Solar Integrated Unit to Reduce Power and Cooling Penalty of a Natural Gas Combined Cycle Plant integrated with a Carbon Capture System

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Abstract. Integrating solar assisted plant with a carbon capture unit to provide the required reboiler heat duty has been recently investigated extensively to reduce the negative impact of carbon capture unit on plant performance. However, using solar assisted plant to provide the required energy in the reboiler of the stripper leads to increase plant’s condenser duty unfavorably. In the present study, two novel configurations have been proposed for a concentrated solar assisted power plant to generate the required reboiler duty in the stripper of a post-combustion carbon capture unit (PCCC-SAPP) in a (630 MWe) natural gas combined cycle (NGCC) power plant to reduce both the condenser duty and power penalty of the plant simultaneously. In the present study, both the solar plant and plant’s low-pressure steam (LPS) are contributing to deliver the required reboiler thermal energy in the first method while the extraction is from the cooling system load in addition to the solar plant in the second method. Solar contribution factor (SCF) is the main criteria which has been used to evaluate the findings. Condenser duty with its associated water requirements, power penalty, and the required solar field land area are the parameters which have been investigated in the preset study. It has been found that the second configuration method has better impact on the performance of the plant and its associated cooling system than the first configuration method where zero power penalty is consumed in the second configuration as well as reducing the condenser duty with its related water usage amounts. In addition, it was shown that raw water withdrawal and consumption...
amounts in term of \((\text{gal/min})/\text{MW}_{\text{net}}\) decrease with increasing SCF in the first configuration where raw water withdrawal and consumption amounts are 7.23 \((\text{gal/min})/\text{MW}_{\text{net}}\), and 5.17 \((\text{gal/min})/\text{MW}_{\text{net}}\) at SCF equals to 0 while these amounts reach to 6.74 \((\text{gal/min})/\text{MW}_{\text{net}}\) and 4.82 \((\text{gal/min})/\text{MW}_{\text{net}}\) at SCF of 0.95 respectively. On the other hand, these amounts increase with increasing SCF in the second configuration where water withdrawal and consumption values approach 6.75 \((\text{gal/min})/\text{MW}_{\text{net}}\), and 4.92 \((\text{gal/min})/\text{MW}_{\text{net}}\) at SCF equals to 0 while the amounts are equal to 7.93 \((\text{gal/min})/\text{MW}_{\text{net}}\) and 5.81 \((\text{gal/min})/\text{MW}_{\text{net}}\) at SCF equals to 0.95 respectively despite that condenser duty is increasing in the both methods. This comes from the fact that the net produced power is increasing in the first scenario with SCF while it keeps constant in the second scenario. Furthermore, the relationship between the solar field’s required land area and solar direct normal irradiation (DNI) was investigated in the present paper under four different SCF; 0.2, 0.4, 0.6, and 0.8. It was found that reducing the solar field’s required land area requires increase in the DNI and decrease in the SCF where the reboiler heat duty is constant in the PCCC and the relationship is almost exponential. The validation was performed with an American governmental report (NETL, 2015) showing that the presented results has a significant agreement with the report.

**Keywords:** Carbon capture unit, Solar assisted power plant, Natural gas combined cycle, Carbon capture reboiler duty, Water energy nexus in power plant, Cooling efficiency in thermal power plants.

