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SUISTAINABILITY OF INTEGRATED SOLAR COMBINED CYCLE SYSTEMS ON THE ENERGY TRANSITION IN ALGERIA

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Declaration

I declare that this thesis report is my own, unaided work, except where it is referred to the authors. It is being submitted for the degree of Master of Energy, Engineering track at the PAU institute of Water and Energy Sciences (including clime change) in Tlemcen, Algeria. It has not been submitted before for any degree at any other university.

Signed on the 28th day of August, 2016 at Tlemcen

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Dedications

All Words will not express the gratitude, love, respect, recognition ... well, it's just that I dedicate this thesis …to ***my dear parents****; dedications cannot express my respect, my eternal love and my account for the sacrifices you made for my training and welfare. Thank you for all the support and love you have shown me since my childhood and I hope that your blessing is always with me. This modest work is the fulfilment of your wishes as formulated, the fruit of your countless sacrifices, although I will never pay you enough. May God, the highest, grant your health, happiness, long life, and ensure that I will never disappoint you.* ***To my adorable sisters*** *for constantly being there whenever I need them.* ***To my dear nephews****, may God keep you and light your way.* ***To all my friends*** *for the continuous supports and encouragements. Please, find in this work the expression of my deepest respect and my sincere affection. To all those who participated in the development of this work to all those I have failed to mention.*

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Abstract

Economic development and high population growth are the causes of the increasing energy demand in Algeria. Algeria relies mainly on the fossil fuels to supply the increasing energy demand. Although this long adopted pattern ensures power accessibility at all times through the cheapest cost, it is unsustainable due to its extremist impact on the environmental emissions and depletion of the resources. Integrated Solar Combined Cycle power plants (ISCCs) among all other renewable energy technologies, composed of a Concentrated Solar Power (CSP) and a Natural Gas Combined Cycle (NGCC) power plant have the potential of replacing conventional power plants to reduce Carbon emissions and to integrate the costs of the solar power.

A literature reviews of the current CSP technologies and their ability for integration into a conventional power cycles was illustrated, the best option was found is Parabolic Trough Collectors (PTC). This study evaluates the performance of the NGCC standalone and with integrating PTC using both configuration (Direct Steam Generation (DSG) and Heat Thermal Fluid (HTF)) in two different climates.

Furthermore, an economic and environmental assessment is conducted in order to choose which configuration and climate are most suitable for the integration. The results have shown that the best levelized cost of electricity (LCOE) in the range of 3.79 to 3.97 c$/kWh and CO_2 emissions saving of 106.092 to 120.301 tons /years were recorded with 20 % solar share using HFT configuration in Bechar compared to 3.78 to 4.06 c$/kWh and CO_2 emissions saving of 106.623 to 141.330 tons /years using DSG configurations in Annaba. To deduce, both technologies in both locations are convenient to be installed. However, using DSG is more suitable solution to reduce CO_2 emissions.

The results from the study indicate that the ISCC plants can pave the way of renewables energies and on the same time reduce the environmental impact in our existing power plant systems.

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List of Abbreviations and Symbols

Abbreviations

CC	Combustion Chamber
CO_2	Carbon dioxide
CRF	Capital recovery factor
CREG	Electricity Regulatory Commission and Gas
CSP	Concentrated Solar Power
DLR	German Space Centre
DNI	Direct Normal Irradiance
DSG	Direct Steam Generation
GT	Gas turbine
HFC	Heliostat field collector
HP	High pressure
HTF	Heat Thermal Fluid
IPCC	Intergovernmental Panel on Climate Change
ISCC	Integrated Solar Combined Cycle power plant
LCOE	Levelized cost of electricity
LFR	Linear Fresnel reflectors
LHV	Low heat value
LP	Low pressure
MP	Medium pressure
NGCC	Natural Gas Combined Cycle
PDC	Parabolic dish collector

PV	Photovoltaic
PTC	Parabolic Trough Collectors
SM	Solar multiple.
SRC	Solar Rankine Cycle
ST	Steam turbine
TES	Thermal energy storage
UNDESA	United Nation Department of Economic and Social Affairs

Symbols

G_{on}	Extraterrestrial radiation for a given day
Gsc	Energy from the sun per unit time
A_{AP}	Aperture area
A_{ABS}	Absorber area
C	Concentration ratio
T_a	Ambiant temperature.
A	Absorptance of the absorber surface
ε	Emmitance of the absorber surface.
Σ	Stephan Boltzmann constant.
I_T	Incident solar radiation
t_{sol}	Solar time
t_{std}	Standard time
L_{std}	Standard meridian

L_{oc}	Meridian of the observer
E	Equation of time
t_{GW}	Greenwich Mean time.
Θ_{lat}	Latitude
σ	Declination
ß	Slope
γ	Surface azimuth angle
Θ_{hour}	Hour angle
ω	Angle of incidence
Θ_Z	Zenith angle
γ_s	Solar azimuth angle
α_s	Solar altitude angle
P_{el}	Electric power.
n	Solar-to-electric efficiency
τ_b	Atmosphere transmittance
ζ	Glass transmissivity
α	Absorptivity
τ	Mirror reflectivity
Σ	Interception factor
b	Collector width
d_f	Focal distance of the collector.

L	Length of the collector
n_1	Number of loops
R	Percentage of natural gas mass
R_{ch}	Load yield losses
C_c	Carbon cost.

CHAPITER 1

GENERAL INTRODUCTION

Chapter 1: GENERAL INTRODUCTION

The chapter 1 outlines the proposed research with its objectives and the methodology that will be followed in order to complete the objectives of this work. Finally the chapter layout of this study will be given.

1.1 Introduction

Energy is the most crucial element for life and economy. Current world energy consumption shows that approximately 84% of the world energy is supplied by fossil fuels and approximately 10.8% by renewable energy sources [1]. Algeria faces a steady increase in the energy demand in the last decade due to its rapid growing population, broadening economy and large infrastructure projects, e.g. the East-West Highway that links the Tunisian border to the Moroccan border. In September 2015 the national energy consumption continued to growth, to 43 million tons of oil equivalent, against 40 million over the same period last year [2].In 2012 only 2.2% of the energy consumed was produced by renewable sources and the majority of the renewable energy was coming from hydroelectric plants [3]. According to Sonelgaz[1], the electricity generation power plants amount to 15.2 GW at the end of 2013, 12.9 GW at the end of 2012 and 11.4 at the end of 2011. Moreover the annual electricity consumption knew a significant increase (approximately 8%) from 2008 to 2014 [4].

Algeria's population has grown rapidly. According to the United Nation Department of Economic and Social Affairs (UNDESA), it has increased by an annual average of 1.60 and 1.92 percent in 2010 and 2015 respectively [5]. In future, Algeria will be

[1] Sonelgaz (*Socièté Nationale de l'Electricité et du Gaz,* National Society for Electricity and Gas) is a state-owned utility in charge of electricity and natural gas distribution in Algeria.

unable to supply the demand. Those different factors encouraged Algeria to develop a balance in the energy mix that includes fossil fuels and renewables energies to its power generation. The objective from including the renewables energies is to ensure alternative sources of energy that are clean, reliable and stable. Therefore guarantees an environmental, economic and social sustainability in the energy sector.

The main focus of this study is to provide an evaluation of renewable energy technologies by focusing on ISCC.

1.2 Motivation and Background

As the world's population and economy have a steady growth, electricity demand is expected a continuous increase, leading to more emissions and harmful environment. However, it is important to predict impact of the event for longer terms and to set the future by considering the environment and not only the cost.

Nowadays, global warming and climate change have become essential issues causing investigation into increasing the share of power generation implementing renewable sources of energy and improving efficiency of the existing systems. According to the latest Intergovernmental Panel on Climate Change (IPCC) report, by 2050 the emissions should be reduced by 40 to 70 % compared to 2010 to ensure that the planet stays below 2 degrees Celsius limit. [6].

