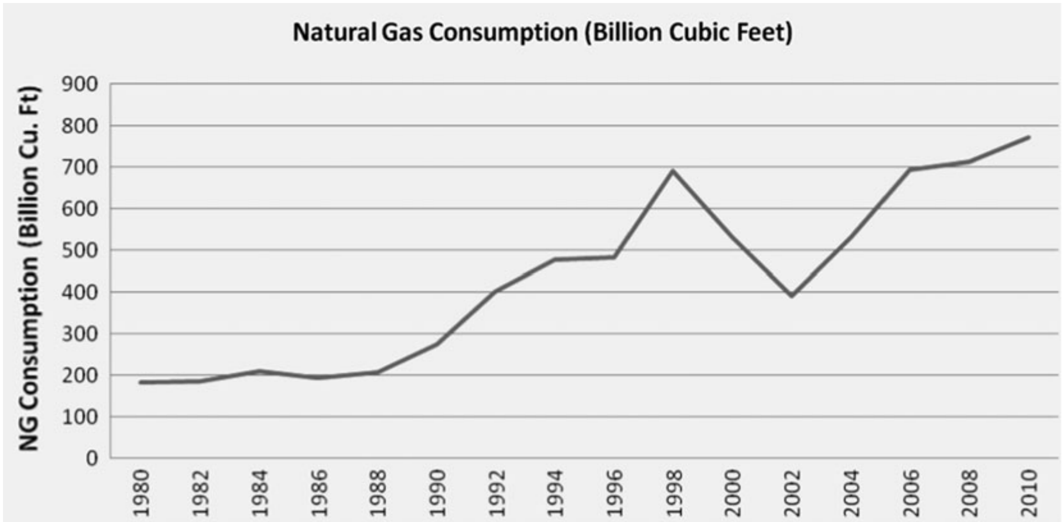

Fig. 1. Qatar NG consumed in equivalent 10^3 bbl/d along the years [1].

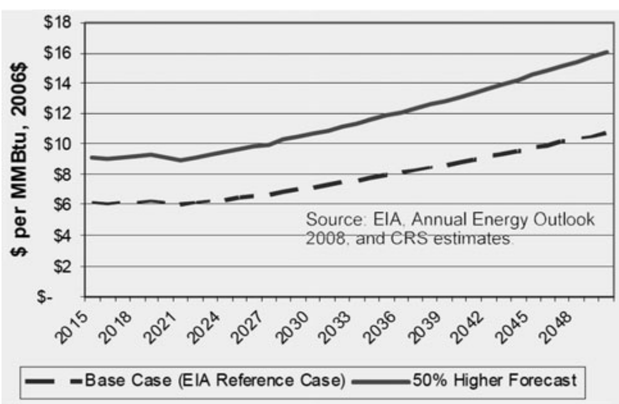

Fig. 2. Natural gas price trends (Henry Hub Spot Price) [2].

hybrid systems integrating CSP technology with conventional NG fired PPs. The most widely used hybrid approach is the integrated solar-combined cycle (ISCC) power plant (Fig. 4) [5].

Solar augmentation to the present power stations using FF is the lowest-cost option for using SE in PPs. The FF plant provides stable power output to the grid while balancing the variability of the solar thermal input as needed. On the other hand, the CC's ST may operate at part load when solar steam is not available, reducing its efficiency.

The ISCC utilizes the benefits of using both SE and the NG, induce technological change to a low carbon economy, capacity building (contribute to learning) on SE technology, significantly raising the efficiency of the CC, and diversifying the power generation mix.

Other combinations than the ISCC include:

- Preheating the feedwater in Rankine steam cycle by CSP collectors (Fig. 5) [6].
- Preheating air in GT cycle before combustion by solar power tower (Fig. 6) [7].

2. Combined gas/steam turbines combined cycle

Fig. 7 shows the concept of CC plant, where the hot gases exhausted from the GT are directed to heat recovery steam generator (HRSG) where steam is generated. This steam operates a steam cycle. Typically, the power output of the steam cycle is around 50–60% of the GT cycle output. In other words, the CC power plant consists of Brayton GT cycle (called topping cycle), Rankine ST (called bottoming cycle), and HRSG.

In Brayton GT cycle (Fig. 8) [8], air is drawn at ambient temperature T_1, and pressure (P) equal to P_1 into the compressor intake, where it is compressed to P_2. Then, it enters the combustion chamber where fuel is injected and combusted at almost constant P. The air at T_2 becomes combusted gases after fuel combustion and its temperature is increased significantly to the cycle highest temperature T_3, called turbine inlet temperature (TIT). The combusted gases leave the combustion chamber at pressure P_3 (slightly lower than P_2). The hot gases at TIT are directed to the turbine, where it expands, produces work, and exits at P_4 (slightly higher than the ambient pressure) and temperature T_4. The value of T_4 (≅500–600°C) is much higher than the ambient temperature T_1. Part of the

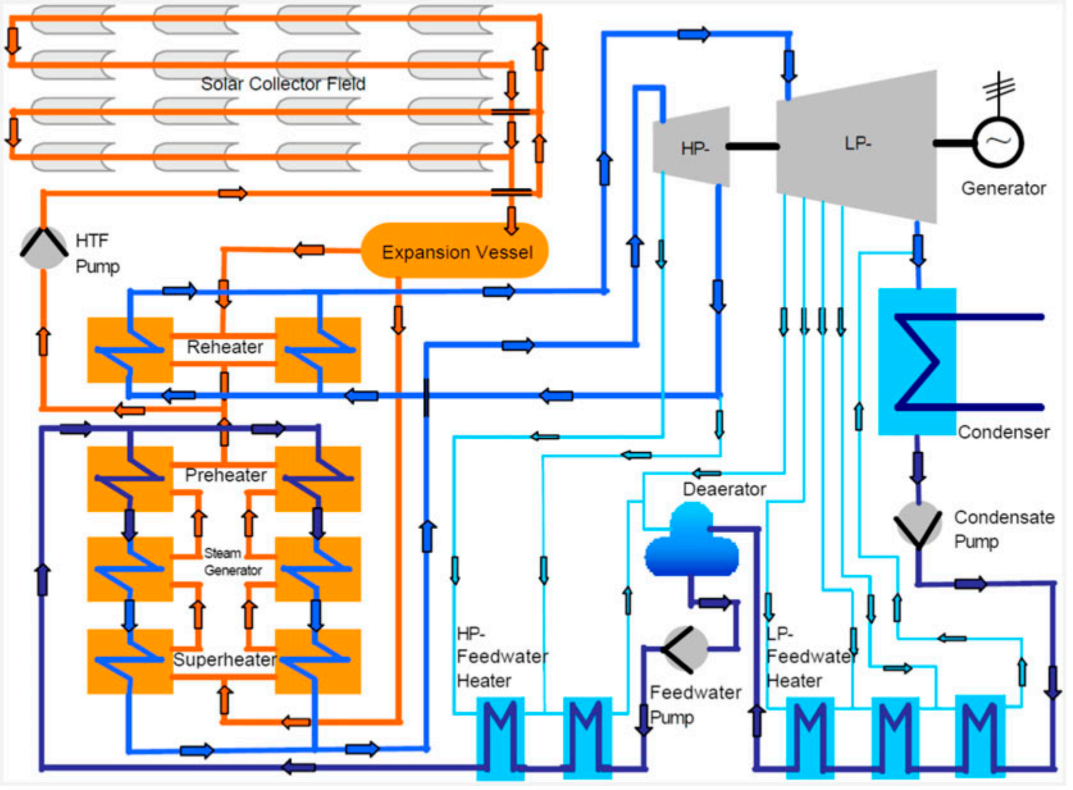

Fig. 3. Representation of a parabolic trough plant with thermal energy storage and auxiliary fossil backup [4].

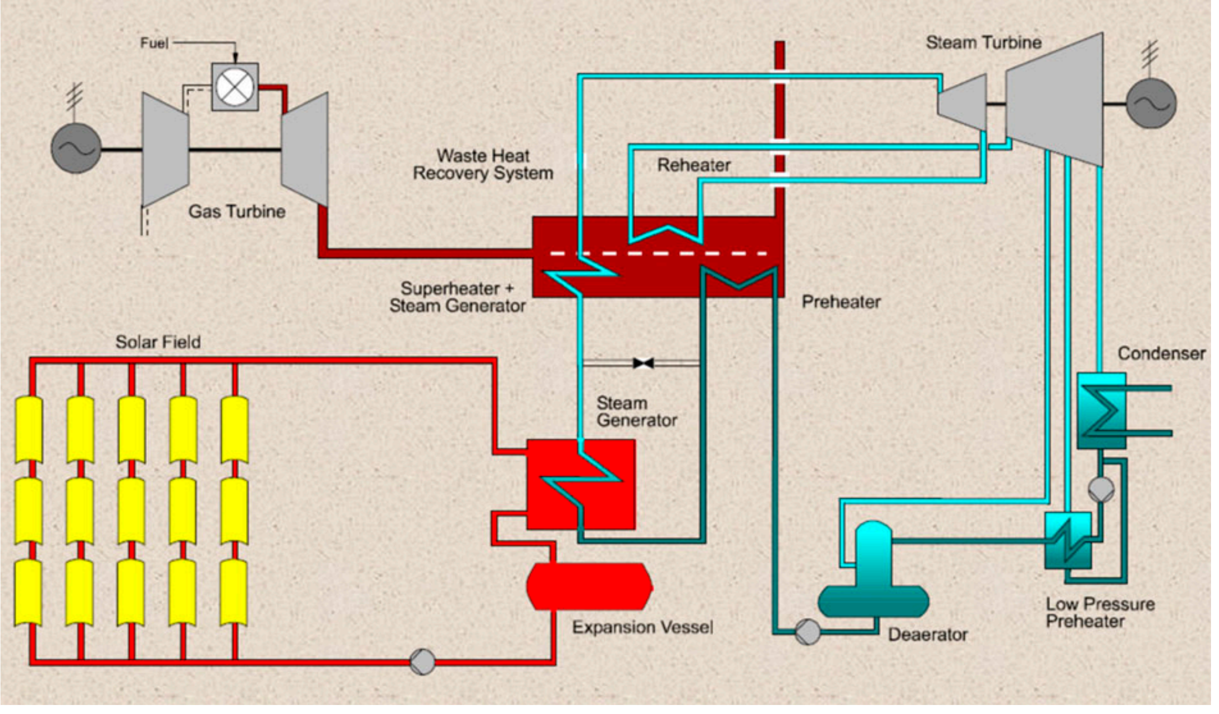

Fig. 4. Integrated solar gas turbine/steam turbine combined cycle [5].