1. **Introduction**

Adding carbon capture unit to thermoelectric power plant almost doubles water requirements in the unit (Zhai and Rubin, 2011). In addition, integrating this unit causes power penalty because of the extracted LP steam from the entrance of the LP turbine to be used for solvent regeneration in the stripper reboiler of the capture unit. On the other hand, this extraction from the LP steam leads to reduce the main plant’s condenser duty by about 30% (Saif W. M. et al., 2019). Although the net waste heat duty is increased because of the additional carbon capture duty, adding the carbon capture unit has an advantage on the main plant’s condenser duty by reducing it. To avoid a such penalty in the net produced power, solar power assisted plant would be integrated with the carbon capture unit to be used for solvent regeneration in the stripper’s reboiler instead of extracting from the LP steam and causing the penalty in the produced power. However, using this solar assisted power plant has two disadvantages; first, large area is required for the solar plant and its related accessories, and this area is involved directly with the net produced thermal energy by the solar plant. This means that increasing or decreasing the produced thermal energy by the solar plant leads to increase or reduce plant’s area directly. The second disadvantage is as there is no required extraction from the LP steam, the main plant’s condenser duty would not be reduced by which the net cooling duty of the plant, including the effect of the carbon capture, is increased remarkably leading to increase in the water usage amounts of the cooling system. Therefore, new approaches should be investigated to reduce both plant’s area and plant’s main condenser duty properly and simultaneously in parallel with reducing the penalty in the turbine’s produced power. The present study investigates two approaches to reduce the condenser duty with its related water requirements in a NGCC integrated with a PCCC and a solar assisted power plant to regenerate the solvent in the reboiler of the capture unit. The concept of using carbon capture solar assisted power plant has been studied extensively in the literature. Cau et al. (2014) studied the economic and technical effect of producing three types of superheated steam by a concentrated solar power plant on a performance of ultra-supercritical (USC) steam power plant integrated with a carbon capture unit. These streams are LP steam for the solvent regeneration in carbon capture unit, IP steam and HP steam to be used in the steam cycle of the (USC) steam plant. It was shown that the LP steam production has the worst impact on the performance of the (USC) plant than the IP and HP steams production. In term of condenser duty, producing the IP and HP...
steam to the (USC) steam cycle shouldn’t go over a certain limit because any undesirable increase in steam production may lead to increase the condenser duty over the favorite limits because of increasing in the steam mass flow rate causing plant power shortage. Liu et al. (2016) conducted a research involves to a technical and economic investigations for using two different solar assisted power plants to be used for solvent regeneration of ammonia-based carbon capture unit; vacuum tube (VT), and Parabolic Trough Collector (PTC). Studying the effect of different regions in China corresponding to its DNI (Direct Normal Irradiation) and weather data has implemented in this work too. It was demonstrated that using the (VT) is the most feasible approach technically than the (PTC). Regarding the economic aspect, the prices of the solar assisted plants should be reduced to a specific limit per area to be viable economically. Mokhtar et al. (2012) investigated an economic feasibility method to utilize solar thermal energy in contributing with LP steam extraction for solvent regeneration in post-combustion carbon capture unit which being integrated with a 300 MWe pulverized coal-fired power plant installed in New South Wales, Australia by using actual weather data and electricity prices. It was found that solar thermal energy can be viable for solar collector price equals to 100 $/m2 when the optimal solar load fraction equals to 22%. Zhai et al. (2018) used thermo-economic theory to evaluate two configurations of solar thermal power plants to be integrated with 1000 MWe coal-fired power plant equipped with MEA based-carbon capture unit. The first design of the solar thermal plant was configurated by utilizing the solar power energy to superheat the HP feed water stream in the steam cycle of the coal-fired power plant where this characterized by (SA-PG-CC) while LP steam extraction was used for solvent regeneration in the carbon capture reboiler. The second one was designed to be used in the stripper reboiler directly for solvent regeneration and characterized by (SA-CC-PG). Both cases were compared with the referenced case which was not integrated with the solar power plant (PG-CC). Overall, the first scenario (SA-PG-CC) is the better choice from the performance point of view and economic point of view.

Number of studies have been conducted to evaluate the net water usage in solar power plants. Erica Suzanne (2015) has developed an optimization model to minimize water and land requirement in power plants by replacing it with three renewable energy technologies; wind, Photo Voltic (PV) solar cell, and Collector Solar Parabolic (CSP). She found that dry CSP consumes higher water without considering land constraint and less with considering it. Saria Bukhary et al. (2018) has performed an evaluation for water and land usage in a solar development system in the U.S in addition to analyzing its associated CO2 emissions. STELLA dynamic system tool, SAM, and Solar DS tools were used to evaluate the cost effectiveness and the efficiency of the system. It was found that PV technology takes the smallest water requirement comparing to CSP system. Regarding CSP systems, it was demonstrated that CSP tower takes the largest land demand, and CSP wet cooling takes the largest water requirement with a good agreement with the literature. X.D. Wu, and G.Q. Chen (2017) had a novel investigation by including water usage through construction stages of solar plant infrastructure in the total water amount by using Input-Output data. It was found that by including this water, solar plant will not be feasible in term of water saving. Integrating solar assisted plant with a pre-combustion and oxy combustion was not absent from the literature scientific works and researches. Li Y. et al., (2013) investigated using solar energy sources to be employed for producing syngas/hydrogen through the pre-combustion CO2 capture processes. Heliostat collector was used as a medium energy source to separate the Methane from the hydrogen in a membrane while parabolic trough collector was used to regenerate the steam as a low solar energy source. Using solar energy as an external energy source to increase the efficiency of the chemical looping system in the oxy-combustion carbon capture was investigated by Hong and Jin (2005). It was found that using the solar energy in oxy-combustion system gives the possibility to store the solar energy chemically where it can be used during the absence of solar radiation at night.