Researchers are proposing the use of renewable energies like solar energy, to curb environmental emissions. Solar energy can be distinguished into two forms; solar photovoltaic (PV) panels and CSP.

PV is the direct conversion of the sun light into electricity by using a semiconductor material. In contrast, CSP is the indirect conversion that based on the heating a fluid to get out a mechanical energy.

Solar energy has the potential to provide the all world’s energy needs due to availability of the sun everywhere; however, today, it represents only a small amount of the world's energy demand. One reason for the lack of CSP utilization is that it requires more land compared to conventional power plants [7], which leads to higher costs. Moreover, cleaning solar reflectors need an extra amount of water [7].Furthermore, solar only thermal power plant has a low efficiency due to the limited temperature of the collectors used, especially at low collecting temperature [8].Another reason is that the sun is variable during the day which makes the supply not stable and intermittent therefore thermal energy storage (TES) is required. Storage leads to increased capital costs.

The possible solution to overcome the intermittency and cost problems is to integrate it with another more permanent power plant. There are many concepts to the hybridization of the CSP, either with conventional (coal, gas turbine, combine cycle, etc.) or non-conventional power generation systems (geothermal, biomass, fuel cell, etc.). Actually, the hybridization of CSP with fossil fuel power process can be grouped in three technics: hybrid solar-gas turbine (solarized gas turbine), hybrid solar-combined cycle and solar reforming. Solarized gas turbines use a CSP system to preheat the compressed air before it enters the combustion chamber. For hybrid solar-combined cycle, solar energy can be used in two technics: either in the gas turbine as solarized gas turbine or as an additional solar heat to the bottoming Rankine cycle [9]. Solar reforming is used to produce hydrogen and syngas.

The hybrid energy systems are more considerable in terms of economic, sustainable, and reliable use of renewable energy to cover all demand compared to renewable resource only facilities [9]. However, this study will focus on a hybrid solar-combined cycle or ISCC. ISCC is here defined as a power combined cycle that utilizes solar energy to supply latent heat or sensible heat.

By integrating CSP into an existing NGCC power station, the thermal produced in CSP field is fed into Rankine cycle of the NGCC. Therefore, either the electricity production rate can be kept constant and saving fuel, or boosting the electricity generation output of the power station. Both operating modes have advantages as well:

- In boosting mode, more electricity can be generated but, the fuel consumption and harmful emissions levels will not decrease.
- In fuel-saving mode, no additional electricity will be generated, but less fuel will be burned, means less harmful gases will be emitted.

Hybridization is a provisional solution to shift the electricity generation to renewable energies [10]. The use of solar and fuel in high efficiencies makes the ISCC more popular than others systems [8]. ISCC is more profitable than CSP power plant, some advantages are [8, 11]: (a) high electricity conversion efficiency; (b) by integrating a solar field into an existing combined cycle, incremental costs could be saved; (c) the instability of steam flow in the turbine could be avoided in integrated plant; (d) TES is not obligatory because at night the plant works as combine cycle ,hence reducing the investment cost; (e) the ISCC provides a better annual off-design performance.

Algeria has the tenth - largest natural gas reserves in the world and the second largest in Africa with 159 Trillion cubic feet [4]. Gas is one of the cleanest fossil fuels and is set to be one of the fastest growing [1], Algeria uses this primary energy for domestic electricity generation. Currently, the Algerian electricity production based on the natural gas represents 77.51% (31.4% of gas turbine (GT), 44.27% of NGCC and 1.8% of ISCC) [12]. The high domestic demand on fossil fuel and the high governmental priority attached, it is expected that gas power plants will be part of the Algerian electricity system in the future. [13].

Located at the northern part of Africa, this advantageous geographical location has made Algeria be one of the countries with the highest solar deposits in the world. Sunshine duration varies from 2000 to 3900 hours annually and depends on the location. The energy received daily on a horizontal surface is approximately 5 kWh/m² on most of the national territory, is near 1700KWh / m2 / year in the north and 2263 kWh / m2 / year in the South[2]. The assessed potential, by the German Space Centre (DLR), of thermal solar sources in Algeria is 169,440 TWh/year [14]. The vast solar resource availability and the high temperatures recorded in Algeria make ISCC an attractive and sustainable method to increase their productivity and meet the future demand.

Algeria can attain its sustainable development goals by embracing more renewable energy resources in power generation given that these are clean, reliable and sustainable. Commendable steps have been taken in this direction given that Algeria has developed its own national program for renewable energy and energy efficiency for the period 2011–2030, in order to diversifying the energy resources toward sustainable development. Also in February 2015, the Algerian government announced a new program for the years 2015 to 2030 [15]. Solar thermal energy takes a significant share.

This vision led to the construction the first ISCC plan (Hassi R'mel) that uses 25 MW of parabolic through solar power plant. Other projects are underway and are planned to launch soon. Furthermore, three ISCC units are to be completed by 2018 using parabolic through collector technology. Each of them increases the capacity of Hassi R'mel to 70 MW [16]. Solar energy is expected to represent 37% of the national electricity production by 2030[12].

Algerian climate differ from the north to the south where it is maritime in the north, semi-arid in the middle and arid in the south. ISCC is the temporal transition model from fossil to renewable energy by combining the two wealth sources; the sun and natural gas [7].Many ISCCs power plant operate around the world (Algeria, Morocco, Italy, Spain, etc.) have proved a significant increase in term of efficiency. The performance of ISCCs has been analyzed by different studies with varying the configuration [17, 18, and 19] and Hassi R'mel [20, 21, 16, and 22]. Juergen et al [23], conducted a study on the conversion of an existing 110 MW GT power plan to 200 MW ISCC using solar tower with TES under Australia climate. This study concluded that it is possible to reduce the payback period by15 % compared to building new ISCC plant.

1.3 Problem Statement:

By considering these references, it is interesting to investigate the feasibility of ISCC power plant under the Algerian climate. Combined cycle power plant hybridization is accomplished by employing PTC with different technologies (DSG and HTF). Two different climates (maritime and arid) are chosen to conduct this study. The insight gained from this study will be used to gain knowledge on some of the design considerations for better control the performance of such plants.

1.4 Objectives:

The research problem can be divided into different objectives that need to be addressed.

- Analyse and quantify the Algeria's solar power potential.
- Technical comparison of the CSP technology in terms; the efficiency, maturity, state of the art, etc.
- Evaluate the performance of the reference NGCC by considering the variation of the ambient conditions.
- Dynamic simulation of the ISCC proposed will be conducted by using mathematical models. Furthermore, the costs will be elaborated.

- Carry out a technical, economic and environmental analysis of ISCC and compare the performance of the ISCC by using two different methods of generating steam.
- Perform a comparison between the two different climates to find the most suitable location for the installation of ISCC.

1.5 Research Methodology:

In order to evaluate the benefits of hybridizing the combined cycle power plants to ISCC plants, two different locations are selected based on the transition of the climate between the north and the south. The methodology adopted in the present work comprises the following steps:

- Collection of meteorological, technical, economic data.
- Selection of the CSP technology.
- Evaluation of the reference NGCC performance under the selected locations.
- Evaluation of the ISCC power plant performance under the same selected locations.
- Economic analysis is accomplished by utilizing LCOE.
- Environmental analysis is carried out by assessing the annual amount of carbon dioxide emission to the atmosphere.
- Comparison analysis to find the most viable system to be used in Algeria.

1.6 Dissertation Overview

This thesis consists of five chapters, of which the first provides an introduction to this study. The literature overviews chapter (Chapter 2) firstly illustrates the importance of the solar energy and gives the theoretical principles of the sun and solar radiation in regard to the CSP technology. Thereafter an overview of the country profile will be given in terms of the development of CSP technology, energy situation, energy potential, electricity production and CO_2 emissions. In order to have a well understanding of how a thermal power plant works, different thermo-dynamical cycles are illustrated. Moreover, a comparison of different CSP technologies is done with the consideration of the heat transfer fluid used. Finally, a critical evaluation of all the literature studied in the chapter will be discussed to decide which technology will best suit this research problem.