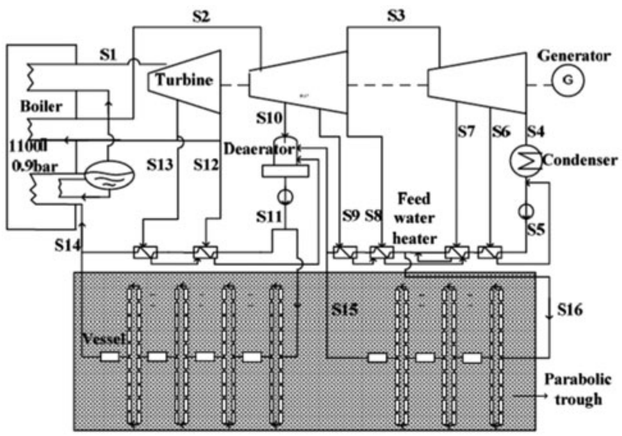

Fig. 5. Solar heat preheating the feedwater from the condenser to the steam generator [6].

turbine work output is used to drive the compressor, and the balance is the net work output driving an electric generator. In simple GT cycle, the hot gases leaving the turbine are rejected to the atmosphere; and most of the simple GT cycles have low efficiency (in the range of 30%).

The hot gases exhausted from GT (say at 500–600°C) can be directed to HRSG to generate steam that can be used to process heat in desalination or cooling. It can also be used to run Rankine steam cycle (Fig. 9). This increases the cycle work output and efficiency to the 50% range.

In the HRSG utilizing the GT's hot exhaust gases, water is heated, boiled, and superheated (if applicable) in economizer, evaporator, and super-heater, respectively. The HRSG can have supplementary firing (called duct firing), or can be operated without adding fuel. The HRSG can be of single pressure stage (Fig. 9), or double pressure stage (Figs. 10 and 11), or even triple pressure stages.

3. Integrated solar-combined cycle

The ICSS (Fig. 4) consists of CC power plant connected to solar field. The thermal energy supplied to the HRSG and by the solar field is used to generate steam that operates one ST. The solar field consists of all equipment necessary to transfer solar irradiation into thermal energy, and uses it to produce steam. These include: solar collectors, heat exchangers, called solar steam generator (SSG) and auxiliaries necessary

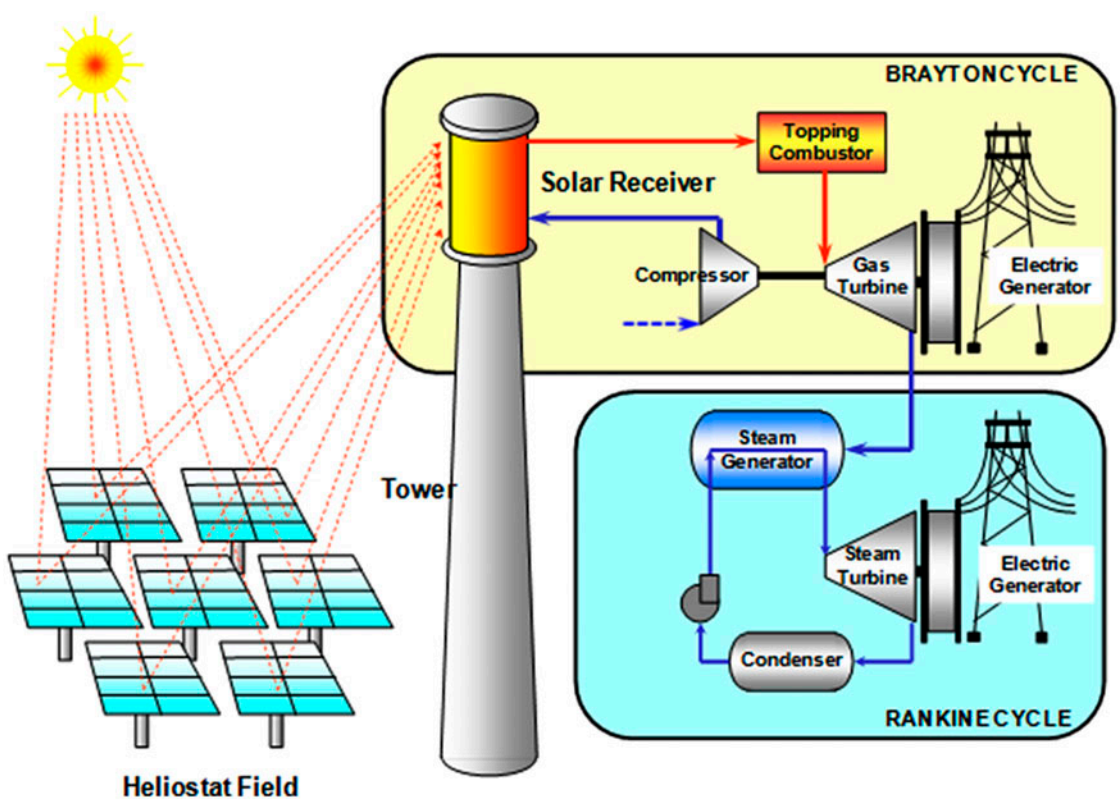

Fig. 6. Solar heating by power tower of the compressed air to the gas turbine [7].

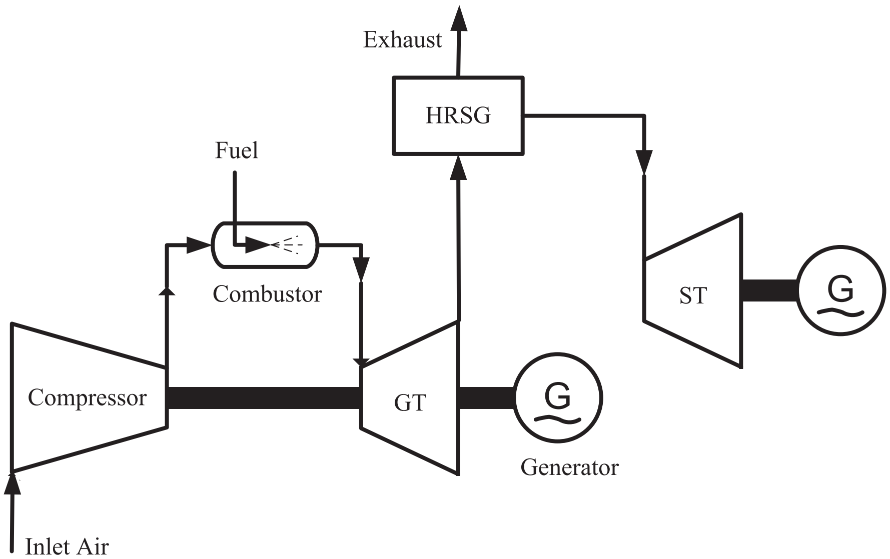

Fig. 7. Concept of gas turbine/steam turbine combined cycle (CC).

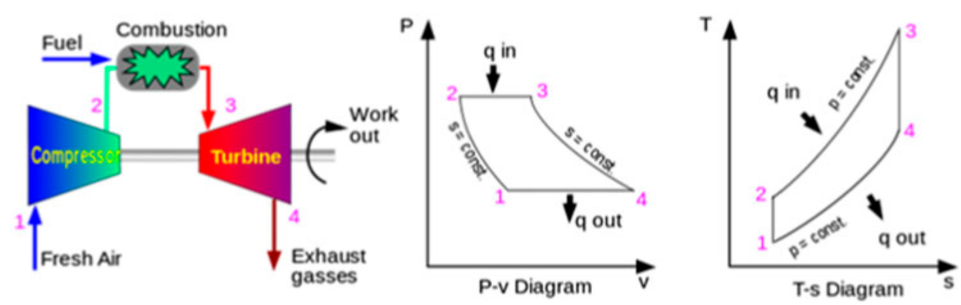

Fig. 8. Brayton gas turbine cycle [8].

to operate the solar field such as pumps, motors, and SE electrical connections.

The steam temperatures provided from the gas turbine exhaust through the HRSG (about 500ºC) are usually higher than that obtained from CSP solar fields, say 370ºC by parabolic trough collectors (PTC) in SPPs. So, it is cost-effective for the larger scale STs that have more stages in the CC than that used in CSP-only power plant, thus providing further increase in ST efficiency. Hence, the SE to electricity conversion is more efficient. The cost of the ST, condenser, grid connection, and site infrastructure are shared with CC power plant.

The incremental costs for using larger steam turbine, the condenser, and cooling system in ISCC are much less than the overall unit cost for solar-only plant. Moreover, the ISCC plant does not have the thermal inefficiencies associated with the daily steam turbine start-up and shut-down.

Steam generated with solar thermal energy (called solar steam) increases the output of NG-fueled CC plant without increasing GHG emissions. This combination helps to reduce the high cost of the solar plant in several ways.

The commonly used solar collectors in the ISCC are PTC (Fig. 12) and linear Fresnel lens collectors (LFC) (Fig. 13), but the PTCs are the most used. In both PTC and LFC, the received solar radiations on reflectors (mirrors) are concentrated and reflected on line receivers located in the focal lines of the mirrors, where heat transfer fluids (HTF) are flowing. The HTF in PTC is oil, and it is directed to heat exchanger (called SSG, where steam is generated). The HTF used in LFC is water, and steam is generated directly in the receiver, i.e. direct steam generator (DSG). The steam generated in both cases joins the steam generated by the GT's HRSG and both are supplied to Rankine steam cycle turbine. The CSP collectors utilize only direct radiation (i.e. light that