In the present study, two novel configurations of a post-combustion carbon Capture-Solar assisted (PCCC-SAPP) power plant have been investigated regarding its impact on plant performance and condenser duty of a NGCC power plant. New parameters have been studied through the present work which have not been studied yet including the effect of the integrated solar units on the water usage amounts in term of (gal/min)/MWnet and their effect on the required land area of the solar field. The first configuration is installed by contributing two LP steam streams to be used for solvent regeneration in the stripper; the extracted steam from the LP turbine, and the solar superheated LP stream. The second design is a novel design in term of carbon capture - solar assisted study. This design is configurated by
extracting heat from the condenser unit to be used and contributed for solvent regeneration beside the solar part contribution by which the net condenser duty of the main plant’s condenser would be reduced. The solar field contribution factor (SCF) has been taken in this study as a criterion for the comparison study. The technical impact of these two configurations on condenser duty with its related water usage, plant power penalty, and solar field area has been studied in the present work. COCO software has conducted in this research to perform all the simulations with enabling Excel Workbook Sheet to implement all the governing equations which be used in the solar field calculations. Concentrated solar collector was used as the solar assisted power plant in the present work.

2. The Effect of post-combustion carbon capture on the plant and cooling system performance.
Carbon capture unit is very necessary to reduce CO\textsubscript{2} emissions from thermoelectric power plants by which its negative impact on global warming would be mitigated. On the other hand, adding this unit requires penalty on the net waste heat duty and the net produced power. Fuel gas stream reacts with MEA solvent in the absorber to absorb most of the CO\textsubscript{2} content in the gas stream to generate a rich CO\textsubscript{2}-Sorbert component which would be separated in the stripper by applying a massive heat amount. A high heating value comes from a reboiler which is integrated in the capture unit’s stripper to regenerate the solvent and separate the CO\textsubscript{2} with a vapor content. LP steam is extracted from the entrance of the LP turbine to be exploited in the stripper’s reboiler by which the net produced power is reduced. However, extracting from the LP turbine leads to reduce the cooling duty of the main condenser by about 30% according to Saif W. M. et al. (2019).

3. Post-combustion carbon capture solar assisted plant (PCCC-SAPP).
To avoid such a penalty in the produced power, solar assisted power plant would be integrated to generate the required thermal energy for solvent regeneration in the stripper instead of extracting from the LP steam so that there will be no penalty in the produced power. Although using solar assisted power plant reduces plant power penalty, there will be no reduction in the plant’s main condenser duty beside the required large land area for the solar plant and its accessories. To reduce both the penalty and condenser duty simultaneously in the NGCC plant which is equipped with the carbon capture unit, two novel configurations have been investigated in the present study by integrating a concentrated solar collector assisted plant with a post-combustion carbon capture (PCCC) unit as being detailed in the next two sections.

3.1. LP steam turbine extraction configuration (First Configuration).
Thermal energy provided by the concentrated solar collector plant beside thermal energy provided by the extracted LP steam from the LP turbine are contributing to regenerate the solvent and separate the CO\textsubscript{2} in the stripper’s reboiler of the PCCC unit. Solar contribution factor (SCF) is the criterion to find the most viable value by which power penalty, condenser duty with its related water usage, and solar plant required area are reduced in a proper way. The distributed heat between the extracted LP steam and solar thermal power plant can be achieved by controlling the net steam mass flow rate. To control solar thermal energy simply and in a proper manner, it has been assumed that the temperature and pressure of the steam at the solar plant outlet are equal to these values for the extracted LP steam from the LP turbine. Thus, the only factor which would control the solar thermal energy is the collector’s medium fluid mass flow rate. Figure 3.1 shows the first configuration of the concentrated solar collector which being integrated with the PCCC’s reboiler and the extracted LP steam from the LP turbine.