The methodology chapter (Chapter 3) is proposed in three parts: Section 3.1 gives the production model and assesses the equations evaluating the performance of the solar fields and the turbines; Section 3.2 covers the economic calculation to convert an existing NGCC to an ISCC power plan. In addition to that, the environmental analysis is illustrated by quantify the fuel saving and CO_2 emissions reductions.

The results chapter (Chapter 4) refers to the results obtain from the methodology proposed for the NGCC only scenario and the ISCC scenarios for different solar irradiance days for both locations (Bechar and Annaba). Furthermore, the economic and the environment implications are also discussed in this chapter.

The conclusion chapter (Chapter 5) in which the summary of this work is documented. In addition, recommendations are addressed to further research in this area by pointing out the expectation from the next works.

CHAPITER 2

LITERATURE REVIEWS

Chapter 2: LITERATURE OVERVIEW

In this chapter, an overview of the basics required that help the readers to comprehend the theoretical principles of the solar energy anal. Thereafter, the country profile is given. Furthermore, an inclusive literature review over all CSP technology is presented to better understand the concept and significance of this research.

2.1 The Solar Background

In this section, the theoretical principles of the sun and solar radiation in regard to the CSP technology are explained.

2.1.1 Sun energy

Many sources of energy have been discovered and can be used the meet the energy needs of the planet. At least, 99.9% of the energy available on the earth comes from the sun [24]. As illustrated in the figure 2.1, 47% of the solar flux reaches the earth's surface. The sun has a spherical shape with a diameter of 1,392,000 Km about (109 earths). The energy in the sun is generated by nuclear fusion process, in which hydrogen is converted into helium [25 and 26]. This energy produced leaves the sun as radiative energy and it resembles in its spectrum the thermal radiation of a black body. It is characterized by a very high density, a very high pressure and very high temperatures of about 15,000,000 K while the surface is thin layer with a temperature of 5777K.the core is located in the centre where heat is produced by fusion processes. The rest of the sun is heated by this energy then that is transferred to the space as electromagnetic radiation or kinetic energy of particles [26].

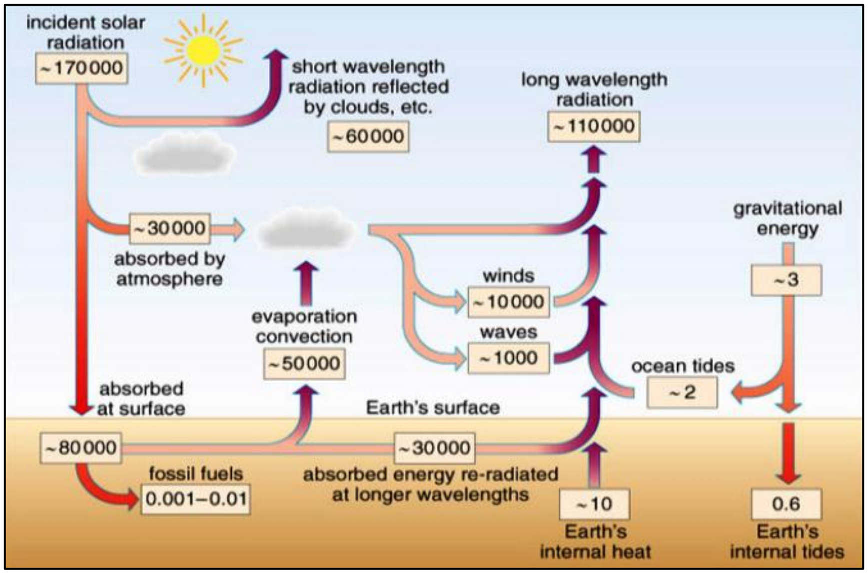

Figure 2.1: The sun power exchanged to the earth (TW) [24]

The sun rotates on its axis once every 4 weeks or region (27 days in the equator region and 30 days in the polar region), but not as a solid buddy [25]. Figure 2.2 shows schematically the geometry of the sun-earth relationships where Gsc is the energy from the sun per unit time received on a unit area of surface perpendicular to the direction of propagation of the radiation outside the atmosphere which is located at an average of 1AU.

The distance between the sun and the earth is in a fluctuation during a year by about ±1.7% to the mean distance[1]. Consequently, the solar irradiance on top of the Earth's atmosphere varies by about ±3.3% relative to the indicated mean value of 1367 W/m².

Figure 2.3, illustrates the variation in extra-terrestrial radiation (G_{on}) during a year. The maximum irradiance is reached in January (the minimum Earth-Sun distance).G_{on}

[1] The mean distance is approximately $1.496*10^{11}$ m

is the amount of extraterrestrial radiation for a given day (DoY, with *DoY=1*, on January 1st) and can be approximated by the following equations[2] [25]:

$$G_{on} = G_{sc}(1 + 0.033 \cos 360° \frac{DoY}{365} \quad (1)$$

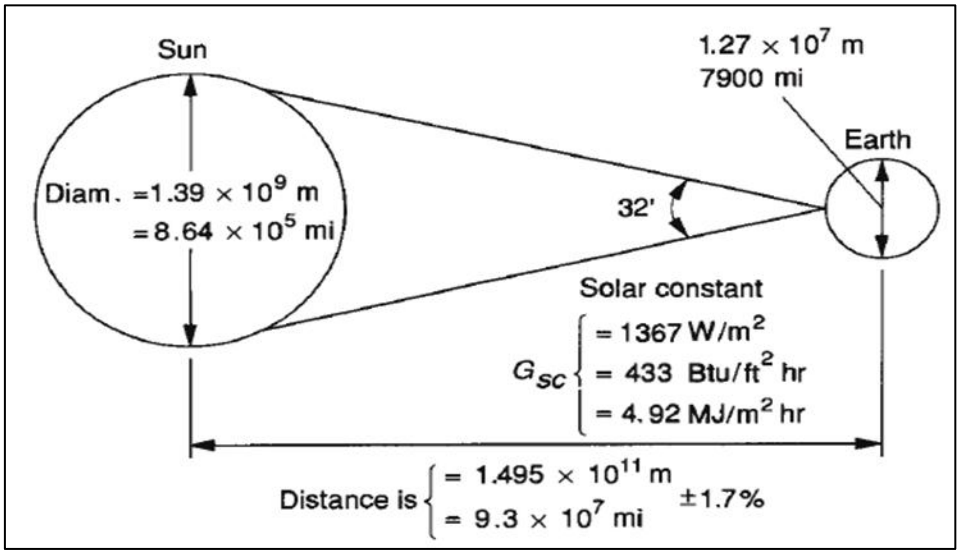

Figure2.2: The sun-earth relationship [25]

[2] Spencer (1971) indicates a more exact formula [25]:
$G_{on} = G_{sc}(1.00011 + 0.034221 \cos d + 0.00128 \sin d + 0.000719 \cos 2d + 0.000077 \sin 2d)$
Where $d = 2\pi(DoY - \frac{1}{365})$