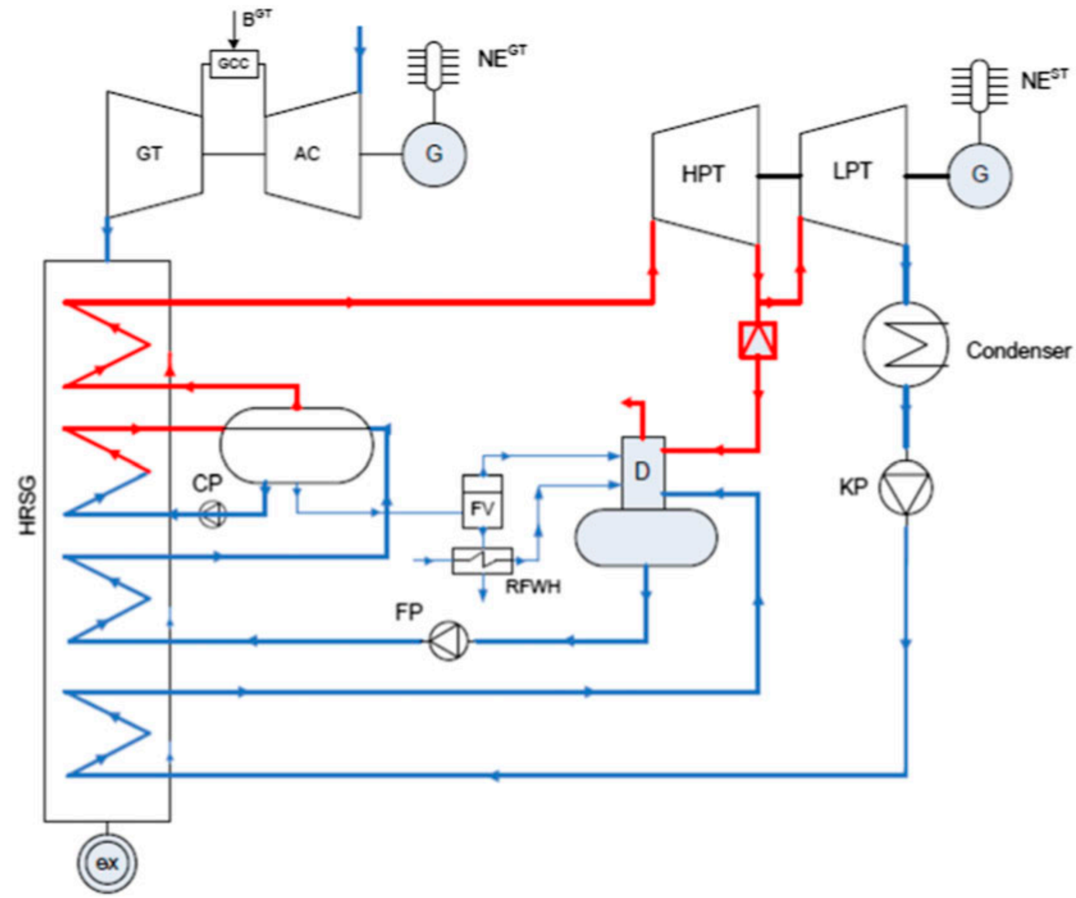

Fig. 9. Schematic diagram of GT/steam turbine combined cycle (CC) with single pressure HRSG (one steam drum) [9].

can be focused effectively by mirrors or lenses), while diffuse type does not. The SGG generates steam (either saturated or superheated) from feedwater returning from the steam cycle. Only thermal energy from solar irradiation is used in (SSG).

The gross electricity output (in MW) of the steam turbine at design conditions is produced by steam supplied to the turbine due to the heat gained by both the HRSG and the solar field and is called electric steam turbine capacity. The gross electricity output (in MW) of the ST that can be attributed to solar heat at its design conditions is called the electric solar capacity.

In ISCC plants, the steam generated by SE (called solar steam) is integrated either at high, or medium, or low temperatures section of the HRSG, as shown later. The general concept is to oversize the ST, using solar heat for steam generation and gas turbine waste heat for preheating and superheating steam. The ST of the ISCC has to be designed for maximum solar heat, i.e. it will be larger than that of CC with the same gas turbine. Hence, at operating points with no solar irradiation, the ST will operate in part load conditions, whereas, in the ISCC it would operate at full load. Usually, the STs have approximately the same efficiency at 85–100% of the nominal load. Thus, limiting the electric solar capacity to 15%, the negative effects of part load become negligible.

Examples of the ISCC in operation or under construction are given in locations, plant electric output, and solar contribution to the output as, [14]:

Kureimat (Egypt), 140 and 20 MW,
Hassi R'Mel (Algeria), 130 and 25 MW,
Ain Beni Mathar (Morocco), 472 and 20 MW,
Yazd (Iran), 430 and 67 MW,
Martin solar, Florida (USA), 480 and 75 MW,
Agua preta (Mexico), 480 and 31 MW,
Victorville, California (USA), 563 and 50 MW, and
Palmdale, California (USA), 617 and 62 MW.

The above mentioned PP uses parabolic trough type collectors and some of them (in Algeria, Morocco, Mexico, and Egypt) are supported partially for the solar part by the World Bank.

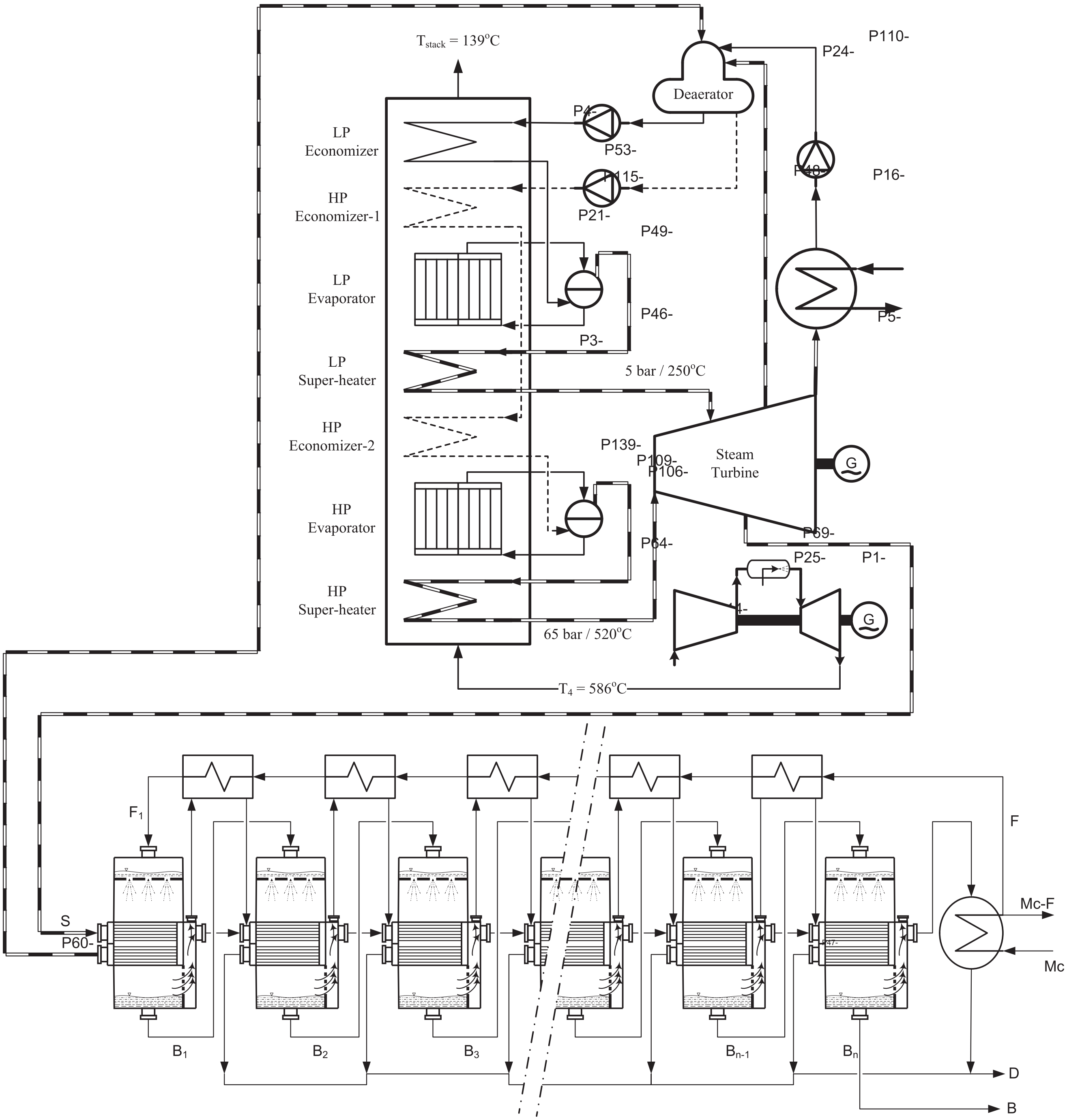

Fig. 10. ISCC using two pressure stages HRSG, with two steam drum, and coupled with desalination plant similar to systems used in the Gulf area [10].

The advantages of the ISCC plants are the reason of several plants currently under construction or recently completed.

The Kureimat (Egypt) ISCC power plant [15] has 140 MW total nominal capacity with and 20 MW solar share. Kureimat (Egypt) is Located about 90 km south of Cairo. The project site is characterized by uninhabited flat desert landscape, high intensity direct solar radiation that reaches 24,008 kWh/m^2/y, (higher than that of Qatar), extended unified power grid, extended NG pipeline near a source of water, and water-cooled plant.

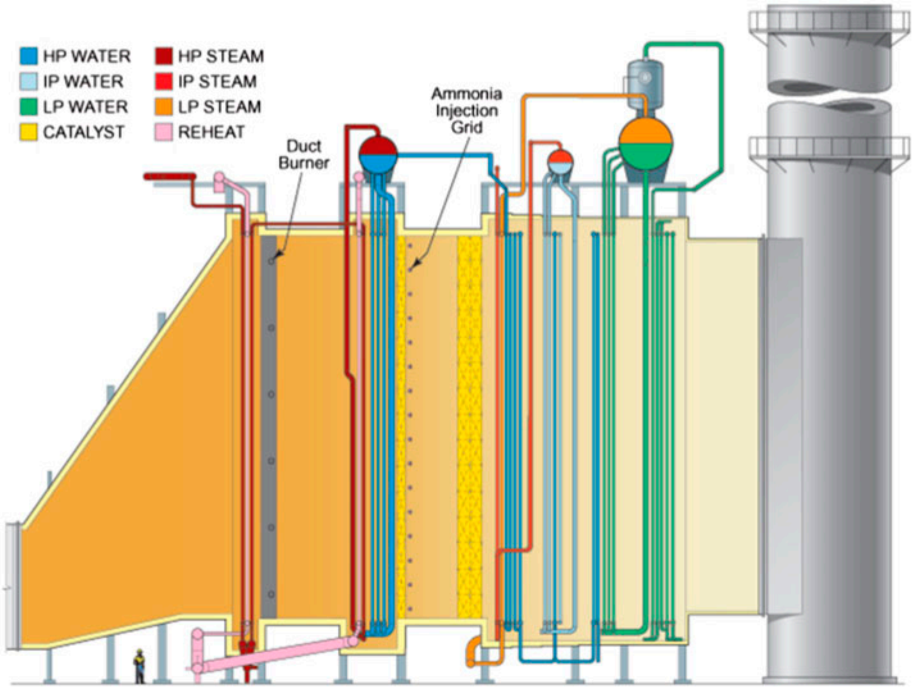

Fig. 11. Two pressure stage heat recovery steam generator (HRSG) [11].