3.2. Condenser duty extraction configuration (Second Configuration).
In this scenario, there would be no LP steam extraction form the LP turbine. Therefore, there would be no penalty in the LP turbine’s produced power. On the other hand, the net waste heat duty in this scenario is less than the net waste heat duty in the first scenario as a result of reducing the main condenser duty by about 30% although that the water requirements per power unit is increasing in this system in contradiction with the first scenario where net produced power is constant in the present configuration while is changing in the first one. To reduce both the condenser duty and the required solar land area with consuming zero penalty, a novel design would be proposed by sharing part of the condenser duty to superheat the medium fluid stream to be contributing beside the solar superheated steam for solvent regeneration in the reboiler by which plant’s main condenser duty can be reduced for the same level of the first scenario or less in addition to reducing the solar required land area because of reducing its...
thermal energy contribution factor (SCF) as being shown in figure 3.2. In this configuration, the total thermal energy duty in the reboiler would be distributed between the gained heat duty from the condenser and the solar thermal energy part.

Figure 3.1. shows the first proposed PCCC-solar assisted plant (First Configuration).

Figure 3.2. shows the second proposed PCCC-solar assisted plant (Second Configuration).
4. Cooling water model including the effect of the carbon capture.
The net cooling water mass flow rate in the plant’s cooling system including the effect of carbon capture unit can be calculated according to Zhai and Versteeg (2011) as:

\[ m_c = \frac{(Hr-3600).MWg.1000.(1+\eta_{aux})-q_r^{CSS}}{C_p\Delta T_w.1000} + m_c^{CSS} \quad (1) \]

Where \( Hr \) is the steam cycle heat rate (kJ/kWh), 3600 is a unit conversion factor, \( m_c \) is the total recirculated cooling water (kg/h), \( m_c^{CSS} \) is the used cooling water in the CCS unit, \( MWg \) is the plant gross electric power, \( q_r^{CSS} \) is the extracted heat for solvent regeneration in the cooling system (kJ/h) where (Zhai and Versteeg, 2011):

\[ q_r^{CSS} = q_{reboiler}^{Duty} + q_{aux}^{CSS} \quad (2) \]

As can be seen, most of the carbon capture duty comes from the reboiler. \( \Delta T_w \) in Eq. (1) is the temperature difference between the inlet and the outlet of the condenser (oC), \( \eta_{aux} \) is the auxiliary loading (%), \( C_p \) is the water specific heat (kJ/kg.oC). In addition, as the used cooling system in the present work is wet cooling system, raw water withdrawal and consumption can be determined according to Saif W. M. et al. (2019) as:

**Raw water consumption**

\[ \text{Raw water consumption} = \frac{\text{Evaporated losses}}{\text{Net Produced Power}} \quad (3) \]

**Evaporated losses**

\[ \text{Evaporated losses} = 0.0008 \times \Delta T_{tower} \times m_c \times 1.8 \quad (4) \]

Where \( \Delta T_{tower} \) is the temperature difference across the cooling tower.

**Blowdown losses**

\[ \text{Blowdown losses} = \frac{\text{Evaporated losses}}{\text{COC} - 1} \quad (5) \]

Where COC is the number of cycles of concentration where four (4) COC are considered in the present work. Furthermore, draft loss is assumed to be equal to 0.1% of the recirculated mass flow \( m_c \) in the present study.

Finally, raw water withdrawal can be calculated as (Saif W. M. et al. 2019):

**Raw water withdrawal**

\[ \text{Raw water withdrawal} = \frac{\text{Evaporated losses} + \text{Blowdown losses} + \text{Draft Losses}}{\text{Net Produced Power}} \quad (6) \]

As it can be seen from equation (1) that extracting heat from the LP turbine entrance has an advantage on plant condenser heat duty and consequently on net water requirements of the system in spite of its impact on reducing turbine’s net produced power. Despite utilizing solar assisted plant thermal energy for solvent regeneration in the stripper leads to reduce power penalty, condenser duty and its associated cooling water mass flow rate would be increased according to Eq. (1). In addition, the related solar land area is involved directly with the solar plant’s produced thermal energy.

5. Solar field and solar contribution factor (SCF) calculations.

To make using solar assisted plant more viable in term of water and condenser duty saving, penalty decreasing, and solar land area reducing, two proposed configurations have been investigated in the present study to share the reboiler required heat duty between the solar thermal energy and the extracted heat form the LP turbine entrance one time and from the condenser heat duty another time as have been mentioned in the previous two sections. Therefore, reboiler duty \( q_{reboiler}^{Duty} \) (W) from Eq. (2) can be calculated as:

\[ q_{reboiler}^{Duty} = q_{soil}^{therm.energ} + q_{extracted}^{therm.energ} \quad (7) \]

Where \( q_{soil}^{therm.energ} \) is the solar produced thermal energy (W) while \( q_{extracted}^{therm.energ} \) is the extracted thermal energy whether from the LP turbine entrance or from the condenser heat duty (W).