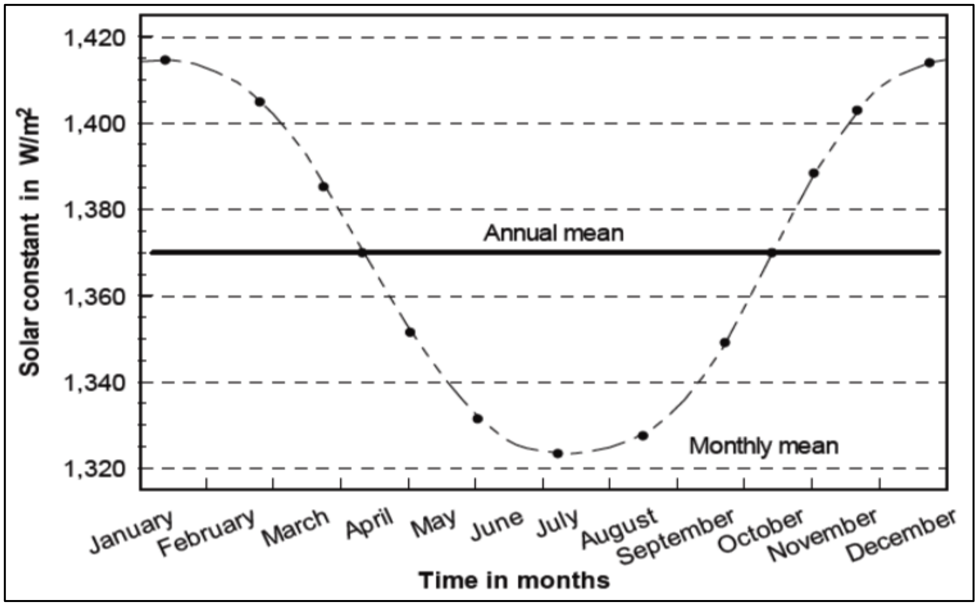

Figure 2.3: Variation of the extra-terrestrial irradiance at normal incidence with Time of Year [27]

2.1.2 Radiation extinction in the atmosphere

The amount of solar radiation reaches to earth's surface in attenuated form which is called extinction process. It can be distinguished in two classes: absorption and scattering (being reflection a special case of scattering) ([25] and [26]). Figure 2.4 show the radiation reduction effects of the different extinction processes.

- Atmospheric absorption is the process of absorbing photon of a certain spectral range.
- Scattering is the process in which radiation is forced to deviate from a straight trajectory by non-uniformities in its way (molecules, dust particles etc.) and it is two types. Mie-scattering,), is the scattering of electromagnetic radiation by particles whose diameter is of about the same dimension as the wavelength or larger. In the atmosphere, water droplets, ice crystals and aerosol particles cause Mie-scattering. Rayleigh-scattering is the scattering of electromagnetic radiation by particles which are much smaller than the wavelength of the radiation.

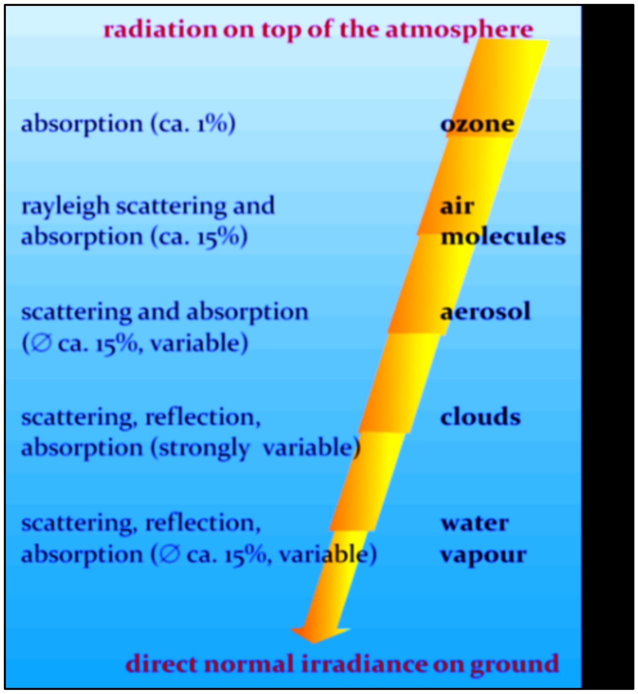

Figure 2.4: Radiation reduction through atmospheric extinction processes [26]

2.1.3 Concentration of solar radiation

Concentrators are an optical device that redirect and focus the solar radiation from an aperture area (A_{AP}) to a small absorber area (A_{ABS}). The concentration ratio is defined as the ratio of collector aperture area to absorber area [25].

$$C = \frac{A_a}{A_r} \quad (2)$$

From the law of the conservation of *étendue* in an ideal optical system, we can determine the maximum concentration on the basis of the beam angel of the incidence radiation [26]. Figure 2.5 illustrates the *étendue* in an optical system.

$$A sin^2 \frac{\alpha}{2} = A' sin^2 \frac{\alpha'}{2} \quad (3)$$

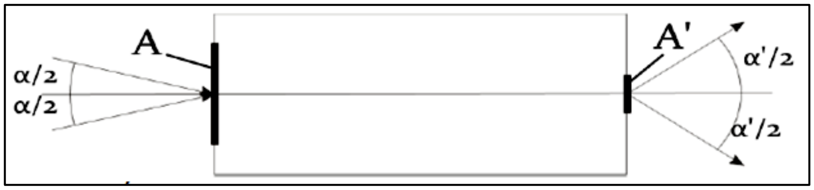

Figure 2.5: étendue in optical system [26].

Solar concentrators can be classified by their focus geometry; either as a point focus systems (solar tower, parabolic dish) or line focusing system (parabolic trough and linear Fresnel)

- For a point focus system (circular concentrator), the maximum possible concentration ratio is given by [25]:

$$C_{3\,dim}^{max} = \frac{R^2}{r^2} = \frac{1}{sin^2\theta_s} \approx 45000 \quad (3)$$

- For two dimensional (linear) concentrators, the maximal possible concentration ratio is given by [25]:

$$C_{2\,dim}^{max} = \frac{1}{sin\theta_s} \approx 212 \qquad (4)$$

The maximum temperature achieved by an opaque flat surface taking into account radiative heat losses only and no heat extraction is given [25]:

$$T_{abs,max} = [T_a^4 + (\propto +\varepsilon)(\frac{I_T}{\sigma})(A_a/A_r)] \qquad (5)$$

Where:

T_a: Ambiant temperature.

α: Absorptance of the absorber surface

ε: Emmitance of the absorber surface.

σ: Stephan Boltzmann constant.

I_T: Incident solar radiation from the sun at 5800 K.

A_a/A_r: Concentration ratio.

2.1.4 Important solar definitions

Some important definitions must be illustrated proceeding to more advanced solar integrated technologies are explained in the following sections.

- **Solar time**: It is known as apparent solar time, or true solar time, is the time based on the apparent angular motion of the sun across the sky; with solar noon the time when the sun crosses the meridian of the observer. It can be calculated based on the observer's location (longitude) and the location that the local standard time is based on. Four minites is taken for each degree deviation from the reference meridian [25]. Solar time is calculated by:

$$t_{sol} = t_{std} + 4(L_{std} - L_{loc}) + E \qquad (6)$$

Where

t_{sol} is the solar time

t_{std} is the standard time

L_{std} is the standard meridian for the local time zone

Ll_{oc} is the meridian of the observer

E is the equation of time

E can be calculated by:

$$E = 229.2(0.000075 + 0.001868\ \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B) \quad (7)$$

And L_{std} is calculated by:

$$L_{std} = 15(t_{std} - t_{GW}) \quad (8)$$

Where

t_{GW} is Greenwich Mean time.

- **Latitude *(Θ_{lat})*** is an angular location with respect to the equator. It is positive for the northern hemisphere and negative for southern. Its value varies between -90°≤ Θ≤90° [25].
- **Declination *(σ)***is an angular location of the sun at solar noon compared to the equator plane. Its value varies from -23.45°≤ σ ≤23.45°. (north is positive) [25]. It is approximatelly calculated as:

$$\sigma = 23.45 \sin(360 \frac{284+DoY}{365}) \qquad (9)$$

- **Slope (*ß*)** is theslope of the surface receiving the solar beam with respect to the horizon and ranges from 0°≤ *ß*≤180° [25].
- **Surface azimuth angle (γ)** is the angle between the projection of the normal of the surface on a horizontal plane and the local meridian while south is taken to be zero. It ranges from -180° ≤ γ ≤180°(west is positive) [25].
- **Hour angle (*Θ_{hour})*** is the angular location of the sun based on the earth’s rotation around its axis for 15° per hour (morning is positive) [25].
- **Angle of incidence (*ω*)** is defined as the angle between the beam radiation on a plane and the normal of that plane[25].
- **Zenith angle(*Θ_Z)*** is the angle between the line of the beam radiation and the normal to a horizontal plane[25].