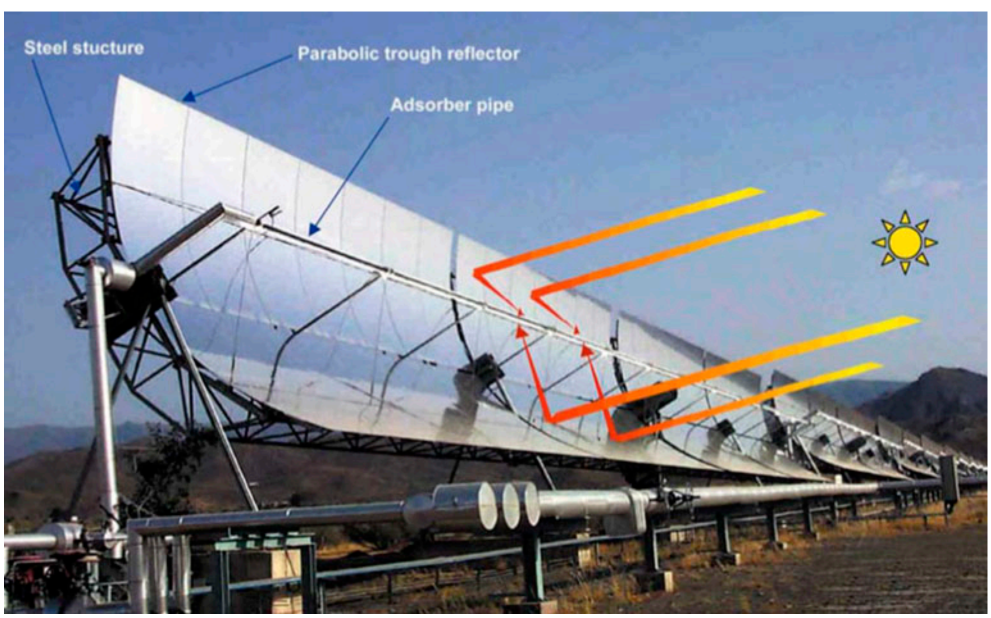

Fig. 12. Parabolic trough collectors [12].

Its power block includes:

- Two GTs of about 41.5 MWe, each firing NG as fuel to generate electricity, in addition to the capability of using fuel oil distillate No. 2 as alternate fuel for emergency;
- Two HRSG using the exhaust gases from the GT to produce superheated steam;

Fig. 13. Fresnel solar collector [13].

- One ST of about 68 MW;
- Cooling system in which the ST exhaust will be condensed in the condenser and pumped to the HRSG; and solar field.

The solar field comprises parallel rows of solar collector assemblies (SCAs) including sets of typical mirrors forming PTC.

The total area of the solar collectors is about 220,000 m^2, connected in series and parallel to produce the required heat by tracking the sun from east to west while rotating on a north–south axis.

The HTF, synthetic oil, is circulated through the receiver heated to high temperature up to 400°C. The fluid is pumped to a heat exchanger to generate steam that can be superheated in the HRSGs and integrated with the steam generated from the CC before entering the ST to generate electricity.

The capacity of solar portion is 30 MW; and thus the collector rea/MW is 7,333 m^2/MW. The EP generated by SE is 65 GWh/y; while that of the total plant is 985 GWhe/y, so the solar share is 6.6%. This gives 38,000 ton/y CO_2 reduction.

The ISCC Yazd Plant in Iran is 478-MW plant operating in CC. It has two 159-MW GTs., one 143-MW ST, and 17-MW solar thermal unit. The plant stands on 2,224-acre (9,000,000 m^2) site near the central Iranian city of Yazd, desert location with high solar radiation. The solar field consists of nearly 4 million ft^2 (371,600 m^2) of PTC in 84 loops (eight collectors per loop), and heating Therminol to 736 F for generating steam [16].

Another example of ISCC is Hassi R'mel in Algeria. The ISCC Hassi R'mel is concentrating solar power (CSP) plant that benefits of SE and CC high efficiency. The solar resource partially substitutes the FF. The project consists of a 150 MWe hybrid power plant composed of a CC and a 25 MWe solar thermal plant.

The plant data is given as [17]

Status date: August 31, 2012

Background

Technology:	Parabolic trough
Status:	Operational
Country:	Algeria
City:	Hassi R'mel
Lat/long location:	33°7′ 0.0′′ North, 3°21′ 0.0′′ West
Break ground:	7-Oct
Start production:	11-Jul
Cost (approx):	315,000,000 Euro
PPA/tariff period:	25 y
Project type:	Commercial

Plant configuration

Solar field

Solar field aperture area:	183,860 m
# of solar collector assemblies (SCAs):	224
# of loops:	56
# of SCAs per loop:	4
SCA length:	150 m
SCA manufacturer (model):	Abengoa Solar (ASTR-Ø)
Mirror manufacturer:	Rioglass
# of heat collector elements (HCEs):	8,064
HCE manufacturer (model):	Schott (PTR 70)
Heat-transfer fluid type:	Thermal oil
Solar field inlet temp:	293°C
Solar field outlet temp:	393°C

Power block

Turbine capacity (gross):	25.0 MW
Turbine capacity (net):	25.0 MW
Turbine manufacturer:	Siemens SST-900
Output type:	Steam Rankine
Cooling method:	Dry cooling
Cooling method description:	Aero condensers

3.1. Solar steam augmentation with the CC [18]

Integration of steam produced with SE (called solar steam here) with that produced by HRSG needs careful study to get the best benefits from the two heat sources.

The used type of solar collector determines the conditions of the solar steam. It is already known that

- High temperature steam of 550˚C can be produced by solar power tower.
- Medium temperature steam of 370˚C is produced by PTC using synthetic oil as HTF.
- Low temperature steam of 270˚C or higher, can be produced by LFC. This low temperature may not be allowed to join the steam inlet to the HP turbine. Recent news shows that solar steam generated by LFC can be at 500˚C.

The solar steam at high temperature of 550˚C is close to that of the main stream supply to the HP turbine. So, it can be supplied directly to both HP and LP STs after reheating in the solar field. It can join simply the HRSG's super-heater and re-heater outlets as shown in Fig. 14(a). Fig. 14(a) shows three pressures stages—HRSG with water returning to the solar field from the HP economizer of the HRSG. Also Fig. 14(b) shows the same but for two pressure stages HRSG and LFCs.

Medium temperature solar collector like PTC produces steam at 370˚C, and at pressure close to that of steam supplied to the HP turbine. The temperature is lower than that supplied to this turbine, say at 500˚C. The solar steam can be supplied to the HP steam drum in the HRSG, and it is then superheated in the HRSG as shown in Fig. 15(a). Fig. 15(a) shows

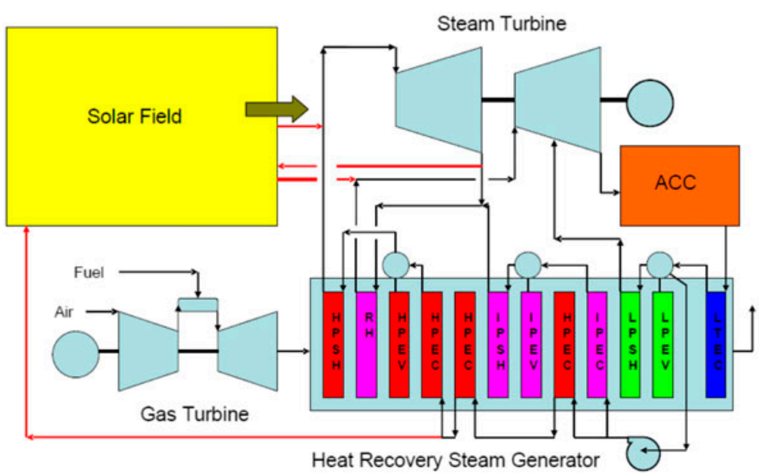

Fig. 14(a). Three pressure stages HRSG with steam generated in the solar field supplied directly to the HP and LP turbines [18].

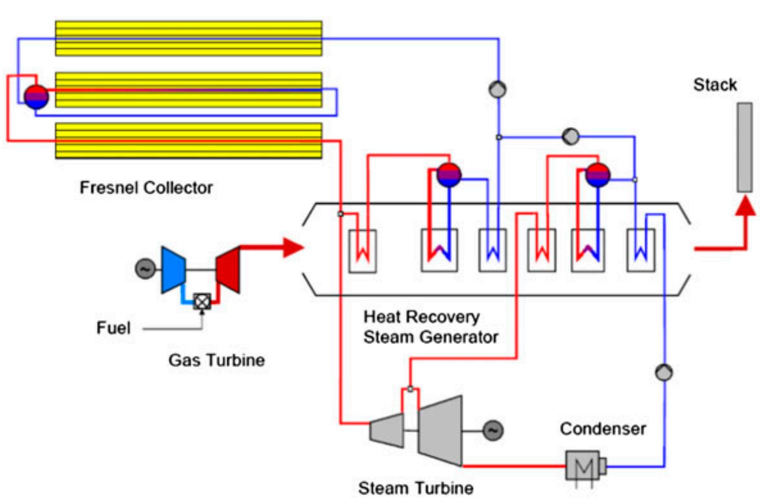

Fig. 14(b). Two pressure stages HRSG with steam generated in the solar field supplied directly to the HP and LP turbines.

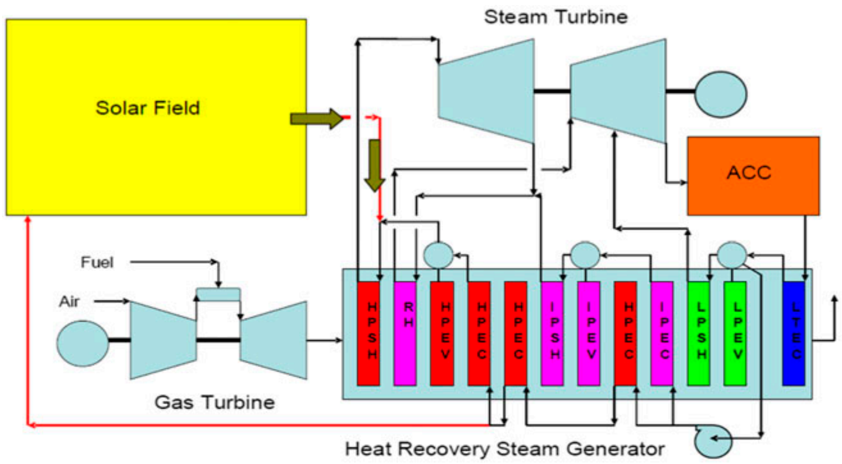

Fig. 15(a). Three pressure stages HRSG with solar steam supplied to the HRSG for super-heating before supplied to the HP turbine [18].