Now, to calculate the solar plant’s required land area, the below steps should be followed (Zhai and
Versteeg, 2011):

\[ q_{\text{solr, energy}} = m_{\text{fluid}} \times (h_{\text{out}} - h_{\text{in}}) \]  \hspace{1cm} (8)

\[ q_{\text{solr, energy}} = q_{\text{rec}} - q_{\text{losses}} \]  \hspace{1cm} (9)

\[ q_{\text{losses}} = F \times Ac \]  \hspace{1cm} (10)

Where \( m_{\text{fluid}} \), \( h_{\text{out}} \) and \( h_{\text{in}} \) are the mass flow rate and the inlet and the outlet enthalpy of the solar superheated fluid stream, \( q_{\text{rec}} \) is the heat transferred to the collector receiver, \( F \) is losses factor. In the present study, it has been assumed that \( F \) is equal to (0.008 W/m²°C).

On the other side,

\[ q_{\text{rec}} = Q_{\text{Solr}} \times \eta_{\text{opt}} \times IAM(\theta) \times \eta_{\text{END}} \times \eta_{\text{CLN}} \]  \hspace{1cm} (11)

\[ Q_{\text{Solr}} = DNI \times Ac \]  \hspace{1cm} (12)

Where \( \eta_{\text{opt}} \) and \( \eta_{\text{CLN}} \) are the optical and cleanliness efficiencies provided by the manufacturer, \( DNI \) is the direct normal irradiation (W/m²). \( IAM(\theta) \) is the incident angle modification, \( \eta_{\text{END}} \) is the end losses efficiency, and this can be calculated as (Zhai and Versteeg, 2011):

\[ \eta_{\text{END}} = 1 - \frac{F_L}{M_L} \tan(\theta_L) \]  \hspace{1cm} (13)

\( F_L \) is the collector focal length while \( M_L \) is the collector module length. \( \theta_L \) is the longitudinal angle in degree between line perpendicular on the horizontal surface and solar rays’ projection on the collector longitudinal plane. This angle can be calculated as (Zhai and Versteeg, 2011):

\[ \theta_L = \sin^{-1}(\cos(\gamma) \cdot \cos(\alpha)) \]  \hspace{1cm} (14)

Where \( \gamma \) is the azimuth angle between solar ray’s horizontal plane projection and the south side while \( \alpha \) is the elevation angle between solar rays and their projection on a horizontal plane. Figure 5.1. shows a concentrated solar collector configuration showing all the relevant angles and dimensions.

To calculate solar contribution factor (SCF) two different models be would be derived from the two different proposed configurations according to the previous equations. For the first method, the net steam mass flow rate can be calculated as:

\[ m_{\text{rebiir, strm}} = m_{\text{LP, TRBN, EX}} + m_{\text{LP, Solar}} \]  \hspace{1cm} (15)

Where \( m_{\text{rebiir, strm}} \) is the net steam mass flow rate which comes from both the LP extracted steam and the solar superheated steam to be used in the reboiler while \( m_{\text{LP, TRBN, EX}} \) and \( m_{\text{LP, Solar}} \) are the mass flow rates of steam streams for both the extracted LP steam and the solar superheated steam part respectively. Thus, solar contribution factor (SCF) would be calculated in the present configuration as:

\[ SCF_{\text{first, Conf.}} = \frac{m_{\text{LP, Solar}}}{m_{\text{rebiir, strm}}} \]  \hspace{1cm} (16)

While in the second configuration, the total thermal energy duty in the reboiler would be distributed between the gained heat duty from the condenser and the solar thermal energy part as below: -

\[ Q_{\text{reboiler-duty}} = Q_{\text{Condenser-Duty}} + Q_{\text{Solar-Thermal}} \]  \hspace{1cm} (17)

\( Q \) in Eq. 17 represents the heat duty of the system. Thus, solar contribution factor (SCF) can be calculated in the current design as:

\[ SCF_{\text{second, Conf.}} = \frac{Q_{\text{Solar-Thermal}}}{Q_{\text{reboiler-duty}}} \]  \hspace{1cm} (18)
Figure 5.1. Shows all the relevant angles and dimensions for the concentrated solar collector (Sup A. B. et al., 2015).