- **Solar altitude angle (α_s)**is the angle between the line of the beam radiation and the horizontal. This angle is the complement of the zenith angle[25].
- **Solar azimuth angle *(γ_s)*** is the deviation of the projection of the beam radiation on a normal plane from south. East is considered to be negative[25].
- **Direct normal irradiance (*DNI*)** is another important indicator in solar energy and it is calculated by [25]:

$$DNI = G_{on}cos(\theta_z)\tau_{sct}\tau_{wv}\tau_{oz}\tau_{cg}\tau_{aer}\tau_{cld} \qquad (10)$$

Where θ_z is the angle between solar radiation and the normal on the horizontal surface, τ_{sct} is the attenuation transmission coefficient for scattering, τ_{wv}, τ_{oz}, τ_{cg}, τ_{aer}, are the attenuation transmission coefficients for water vapour, ozone, common gases (O_2 and CO_2), aerosol, and clouds, respectively.

2.2 Algeria

In this section, the country profile will be discussed based in terms of solar energy potential, energy consumption, and renewable energy framework. Those factors identify the ability of Algeria to cover such project like the one studied in this work.

2.2.1 Solar energy

Algeria is located in North Africa between 23-35° of latitude north and 8-128° longitude east [16]. The geographical location made Algeria one of the countries with the highest solar deposits in the world. The Sahara is covering 86 % of the Algerian area. The vastness of the area made the climate transitional from the north, middle to the south. The energy received daily varies from 4.66 kWh in the north to 7.26 kWh in the south [28]. Moreover, sunshine duration varies from 2000 to 3900 hours annually and depends on the location. The technical potential assessment of thermal solar sources in Algeria, by the German Space Centre (DLR), is 169,440 TWh/year [13].

Table 2.1: Solar potential in Algeria [2].

Region	Costal	Haut Plateau	Sahara
Area (%)	4	10	86
Sunshine duration (h/year)	2650	3000	3500
Received energy (kWh/year)	1700	1900	2650

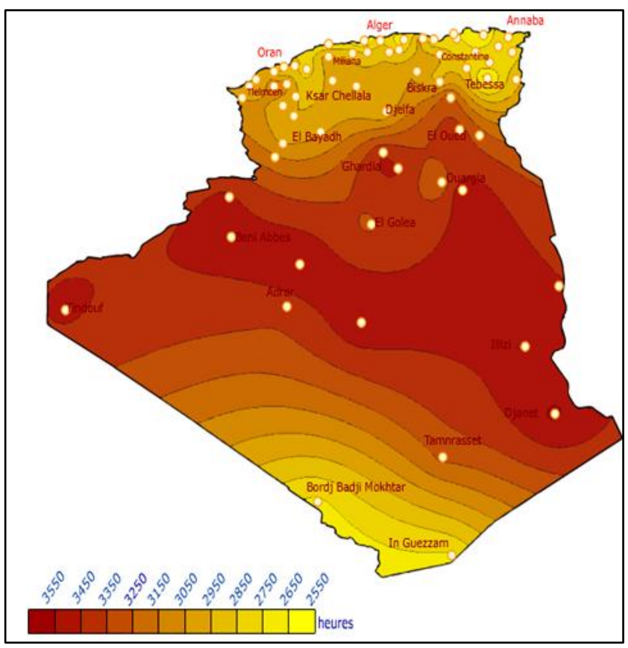

Figure2.6: Annual sunshine duration [15]

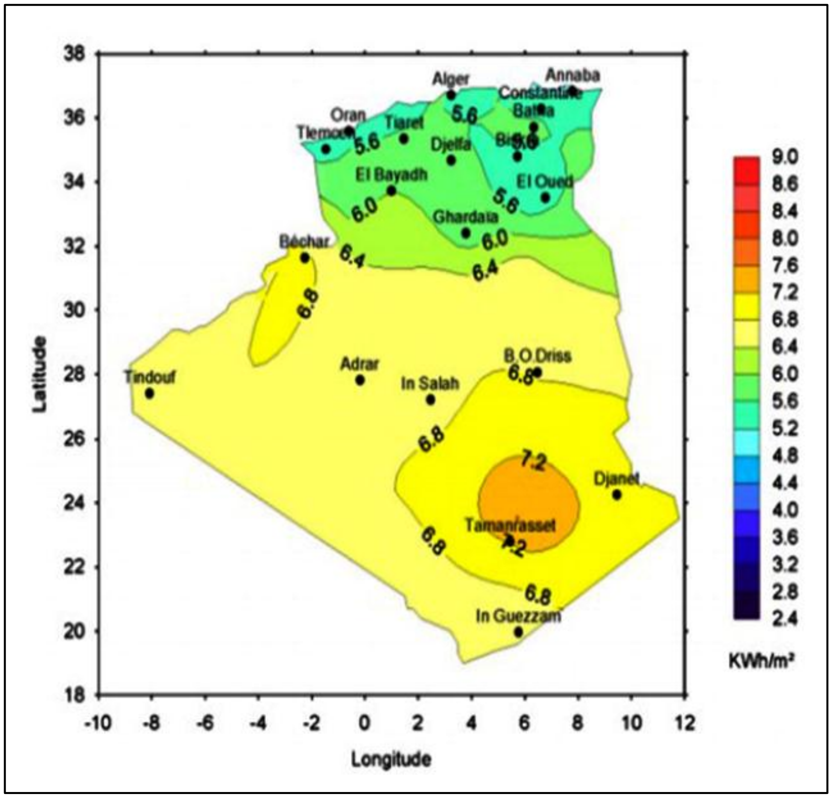

Figure2.7: Daily direct normal irradiation kWh/m²/day [29]

2.2.2 Electricity consumption

Algeria faces a significant increase in electricity consumption. It is reported that peak load demand in 2011was 38.9 TWh, up 8.7% compared to 2010. During the period 2000-2011, the average recorded growth of 5.9% per year [30]. It clearly demonstrates that Algeria faces a rising demand for electricity in the coming years.

Electricity Generation increases to 63.988 TWh in 2014 compared to 59.447 TWh in 2013 [2]. In 2011, electricity generation reached 48.9 TWh, up 8.2% compared to 2010 [30]. Consequently, new power plants are programming in the period 2013-2016 [30]. The total capacity is 5530 MW. The table 2.2 shows the capacity and the projected years of commissioning.

Table 2.2: Electricity power plant generations (2013-2016) [30]:

Sites	N° of group	Capacity (MW)	Commissioning years
Koudiet Eddraouach	1	382	12/2012
	2	382	01/2013
	3	382	02/2013
Ain Djasser	1	132	09/2013
	2	132	11/2013
Labreg	1	140	11/2013
	2	140	01/2014
	3	140	06/2014
Boutlelis (NGCC)	1	200	08/2014
	2	200	08/2014
Ras djinet (NGCC)	1	400	12/2015

	2	400	01/2016
	3	400	02/2016
Ain Arnat (NGCC)	1	400	12/2015
	2	400	01/2016
	3	400	02/2015
Hassi Messouad oust (TG)	1	150	01/2016
	2	150	03/2015
	3	150	05/2015
	4	150	06/2016
Hassi R'mel (TG)	1	150	2015
	2	150	2015