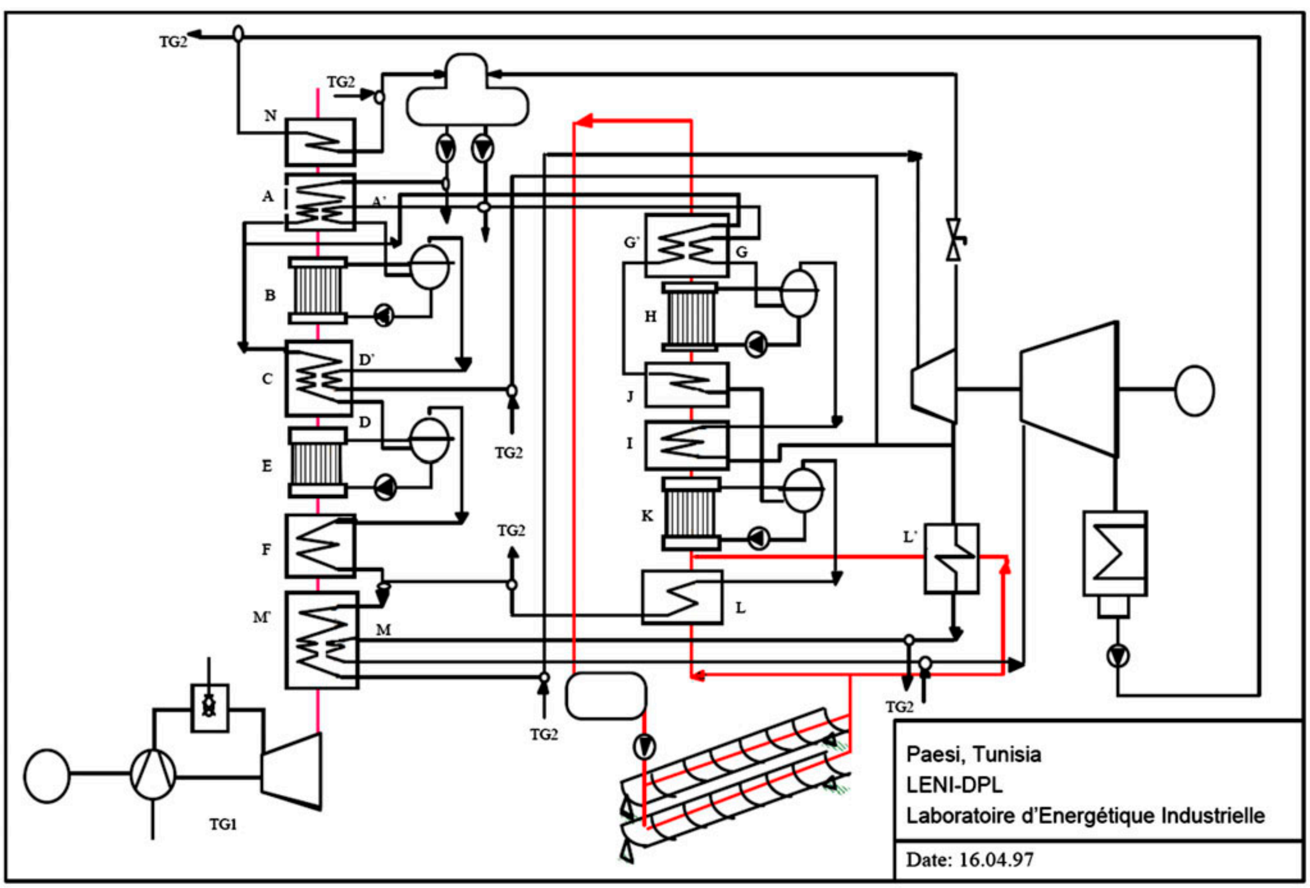

Fig. 15(b). Two pressure stages HRSG with solar steam supplied to the HRSG to be super-heated before supplied to the HP turbine [19].

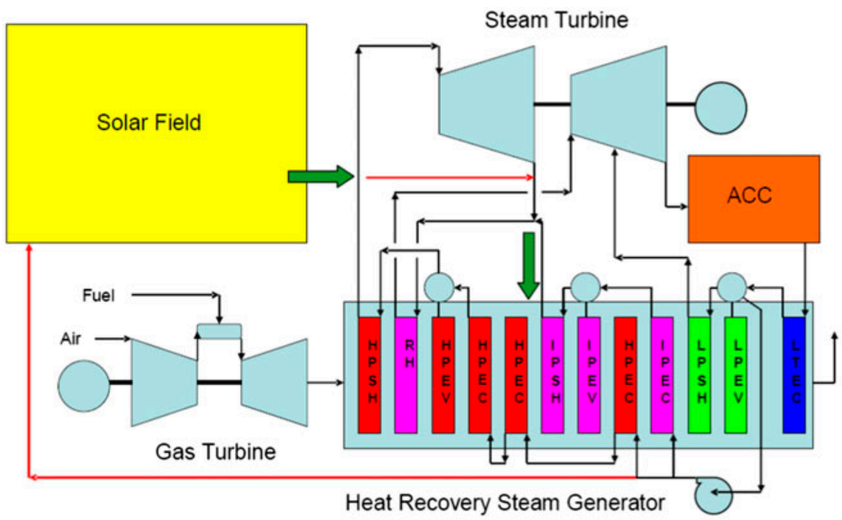

Fig. 16. Three pressure stages HRSG with solar steam joined the cold reheat from the HP turbine, and supplied to the HRSG re-heater [18].

three stage steam generators with water returning to the solar field from the HP economizer of the HRSG. Fig. 15(b) shows two pressure HRSG stage steam generators, and that the water returning to the solar field is extracted from the HP economizer of the HRSG.

The low-temperature solar collector like LFC produces steam at 270˚C and at *P*, close to LP turbine supply pressure. Its temperature is lower than that supplied to the LP turbine. In this case, the solar steam is mixed with the cold reheat leaving the HP turbine and both streams are then introduced to the HRSG re-heater and to the LP turbine, as shown in Fig. 16. Fig. 16 shows three pressure stages HRSG with water returning to the solar field from the LP economizer of the HRSG.

4. Case study for CC attached to MSF desalting units

4.1. Transfer Shuaiba CC to ISCC generating (EP) and desalted seawater (DW)

4.1.1. Requirement statement

Cogeneration power desalting plants (CPDP) using CC, and integrated with multi-stage flash (MSF) or multi-effect distillation (MED) are widely used in the Arabian Gulf area. Examples are: Shuaiba North in Kuwait, Jabal Ali in United Arab Emirates (UAE), and Ras Girtas, and Mesaieed in Qatar.

The Shuaiaba North plant, shown in Fig. 17(a), is considered here to be integrated with solar field to become ISSC, and thus, raising both the ST and desalting seawater outputs about 15–20%. The plant has CC power block combined with three MSF desalting units of 15 MIGD each. One MIGD is 4,546 m^3/d. The plant has three GTs of 3 × 215.5 MW with their three HRSG, and one back pressure steam turbine (BPST) discharging its steam to three MSF units. The plant's design summer ambient temperature is 50˚C. The temperature of the exhaust gases leaving the GT is around 600˚C. The gases from each GT are supplied to single pressure HRSG to generate steam. The steam generated from the three HRSG is supplied to one BPST in the bottoming cycle. This BPST has power output capacity 215.7 MW, and all its discharged steam is supplied to the three MSF units at 2.8 bar. The CC plant net output capacity is (3GT × 215.5 + 1 BPST × 215.5) = 819.7 MW of EP, and 45 MIGD of DW. In the HRSG, the total enthalpy increase from the feedwater inlet to the super-heated steam outlet is almost equal to the enthalpy loss of the exhaust gases in ideal cases. The plant overall thermal efficiency is high, 45–55%, and its fuel is cheap and clean NG.

It is required to add PTC solar field to increase the steam power output about 15–20% of its present 215.7 MW output. The solar field also will increase the desalting capacity to 15–20% of its 45 MIGD capacity.

4.2. Shuaiba CC specifications

The plant has several power blocks. Each block has 3 GT × 215.5 MW each + 3 HRSG + 1 BPST × 215.7 MW + 3 MSF of 15 MIGD each. Some of the plant technical specifications are given in Table 1. Fig. 17(b) shows

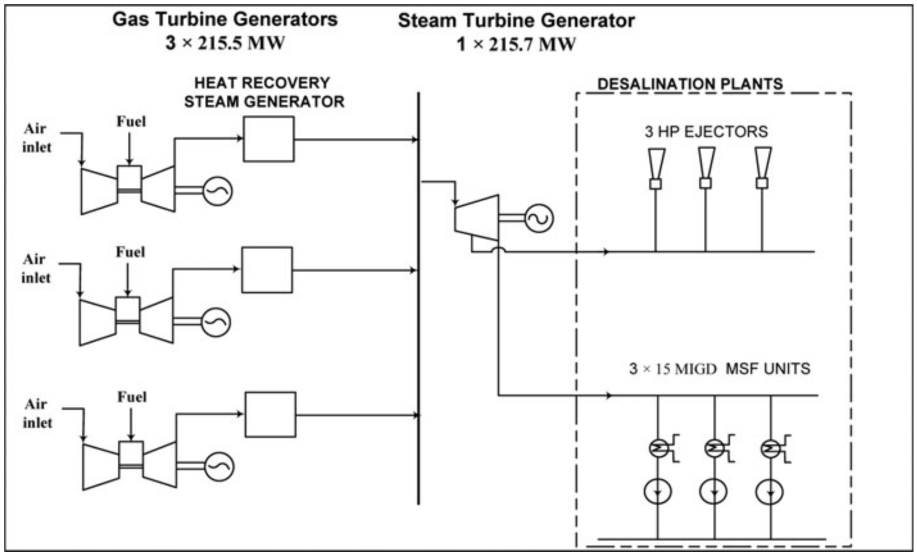

Fig. 17(a). Schematic diagram of Shuaiba North gas/steam combined cycle (GTCC).