6. Results and Discussion.
The effect of solar contribution factor (SCF) on plant’s main condenser duty with its associated water usage, plant’s power penalty, and the required solar field area at different direct normal irradiation (DNI) values under four different SCF; 0.2, 0.4, 0.6, 0.8 would be discussed in this section.

6.1. Result Validation.
The result has been validated for a 559 MWe NGCC power plant by comparing the based plant simulation outputs with a data provided by NETL report (2015). As being shown in the table below.

Table 6.1. Result validation with the NETL report (2015) for the based NGCC equipped with a PCCC unit.

| Parameters for Validation                          | NETL report Result | Present Study Result |
|---------------------------------------------------|--------------------|----------------------|
| Plant Gross Power with PCCC (MWe)                 | 601                | 601                  |
| Steam LHV efficiency with PCCC                    | 33.5               | 33.5                 |
| Net LHV Efficiency with PCCC                      | 50.6               | 50.7                 |
| Condenser Duty Without PCCC (MWth)                | 355.83             | 373.90               |
| Raw Water Withdrawal without PCCC (gal/min)/MWe_{net} | 4.20              | 4.26                 |
| Raw Water Consumption without PCCC (gal/min)/MWe_{net} | 3.30              | 3.32                 |
| Condenser Duty with PCCC (MWth)                   | 246.66             | 260.98               |
| Raw Water Withdrawal with PCCC (gal/min)/MWe_{net} | 7.20              | 7.34                 |
| Raw Water Consumption with PCCC (gal/min)/MWe_{net} | 5.40              | 5.72                 |

It can be seen from table 6.1 that all the main parameters of the simulated NGCC plant, which is integrated with the PCCC unit, have been validated properly with the corresponding data from the report except a minor difference in the values related to the condenser duty and its involved water requirement. This likely happens because of using different thermophysical property method for the saturated steam calculations than the method which was used by the NETL report to calculate the thermophysical properties of the saturated steam.

Table 6.2. shows the main parameters which would be used in the solar field calculations according to Cau et al. (2014).
Table 6.2. represents the main the parameters used in the solar field calculations of the present sturdy.

| The parameters                  | The corresponding value |
|---------------------------------|-------------------------|
| Elevation Angle / Azimuth Angle (degree) | 75.0°, 0.0°        |
| Focal Length (m)                | 7.4                     |
| Module Length (m)               | 45                      |
| IAM (θ)                         | 0.19                    |
| 𝜂_{opt}                         | 0.66                    |
| 𝜂_{C,N}                         | 0.98                    |

6.2. The effect of SCF on plant performance and cooling system performance.

The increase in the solar contribution factor (SCF) means that solar thermal energy is increasing as a part of the reboiler duty in the carbon capture unit. Any raise in the solar part thermal energy has consequences on plant performance where the net produced power would be changed in addition to its effect on the performance of the cooling system as a result according to Eq. (1). Thus, the increase in the SCF leads to a reduction in the power penalty or increase in the net produced power and increase in the net condenser duty. Figure 6.1-a and Figure 6.1-b demonstrate the effect of increasing the solar contribution factor (SCF) on both the plant’s net condenser duty and plant’s power penalty respectively for the proposed scenarios. Figure 6.1-a shows that the increase in the SCF leads to increase in the condenser heat duty for both scenarios. However, the increase in the cooling load for the second scenario is less than the increase for the first one for SCF less than 0.7. This comes from the fact that net produced power and mass flow rate of the LP-steam would not be changed in the second scenario where the extraction will be from the condenser heat duty directly. On the other hand, the increase in the SCF in the first scenario would be accompanied with a change in the net produced power and in the mass flow rate of the LP-steam leading to more increase in the cooling load. While after SCF equals to 0.7, the change in the net produced power and mass flow rate of the LP-steam in the first configuration will not be significant comparing to the second case and the difference in the condenser heat duty would be minor between both designs.

![Figure 6.1-a](image_url)

**Figure 6.1-a** Shows the effect of solar contribution factor (SCF) on the Condenser Duty for both scenarios.
Figure 6.1-b shows the effect of solar contribution factor (SCF) on the power penalty for both scenarios.