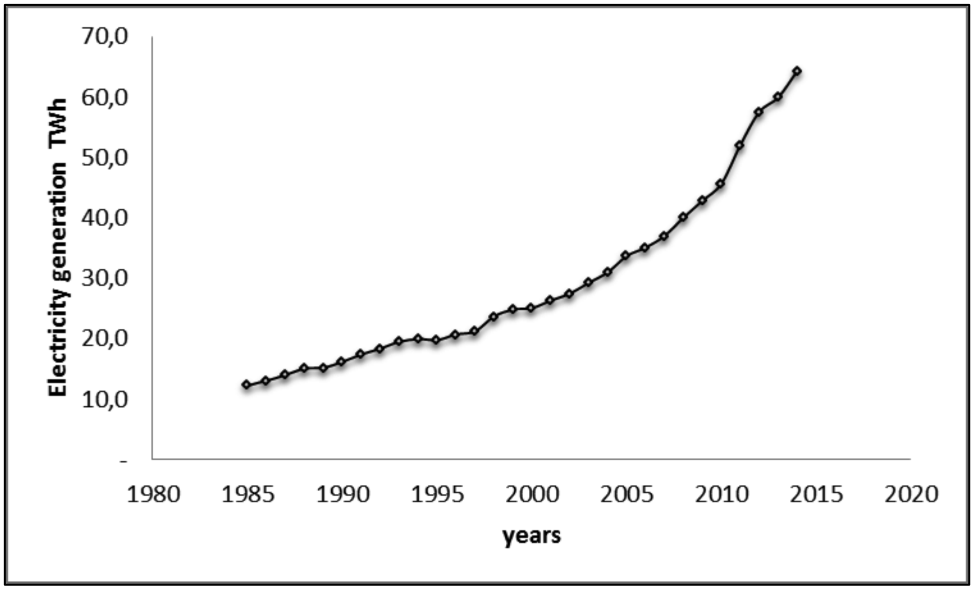

Figure2.8: Electricity generation [1]

2.2.3 Renewable energies policy framework

The promotion of the renewable energies is one of the Algerian targets. In order to introduce the terms of sustainably and to ensure the safety of the environment, Algeria set a legal framework for renewable energies.

The national program for renewable energy incorporates the implementation of 67 projects, six solar thermal power plants, seven wind farms, 27 solar power plants, and 27 hybrid power which will cover 40% of the national needs by 2030[31].

An Official Decree n ° 13-218 of 18 June 2013 sets out the conditions for allowing premiums for the costs of enhancement of power generation from renewable energies [32].

The power generated from the following sources:

- Solar photovoltaic and thermal.
- Wind energy

- Geothermal
- Waste recovery
- Biomass
- Any current hybrid system has an annual production of electricity from renewable energy more than 5% on the date of announcement of this decree in the Official Journal.
- Any power plants have a cogeneration system whose not surpass 50 MW.

The official Decree ensures and guarantees the purchase price of electricity produced that must be fed in the national network. The producer must submit a demand to the Electricity Regulatory Commission and Gas (CREG) [32].

2.2.4 Concentrating solar power

Several studies focus on the solar energy, especially CSP technologies within Algeria. ISCC Hassi R'mel is the first thermal power plant utilizing CSP technologies in Algeria. ISCC Hassi R'mel has a total output of 150MW with 25 MW of CSP [2]. This power plant is located at Hassi R'mel uses 224 solar collector assemblies (183 860 m², aperture area). HTF used is thermal oil. The temperature of the oil inside the tubes varies from 290°C to 393°C [33]. ISCC Hassi R'mel is implementing dry cooling to reduce the amount of water [34]. Other on-going projects are planned to start from 2016 to 2021. The sites of implementation of CSP are identified and given in the table 2.3 [30].

Table 2.3: Implementation of CSP power plant [30]

Unity : MW	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2015-2021**
Bechar						150	150

Beni Abbes	150						150
El Oued		150					150
Naama		150					150
M’Ghair			200				200
Ghardaia				150		150	300
Ouargla					500		500
Laghouat						200	200
Adrar				175			175
Total	150	300	200	325	500	500	**1975**

2.2.4 Carbon emissions

CO_2 emission is increasing in Algeria. CO_2 emissions rose from 102.4 to 135.1 million tons in a period of only five years [1]. It is noticed that 38.47% of the CO_2 emission is associated with electricity and heat production [35]. This amount can be significantly reduced by introducing renewable energy for electricity and heat applications.

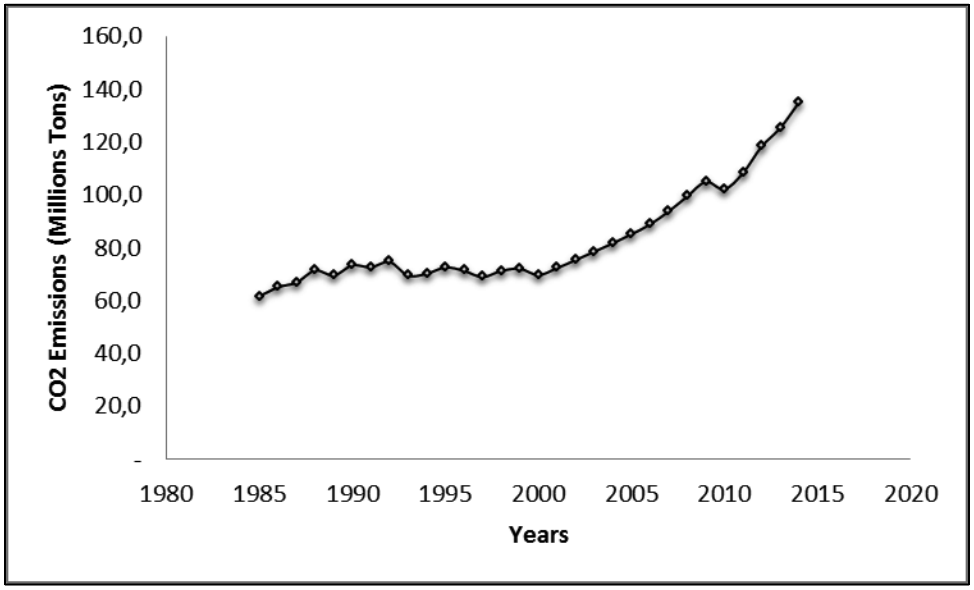

Figure2.9: CO_2 Emissions [1].

2.3 Hybridization Schemes

In this section, the different hybridization schemes that have been previously proposed will be discussed. As aforementioned, the three main schemes are: solarized gas turbines, hybrid combined cycles and solar reforming systems.

2.3.1 Solarized gas turbine

Solarized gas turbine, is a system that uses CSP field to preheat the compressed air (to a high temperature-around 1070 K) before it enters the combustion chamber (CC). Increasing compressed air temperature leads to reduce the fuel consumption and thus the reduction of exergy losses in the CC.

Consequently, this integration can increase the efficiency of the system compared to gas turbine only. This higher solar to electricity efficiency leads to a reduction in the cost of the solar application. Also, it ensures the power cycle to operate at full load and even when there is no solar energy available.

- **Example of solarized gas turbine:**

SOLGATE Project was started in 2002 by ORMAT to build a prototype of a solarized gas turbine. This project consists of modified 250 kW_e turbine and two volumetric receivers and one tubular receiver in series. The aims of this project is to Modify GT for external air heating; development of pressurized receiver technology with air outlet temperature of up to 1000°C; verification of the predicted performance of the system and its components [36].

The receiver consists of 3 modules connected in series. Each receiver module was equipped with a hexagonal secondary concentrator to enable installation side by side in the aperture plane. These receivers are tested in Spain (Almeria), the efficiency of the receivers ranged from 63% to 75% with a pressure drop across the receiver of 18 mbar [36].