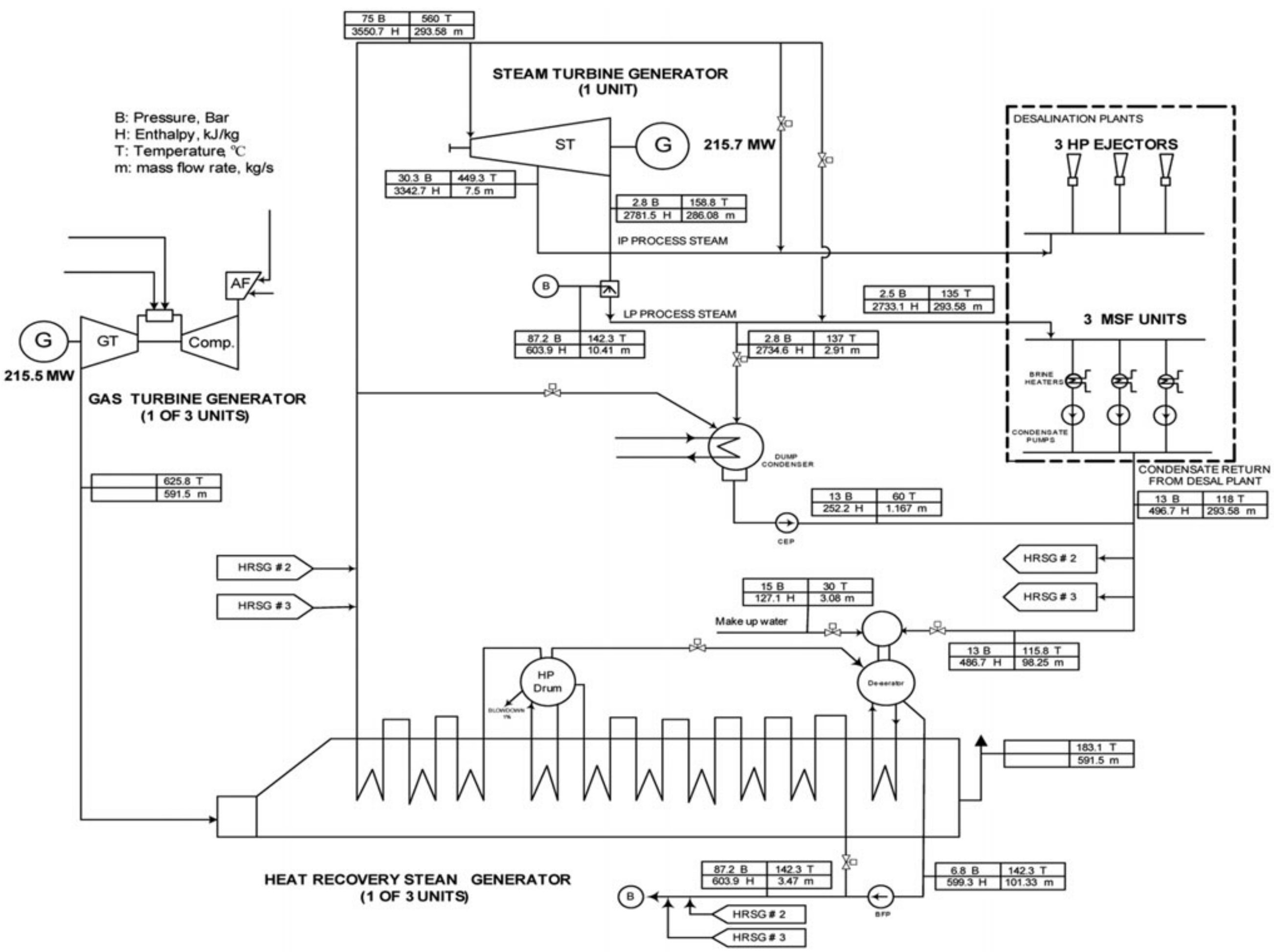

Fig. 17(b). Mass and heat balance diagram of Shuaiba North GTCC power-desalination plant.

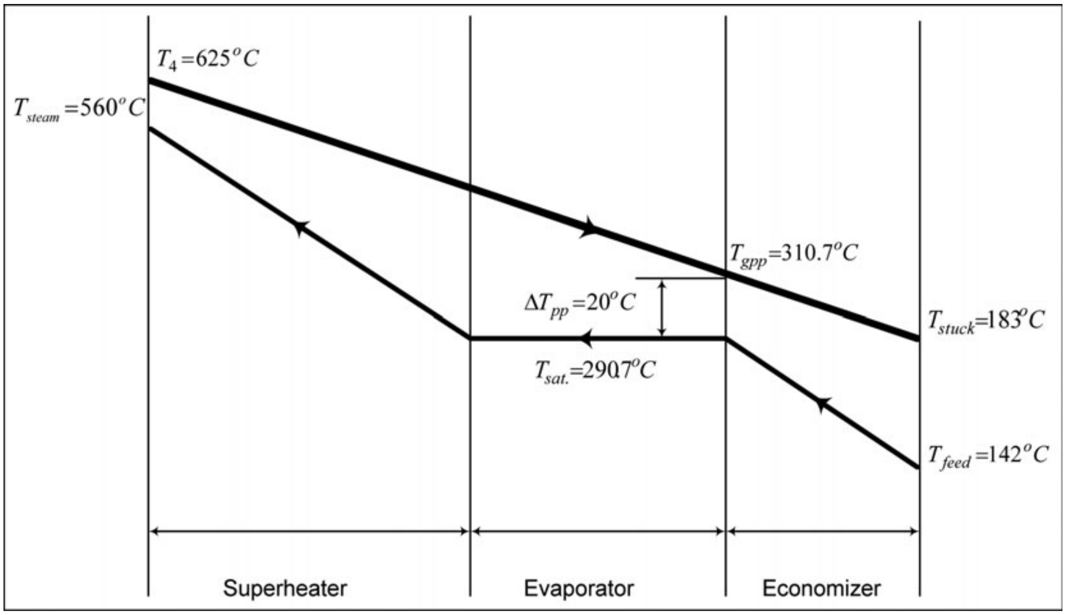

Fig. 17(c). Gas and steam-water temperature profile of the HRSG.

some of its data. The temperature profile in the HRSG is given in Fig. 17(c).

The HRSGs steam mass flow rate, 3 m_s = 1056.9 t/h (293.58 kg/s), where m_s is the steam flow from each HRSG; m_s = 97.86 kg/s. The water heat gained in the three HRSG, Q_{HRSG}, is:

$$Q_{HRSG} = 3m_s \times (h_s - h_f) = 3 \times 97.86 \times \frac{(3,550.7 - 599.3)}{1,000} = 3 \times 288.82 = 866.46 \text{ MW}$$

4.3. Desalination units

The steam mass flow rate to each MSF unit is 97.86 kg/s (1/3 of the steam discharged from the BPST. Each MSF unit produces D = 15 MIGD (789 kg/s). This gives:

$$\text{Gain ratio} = \frac{\text{Mass of desalted water}}{\text{Mass of consumed steam}} = \frac{789}{97.75} = 8.06$$

It is more rational to express the heat supplied to the MSF by its real value in terms of mechanical equivalent energy. The turbine work loss by discharging its steam to the MSF units, rather than its expansion to conventional condenser can be calculated. If this steam was expanded in low pressure (LP) turbine to a condenser pressure of 10 kPa, and 0.9 dryness fraction, its enthalpy would be 2345.5 kJ/kg, and would produce work equal to:

$$W_{de} = m_s \times (h_{MSF} - h_{conenser}) = 97.86 \cdot \frac{2,781 - 2,345.5}{1,000} = 42.6 \text{ MW}$$

This work W_{de} = 42.57 MW is equivalent to the heat Q_{de} = 218.68 MW supplied to the MSF unit.

Another small amount of steam is extracted from the ST, but at higher pressure to operate the MSF steam ejectors MSF plant at 2.5 kg/s flow rate to each MSF unit at 30.3 bar, 449.3℃, and 3,342.5 kJ/kg enthalpy. If this steam was expanded in a turbine to 10 kPa condensing pressure, 90% dryness fraction, and 2,345.5 kJ/kg enthalpy, its work output is:

$$W_{ejector} = m_{ejector} \times (h_{ejector} - h_{conenser}) = 2.5 \cdot \frac{(3,342.5 - 2,345.5)}{1,000} = 2.4925 \text{ M}$$

So, the total work loss by the steam supplied to one 15 MIGD (789 kg/s) is:

$$W_{th} = W_{de} + W_{ejector} = 42.6 + 2.5 = 45.1 \text{ MW}$$

or

Table 1
Technical specifications of Shuaiba North GTCC power-desalination plant

Gas turbine, GT	GE912FA
No. of units	3
Type of fuel	Natural gas
LHV, kJ/kg	47,806
Gross output, MW	215.5
Ambient temperature, ˚C	50
Humidity, %	30
Pressure, bar	1.013
HRSG, type	Natural circulation
No. of HRSG	3
Integral type de-aerator	3
HRSG blow down, %	1
Steam turbine, ST	BPST
No. of ST	1
Gross capacity, MW	215.7
Cooling seawater temperature, ˚C	33
Desalination	MSF
No. of units andcapacity	3×15 MIGD
Gas turbine combined cycle, GTCC	
Gross GTCC output, MW	862.2
Net GTCC output, MW	819.7

$$W_{\rm th} = \frac{45,100\ \text{kW}}{789\,\frac{\text{kg}}{\text{s}}} = 57.16\,\frac{\text{kJ}}{\text{kg}} = 57.16\,\frac{\text{kJ}}{\text{kg}} \times \frac{1,000\,\frac{\text{kg}}{\text{m}^3}}{3,600\text{s}} = 15.9\,\frac{\text{kWh}}{\text{m}^3}$$

Then, the mechanical energy equivalent to thermal energy consumed to produce 45 MIGD (2,367 kg/s) desalted seawater (DW) is:

$$W_{\rm eqt} = \left(57.16\,\frac{\text{kJ}}{\text{kg}}\right) \times \frac{2,367\,\frac{\text{kg}}{\text{s}}}{1,000\left(\frac{\text{kW}}{\text{MW}}\right)} = 135.3\ \text{MW},\ \text{or } 3.0\ \text{MW/MIGD}$$

Since the pumping energy of the MSF is in the range of 4 kWh/m^3 (14.4 kJ/kg), the total equivalent mechanical energy (counting for pumping and thermal energy) to produce one m^3 of desalted water is:

$$W_{\rm eq} = W_{\rm th} + W_{\rm p} = 15.9 + 4 \cong 20\,\frac{\text{kwh}}{\text{m}^3} = 72\,\frac{\text{kJ}}{\text{kg}}$$

This means that the Shuaiba CC equivalent power output for 3 GT (3 × 215.5 MW = 645.5 MW) + 1 BPST of 215.7 MW + 3 MSF producing 45 MIGD is similar to that CC of 3 GT (3 × 215.5 MW) + 1 ST of 350.7 MW = 997.2 MW.

5. ISCC efficiency and solar field

5.1. Estimation of the solar section thermal efficiency

In the suggested arrangement, the solar steam joins the HRSG steam in the HRSG's steam drum, which has approximately the same steam pressure. The two flows, combined in the drum, then go through the HRSG super-heater.