Figure 6.1-b shows that power penalty is reduced with increasing SCF in the first scenario while it keeps constant in the second scenario. As has been mentioned before, the reason behind this is that the extraction from the LP-turbine is reduced gradually with increasing the SCF leading to decrease in the power penalty or increase in the net produced power consequently. In contrast, the extraction would be from the condenser heat duty directly in the second scenario without need to extract from the LP-turbine causing zero penalty in the net produced power by neglecting the effect of the back pressure in the condenser.

Figure 6.2 demonstrates the effect of SCF on the net raw water withdrawal and consumption in the integrated wet cooling system for both the first and the second scenarios in term of flow rate unit per power unit. It is shown that increasing SCF leads to reduce these amounts in the first scenario in contrast with the second scenario where these amounts would be increased. This is caused by the increase in the net produced power with increasing the SCF in the first scenario while net produced power keeps constant in the second scenario. Therefore, because the water amounts in figure 6.2 is in term of flow rate unit per power unit where power amount is increased in the denominator for the first scenario and keeps constant in the second scenario, the increase in the SCF leads to a reduction in the water amount per unit power in the first scenario and increase in this amount in the second scenario. This comes as a result of two reasons; first, there is no power penalty in the second scenario leading to a constant produced power with increasing SCF while the increase in the SCF of the first scenario causes reduction in the penalty leading to increase the net produced power as has been demonstrated in figure 6.1-b. However, as increasing SCF leads to increase in the net condenser duty for both scenarios as was shown in figure 6.1-a, the increase in the SCF leads to increase in the water usage amounts without considering the effect of the power unit in the denominator because the consumed water amount relates directly with the net condenser duty.
6.2. Shows the effect of solar contribution factor (SCF) on water withdrawal and consumption.

6.3. The effect of the SCF on the solar field required area.

In addition to its effect on the plant and cooling system performance, SCF has a direct and significant impact on the required solar field land area.

Figure 6.3. Shows the effect of solar contribution factor (SCF) on the solar field land area at different DNI (W/m²) for any of the above studied cases because the required solar energy is constant for both methods.
Figure 6.3. shows the relationship between the required solar field land area and the direct normal irradiation (DNI) at four different SCF; 0.2, 0.4, 0.6, and 0.8. As the figure demonstrates, as DNI increases, the required solar field land area decreases exponentially when the reboiler heat duty keeps constant. This behavior is expected because large DNI, small land area is required when the produced thermal energy keeps constant. However, this relation has been discussed to get an indication about the required solar land area at different SCF and different DNI values. An interesting finding is that a significant reduction in the solar field land area at large DNI values was observed from figure 6.3 as a result of the exponential relationship between the land area and the DNI. In addition, it is noticed from figure 6.3 that as the increase in the SCF leads to increase in the solar field land area expectedly, the differences in the land area values under different SCF at large DNI is much lower than these differences at small DNI values. This likely happens because of the exponential relationship between the solar field land area and the DNI values.

7. Conclusions and recommendation.

Two novel configurations have been proposed in the present work for a solar assisted power plant to be integrated to a post combustion carbon capture unit (PCCC) of a (630 MWe) natural gas combined cycle (NGCC) power plant. The effect of these configurations on the performance of the plant produced power and the cooling system load was investigated in this study. In addition, the effect of the proposed configurations on the required solar field land area has been impeded in the present study too. The results were evaluated in the present work using the SCF as the main criteria. It was shown that the second configuration method is better than the first one regarding condenser cooling load and power penalty reduction. However, water usage amounts in term of flow rate unit per power unit are reduced with increasing SCF in the first method rather than the second one in spite of the increasing in the condenser heat duty with SCF in both scenarios because the net produced power would be reduced with increasing the SCF in the first configuration while it keeps constant in the second configuration as the second configuration consumes zero penalty from the plant produced power. Another interesting finding is that at high DNI values, the required solar land area would be reduced significantly where the smallest area was 0.518 Km² at SCF equals to 0.2 when the maximum solar radiation value reaches 1000 W/m² concluding that the solar assisted plant is more viable in regions provided higher concentrated solar radiation. Finally, the validation with the NETL report (2015) proves the reliability of the results presented in the current paper. For the future work, it is recommended to use different configuration for the second method where this method represent the most feasible case as was proven above. The recommendation is that controlling the SFC factor would be by controlling the mass flow rate of the LP-stream instead of controlling the SCF by the partial heating between the solar and cooling systems.

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