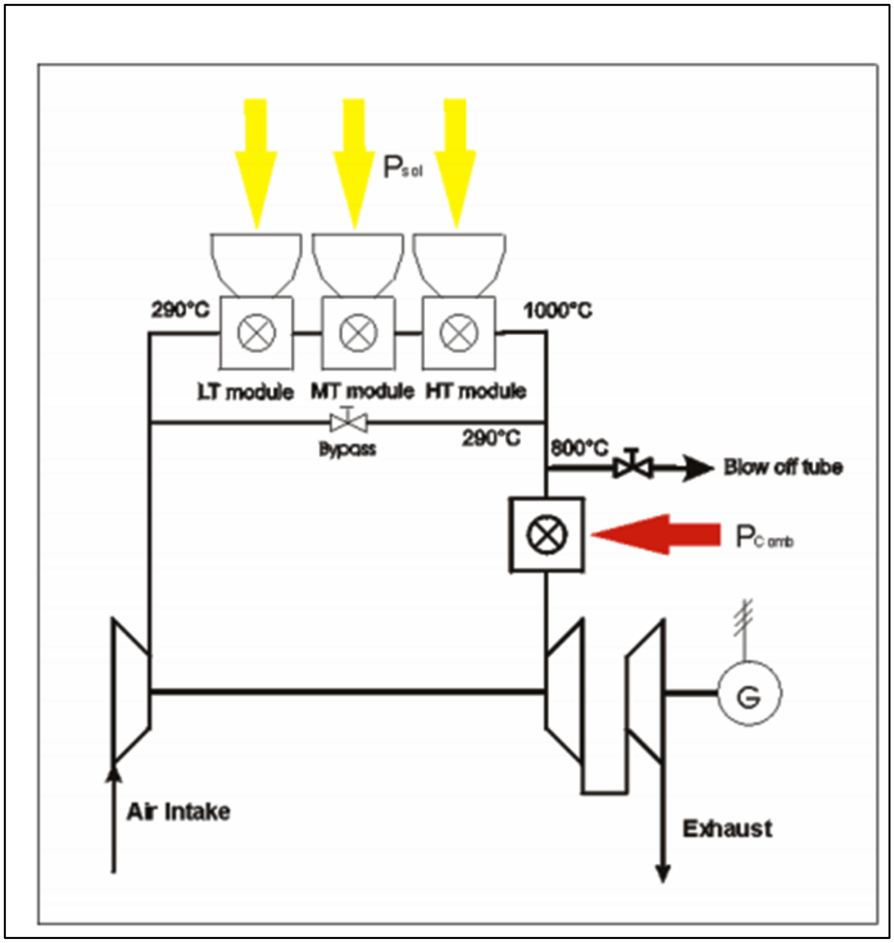

Figure2.10: Scheme of the SOLGATE system [36].

2.3.2 Solar reforming

Solar reforming uses CSP technology as source of high temperature heat source to convert solar energy into chemical energy, which can either be used immediately for power generation or stored for later use when solar energy is not available [37].

Solar reforming process is a catalytic reaction between hydrocarbons such as methane with steam. The product of this reaction is mainly a mixture of CO and H_2 called synthetic gas or "syngas" [37].Reforming reaction for methane is:

$$CH_4 + H_2O\ (l) \rightarrow CO + 3H_2 \quad (11)$$

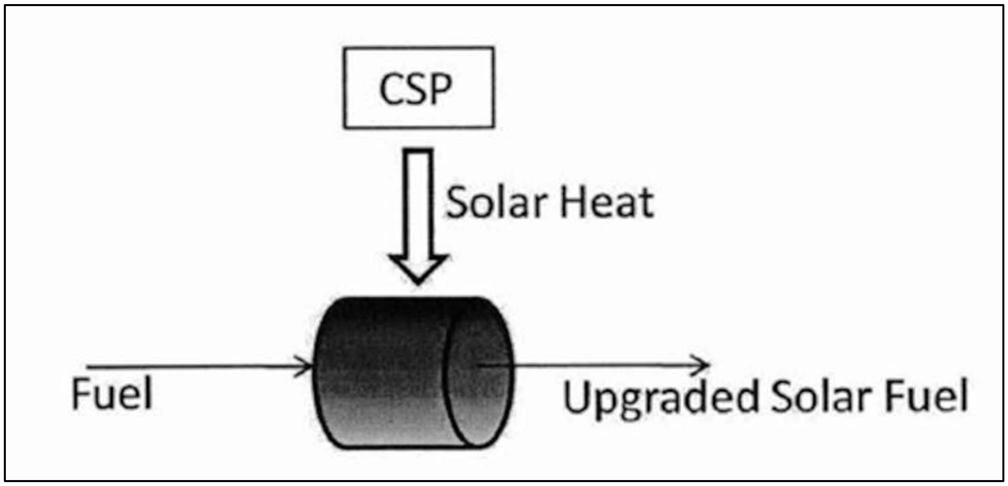

Figure2.11: General schematic of solar reforming [37].

2.3.3 Integrated solar combined cycle

ISCC is a technology that is used to help reducing the cost of solar energy power generation. ISCC power plant combines a CSP power plant and NGCC power plant [38]. CSP technology generates steam and this steam will be introduced either into the heat recovery steam generation (HRSG) or in the steam turbine directly [39]. Other ways, CSP could heat the compressed air in the gas turbine before entering in the CC.

Currently, there are many ISCCs plants over the world; 75 MW in Florida, 20MW in Morocco, 25 MW in Algeria, 20MW in Egypt and 17 MW in Iran [42 and 43]. The operational alternatives and present costs for the extant ISCC plants are discuss in Algeria [43], Spain [44], and Egypt [45]. Most of the cases concluded that ISCC is a solution to introduce renewable energies on the energy production.

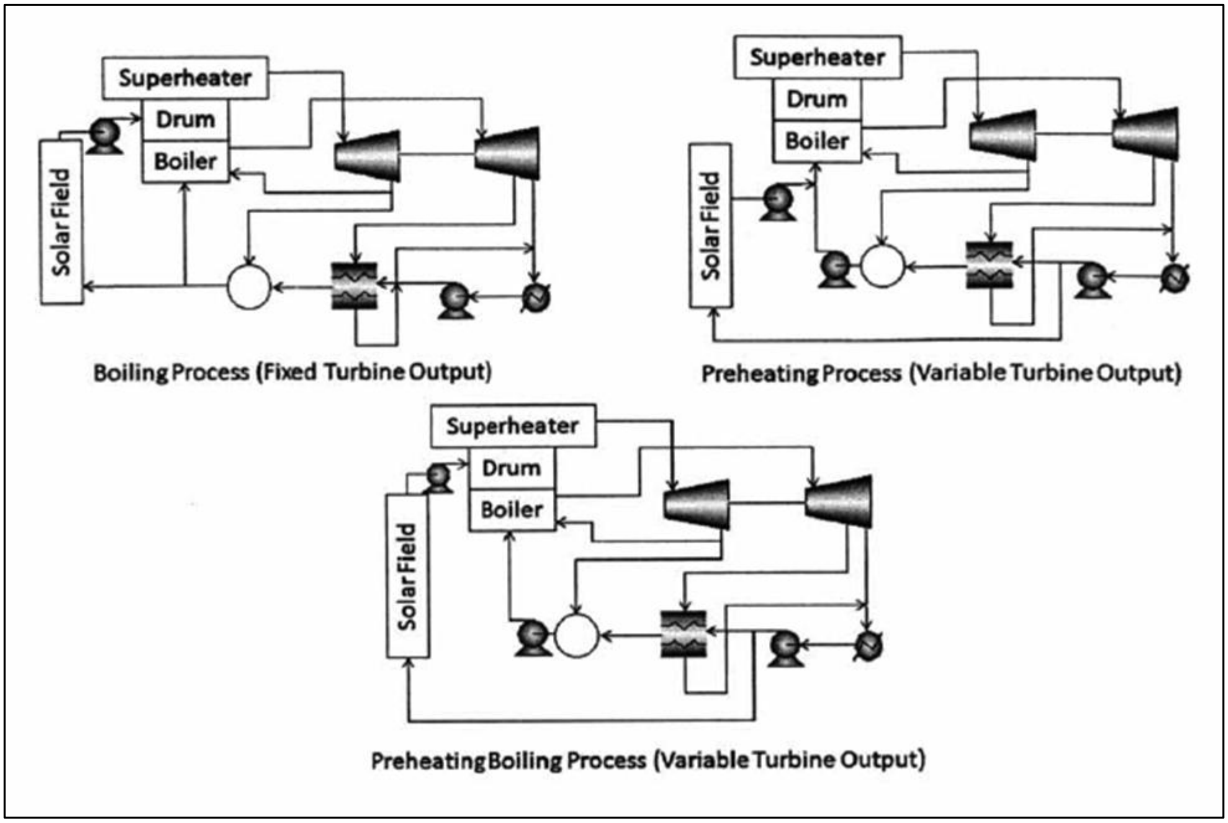

Figure2.12: Three different solar integration methods in steam cycle [40].