The feedwater returning to the HRSG is at relatively high temperature of 142˚C (Fig. 17(b)). Part of this water should return to the SSG, where it becomes saturated liquid, at 290.7˚C, boiled to saturated steam. This saturated steam is directed to the steam drum of the HRSG. So, the SSG produce steam at pressure higher than 75 bar in order to be mixed with the steam drum of HRSG.

So, the SGG inlet liquid water condition is at 142˚C, with 593 kJ/kg specific enthalpy (h) and 1.75 kJ/kg K specific entropy, (s). It leaves the SSG as saturated vapor condition of 75 bar, 290˚C, 2,765 kJ/kg enthalpy, 5.77825 kJ/kg K specific entropy, s. This means that the average temperature at which heat is added in the SSG is:

$T_{\rm h}$ (average) is $\Delta h/\Delta s$ = 539.2 K

The standard heat rejection temperature in the PP condenser in Qatar cooled by once through seawater is about 320 K. If the heat gained by SE was driving the ideal Carnot cycle, its efficiency would be:

η(Carnot) = 1 – (320/539.2) = 0.4065

By assuming the ratio of actual power out from actual heat engine to that Carnot cycle is equal to 0.9 due to mechanical cycle losses, then the net efficiency of the actual cycle operated by steam generated by the SSG is almost 0.36.

This means that for a cycle producing 54 MW equivalent work (representing the increase of both ST and desalting capacities output), the required heat input by the solar steam is equal to 150 MW thermal (MWt). The 54 MW equivalent work is an assumption to be checked later after finding the required solar field. Then, it is required to figure out a solar field capable of delivering 150 MW to the SSG. The efficiency of SPPs using PTC is in the range of 18%, and then the collector efficiency (heat gained by the SSG to incident solar energy) is usually in the range of 0.5. The use of 0.5 collector efficiency gives the required incident SE in the range of 300 MWt (Table 2) [20]. This gives the electricity to solar efficiency equal 18%.

5.1.1. Solar field sizing

For nominal conditions of maximum incident solar radiation of 950 W/m^2, and considering solar multiple of 1.2, the required collectors' aperture area is:

$$\frac{300 \times 1,000}{0.95} \times 1.2 = 378,947 \text{ m}^2 \text{ or } 7,579 \text{ m}^2/\text{MW}$$

This results match with information obtained from ISCC Hassi R'mel (ISCC Hassi R'mel) in Algiers, where power output is 25 MW, and 183,860 aperture area, or 7,354 m^2/MW [17].

So, the required PTC solar field would have 378,947 m^2 aperture area. The solar field is made up of parallel SCA. A schematic of one assembly is given in Fig. 18 [21]. Each four SCA make up a single circuit of cold to hot HTF where two SCAs are aligned end-to-end in a common row and connect to another row of two SCAs making the loop (Fig. 19) [22].

There are two commercial types of SCA; the first has 100 m length and 5 m aperture width, i.e. has aperture area of 500 m^2/SCA. The second has 150 m length and 5.45 m aperture width, i.e. has aperture area of 500-m^2/SCA 817.5 m^2/SCA. The number of SCA should be four multiples the number of loops (e.g. 8, 16, 32, …) and the number of loops should be

Table 2
Itemized solar collectors' losses to calculate collectors' efficiency [20]

Loss	Open trough	Closed trough	Comments
Cover reflection loss	1	0.95	Open trough has no cover. Closed trough has a cover with anti-reflection treatment
Mirror reflectivity	0.93	0.93	Equal quality mirrors
Glass tube reflection loss	0.95	0.95	Equal quality tubes, treated anti-reflection
Intercept factor	0.98	0.98	Equal optical precision supposed
Receiver absorptivity	0.95	0.95	Equal quality receiver surface
Incidence angle cos effect	0.82	0.99	Open trough is horizontally installed, latitude 40˚. Closed trough is optimally tilted north-south axis, with tilting angle adjusted 2 or 4 times a year
End and join loss	0.9	1	Open trough has end loss and loss on receiver supporting structure. No such losses for closed trough
Glass tube multiple travel	0.995	0.99	A small amount of light travels several times through the glass tube. This is slightly more important for the closed trough due to a glass tube of larger diameter
Dust loss	0.94	0.98	Light to an open trough travels 3 times through dust-coverable surfaces. Only once for closed trough
Row-to-row shading	0.98	0.95	Closed trough deliberately adopts a more condensed row-to-row distance, prompted by its lower cost, in order to reduce land use and piping cost The data result from a computer simulation taking into account the atmospheric attenuation and the Sun's angle
Thermal capacity	0.95	0.99	The big open trough has a thicker receiver, hence a higher thermal capacity per unit aperture area. Heat corresponding to the thermal capacity is lost after sunset or cloud coverage. The thermal capacity is 0.36 Wh/m^2 K, or 126 Wh/m^2 for a temperature elevation of 350℃. Assuming an average collection of 2.5 kWh/m^2 per period of sunshine, the loss represents 5% This loss is 6 times less for the smaller closed trough
Efficiency before thermal loss	52.8%	70.6%	Efficiencies above are multiplied; loss below is subtracted
Thermal loss	10%	10%	Assume 800 W average incoming light intensity and 80 W/m^2 thermal loss for both cases
Final efficiency	42.8%	60.6%	This is the efficiency with respect to direct normal insolation

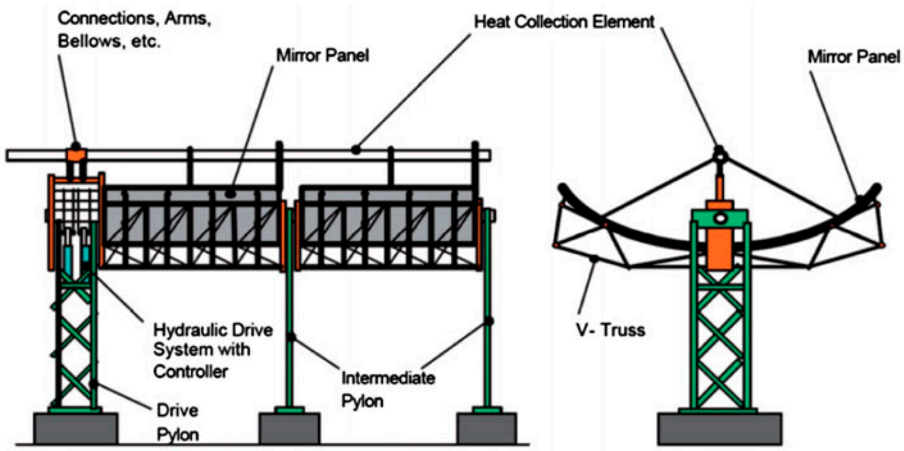

Fig. 18. Solar collector assembly (SCA) [21].

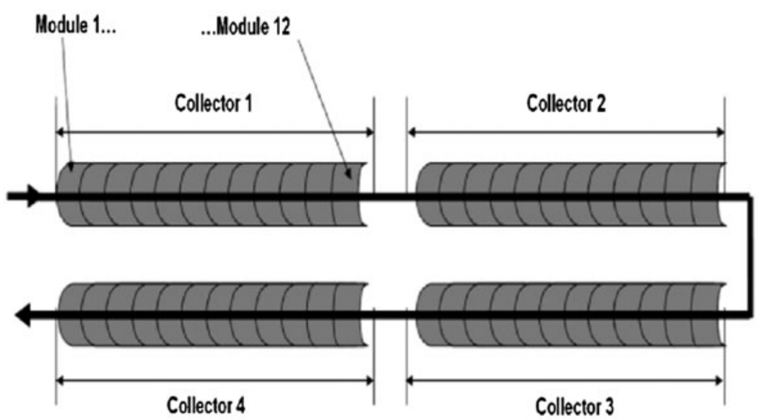

Fig. 19. Solar loop configuration for solar field cooled by Therminol VP-1 [22].

even number when they are arranged along both sides of the power block for large solar field; on any number if arranged on one side of the power block. So, the approximate required number of the SCA is 378,947/817.5 = 463.5. The number of SCA can be taken as 364, which accepts being divided by 4. The number 4 is the number of the SCA in one loop. Then, for four SCA per loop, the number of loops would be 116. The collectors are to be connected in rows oriented north-to-south rows and track the sun from east to west over the course of a day. Sufficient space is to be left between the SCA rows to allow for maintenance access, and to prevent one row of collectors from shading the adjacent row. A distance at least equal to double the width of aperture (10.9 m), or say 12 m should be left between row to allow water spraying cleaning cars to pass through SCA. Fig. 20 [23] gives an idea about the distance required between two rows of SCA, and shows water cleaning car passing through two rows. Fig. 20 indicates that each loop would need land area of width = four times the aperture width or, 36 m, and length of twice the SCA of 150 m, plus say 10 m from each SCA side or 330 m, or 11,880 m^2. In practice, the land area is around four times the

Fig. 20. Trough reflector cleaning at SEGS [23].

aperture area, or 11,5,494 m^2. Since the number of loops is 116, the required solar field land area is $11{,}880 \times 116 = 1{,}378{,}080$ m^2.

An example of the solar collector is the Flagsol SKAL-ET 150, the dimensions of the solar collector are 5.77 m for aperture width, 1.71 m for focal length, 148.5 m for CSA length, and 12 m mirror length per collector module. The geometric concentration is 82. If the HCE length is 4,060 mm, then around 18,379 HCE elements are required [12].

The final combination of the solar field with the CC is shown in Fig. 21. In this figure, saturated solar steam supply from the solar field is introduced to the steam drum, and both streams of solar steam and HRSG is directed to the final super-heater. The feedwater return to the solar field is extracted for the de-aerator as shown in Fig. 21.

The final ST and desalination outputs increase, and the mass flow rate of the solar steam (MS) can be calculated as:

$$(\text{SSG}) = 150 \times 1{,}000 = \text{MS} \times (2{,}765 - 593),\ \text{MS} = 69.06\ \text{kg/s}$$

This solar steam is to be delivered to the three HRSG, or 23.02 kg/s each HRSG.

The introduction of solar steam to the HRSG to raise its enthalpy from 2,765 kJ/kg (saturated condition at 75 bar) to 3,550.7 kJ/kg (of super-heated condition at 500°C) will consume part of the heat delivered to the HRSG. This heat is equal to:

$$23.02 \times (3{,}550.7 - 2{,}765)/1{,}000 = 18.087\ \text{MW}$$

This heat will decrease the original water mass flow rate in each HRSG. The 18.087 MW heat gain by solar steam in each HRSG is to be deducted from the HRSG capacity of 288.82 MW, and will decrease the mass of HRSG water flow m_s.

Then $288.82 = 18.087 + m_s\ (3{,}550.7 - 599.3)/1{,}000$, $m_s = 91.73$ kg/s, and the new steam flow rate through the ST is:

$$3 \times 91.73 + 69.06 = 344.25\ \text{kg/s}$$

This is compared to the original mass flow rate of 293.58 kg/s to the ST, or the mass flow rate increase

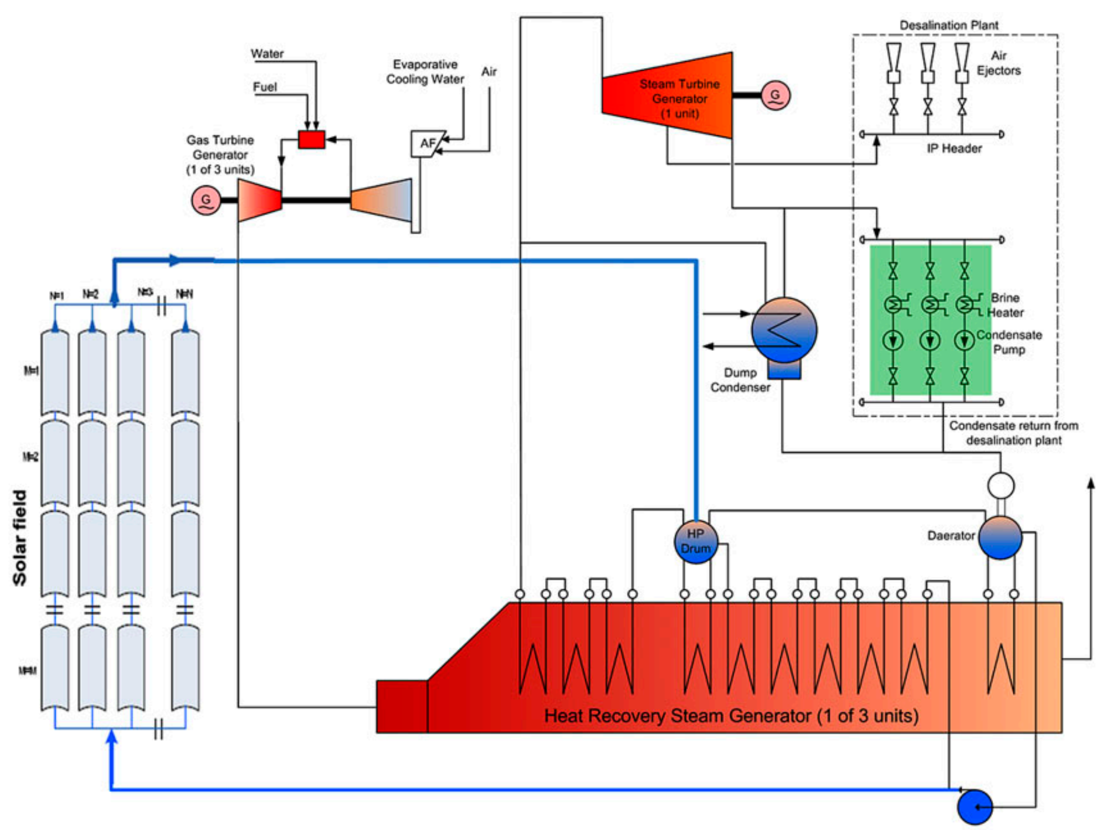

Fig. 21. Final combination of the solar field with the CC.

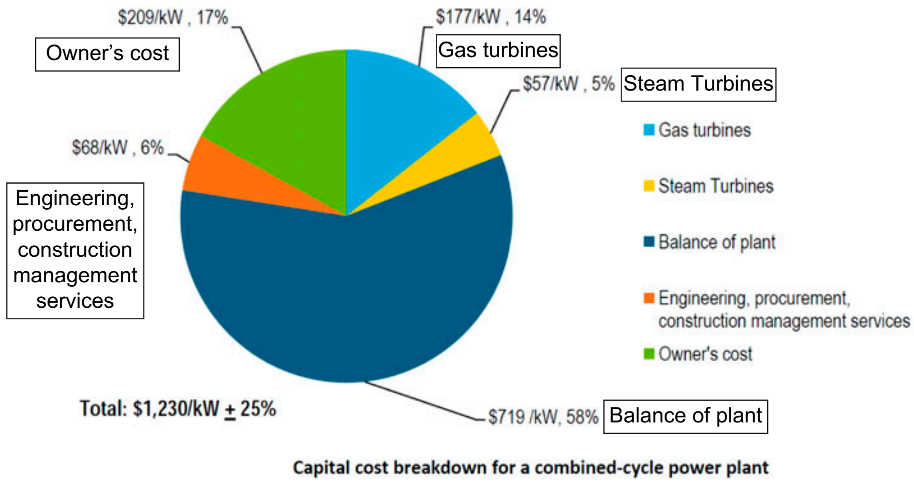

Fig. 22. Capital cost breakdown of combined GT-steam turbine combined cycle [24].

ratio is 347.57/293.58 =1.17, and this would increase the ST power output by 17% or from 215.7 MW to 252.4 MW, or 36.67 MW increase. Similarly, the steam supplied to the desalting plants will be 1.17 times the original steam supplied, as well as the desalination output. Then the increase of the desalination output would be 7.65 MW.

Now, the new CC plant consisting of 3GT × 215.5 MW + 1 ST of 252.4 MW + MSF units producing 51.75 MIGD is equivalent to:

$$3GT \times 215.5\text{ MW} + 1\text{ ST of }252.4\text{ MW} + 51.75 \times 3(\text{MW/MIGD}),\quad \text{or}$$

3GT × 215.5 MW + 1 ST of 407.65, a total equivalent output of 1054.15 MW.

This is to be compared with the original CC before adding the solar field of total 997.2 MW. This shows 56.95 MW equivalent power output increase (36.7 MW for the ST plus 6.75MIGD × 3 = 20.25 MW for desalting plant output increase).

5.1.2. Cost increase

Concerning the involved cost to transfer the CC to ISCC, it is noticed that the capital cost for the CC cycle is $1,230/kW, with capital cost breakdown as shown

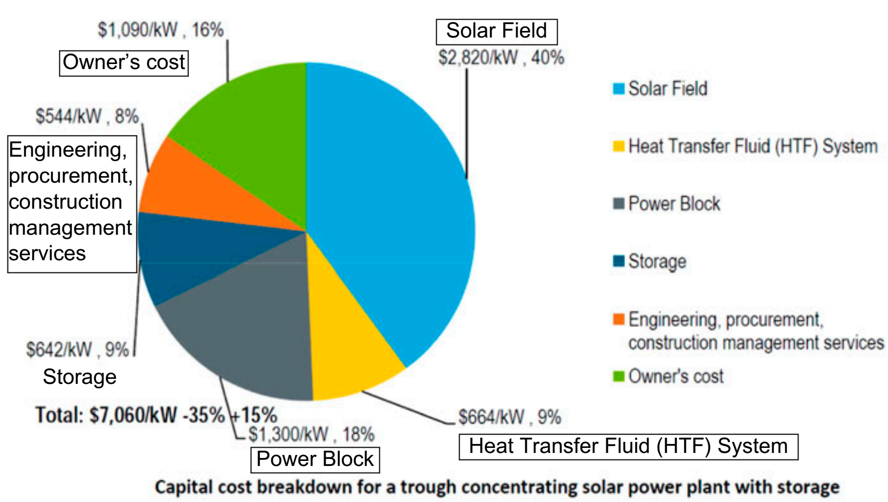

Fig. 23. Capital cost breakdown of thermal CSP solar power plant using PTC [24].

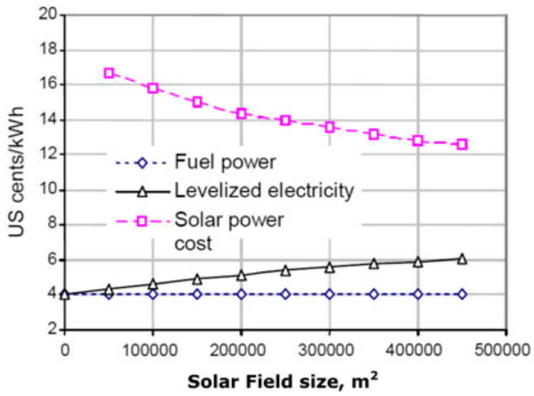

Fig. 24. Power costs vs. size of solar field, without subsidy [19].

in Fig. 22. So, increasing the capacity of the CC plant about 56.95 MW would cost $70.048 Million (M), without including the cost of solar field cost [24].

The solar field cost is $2,820/kW for solar collectors and $664/kW for HTF, or $3,484/kW total cost, as shown in Fig. 23 [24]. So, the additional cost for adding the solar field to generate more 56.95 MW of equivalent work to the power cycle is $198.414 M. So, the total cost to transfer the CC to ISCC, (including the increase of 56.95 MW to the CC and the solar field) is $268.46 M, or $4.714/MW.

This is to be compared with $7.06 M when solar-alone plant was built. This shows that the incremental cost of larger ST is much lower than building a stand-alone solar power.

These results match with results obtained from [19] and presented in Fig. 24.

6. Conclusion

Qatar declared that by 2020, at least 2% of its EP generation should be by solar energy. This means that SPP of at least 640 MW capacity should be operational by 2020. Among the SPP alternatives to be built is the ISCC. In this paper, the main characteristics and equipment of CC are given. Then, the ISCC is introduced and its merits and examples are given. Transformation of well-known CC integrated with MSF desalting plant in the Gulf area to ISCC by adding solar field and increasing the capacity of both the STs and desalination plant is demonstrated. The additional cost was calculated and compared with using solar-alone power plant with Rankine cycle.

Abbreviations

BPST	—	back pressure steam turbine
CC	—	combined cycle
CPDP	—	cogeneration power desalting plants
CSP	—	concentrated solar power
DSG	—	direct steam generator
DW	—	desalted seawater
EP	—	electric power
FF	—	fossil fuel
GHG	—	greenhouse gases
GT	—	gas turbine
GTCC	—	gas turbine combined cycle
HCE	—	heat collector elements
HP	—	high pressure
HRSG	—	heat recovery steam generator
HTF	—	heat transfer fluids
ISCC	—	integrated solar combined cycle
LFC	—	linear Fresnel collectors
LP	—	low pressure
MED	—	multi-effect distillation
MIGD	—	million imperial gallons per day
MSF	—	multi-stage flash
NG	—	natural gas
PPs	—	power plants
PTC	—	parabolic trough collectors
SCAs	—	solar collector assemblies
SE	—	solar energy
SPP	—	solar power plant
SS	—	solar steam
SSG	—	solar steam generator
ST	—	steam turbine
TIT	—	turbine inlet temperature

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