The concept of hybridized combined cycle was proposed by Luz solar International in 1990 [46], which integrate PTC with NGCC. [23], Proposed and studied the preheating and heating air before entering the CC. Bohn et al [41] studied solar preheating in the topping Brayton cycle in which they noticed that the power production is limited by integrating PTC. Petersein et al. [48] compare all the technologies for integrating with Rankin cycle power plants. Behar et al [40] reviewed technically the ISCC plants using PTC over the world. They concluded that the research development and deployment (RD&D) has a significant increase and DSG performs better than other configuration. Nezammahalleh et al. [49] conducted a techno-economic of DSG in PTC. Integrating heliostat field collector (HFC) with NGCC has been studied by Price et al [50]. Franchini et al [77] compare PTC and HFC in Solar Rankine Cycle (SRC) and ISCC and the authors deduced using HFC is more efficient in both layouts at least from an energetic point of view. Furthermore, Horn et al conducted a techno-economic comparison between PTC and HFC integration in NGCC in Egypt and they concluded that the integration of air tower is more beneficial in terms of economy and environment [76].

2.4 Types of Concentrating Solar Power Plant

CSP systems require several components to produce electricity: concentrator, receiver, storage or transportation system and power conversion device. In this section, the types of concentrating solar power will be presented with a short description.

2.4.1 Parabolic trough collector

The parabolic trough collector is the most mature CSP collector technology and widely used around the world. In September 2010, the parabolic trough power plants represented over 90% of the capacity of CSP operating power plants [33]. The largest PTC power plant in the world is located in California with a capacity of 354 MW [39]. The operating temperature of the PTC starts from 50℃ and goes to temperatures as high as 400℃.

Parabolic trough system consist a single axis-tracking concentrators. It contains curve mirrors as reflectors (mostly aluminum or silvered acrylic) in which the solar incident rays are reflecting into a linear focus (the receiver). A HFT flows inside the receiver to absorb the radiation and to convert it to another form of energy [33].

The receiver consists stainless steel pipes treated with selective coating [51]. The low infrared radiation emmitance is the most characteristics required for the pipes. They are enclosed in evacuated glass tubes to minimize convective losses. HTF is used to transfer the heat collected from the receiver to the power block either direct or indirect steam generation. The high pressure super-heated expands through the turbine which drives a generator. Steam is cooled and condensed to return back to the solar field.

The main disadvantages of trough technology are [39]:

- The maximum HTF temperature, which limits the cycle efficiency.
- The use an additional heat exchanger between two fluids in the power blocks.

2.4.2 Heliostat field collector

The heliostat field collector, also known as the solar tower, is relatively an expensive technologie. This has been implemented in the USA and Spain. In particular, HFCs are used in the 10 MW Solar One and Solar Two projects in California, USA. Furthermore, two power plants in Spain; PS10 with 11 MW and PS20 with 20 MW. Because of their high capital cost, HFCs are usually associated with large scale power plants (greater than 10 MW) to benefit from the scale economy [39].

Basically, several flat mirrors are sun tracking in two axes; concentrate the solar irradiation to the receiver. HTF could be water, molten salt, liquid sodium or compressed air [52]. HTF is circulated in the receiver to heat up the water that is used to power a steam turbine coupled with a generator. The water temperature, at close to 545°C, is higher than in line-focus systems [39]. Recently, the molten nitrate is the common HTF used in the constructed power plant that to eliminate the need for the heat exchanger between HFT and the fluid used in the thermal storage [53]

The surface area of each heliostat ranges from 50 to 150m². Moreover, the central tower height can be varied from 75 to 150m [39]. The overall efficiencies can be improved by the implementation of lightly concave mirrors or increasing the height of the tower [58].

2.4.3 Linear Fresnel reflectors

Basically, linear Fresnel reflectors (LFR) operate the same way as PTC with the difference being in the collectors and mirrors design. The reflectors are flat mirrors with a single axis tracking device that focus solar radiation toward a linear receiver [39]. Many mirrors are connected together to form a module and the modules form a long row that could be up to 450 m long. The rows are fixed a steel structure on the ground [38]. Water or a mixture of water and steam with quality of around 0.7 flows within the tubes [52]. Water is separated from the steam and saturated steam is used either for process heat or to generate electricity using a conventional Rankine cycle power block.

The linear Fresnel has the lower investment cost compared to parabolic trough for the same power. It has even low maintenance cost and uses less land space, however, low efficiency [55] and high heat losses due to absence of insulation around the receiver tubes [39]. LFR technology is operated in PE1, a 1.4 MW solar power plant constructed by Novatec Biosel in Spain [39]

2.4.4 Parabolic dish collector

Parabolic dish systems were used in a large application in Shenandoah/Georgia in the early 1980s. It worked until 1990. 114 parabolic dish concentrators were combined to provide electricity (450 kWe), air-conditioning, and process heat (at 173°C) for a knitwear factory [56].

The parabolic dish collector (PDC) is concaved reflector in the shape of a parabola that focuses sun radiation at a single point where the receiver is fixed. Two axis tracking system are used to collect the solar radiation. The concentrated heat is directly converted to electricity in the receiver. Brayton or Stirling cycle engines are the most used as heat engine in the parabolic dish systems [42]. Generally solar dish/engine systems are considered as most suitable for smaller decentralized and off-grid applications [56]. PDC is the most expensive CSP technology [39].

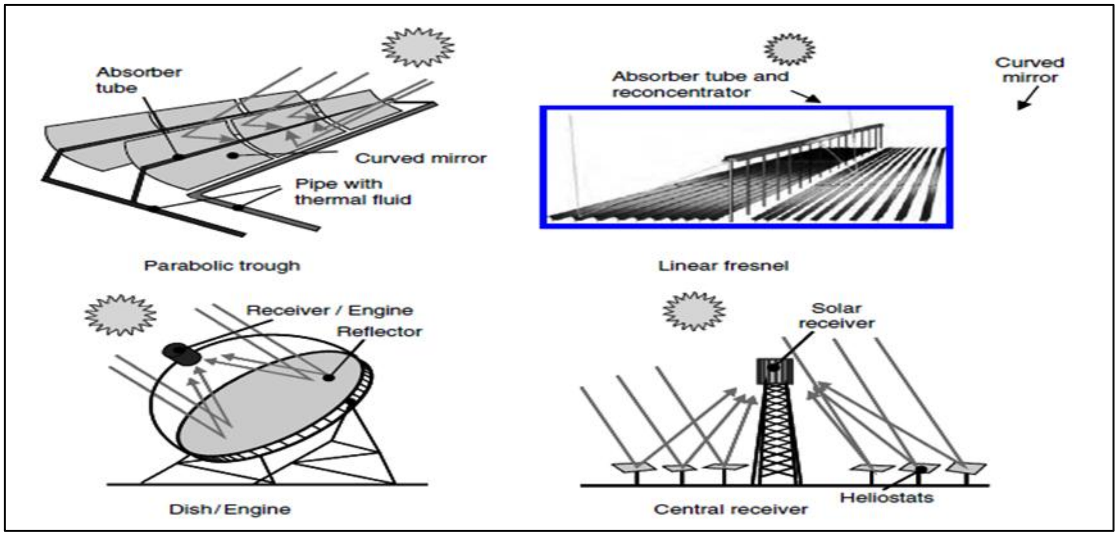

Figure2.13: Schematic diagram for the four CSP systems [57]

2.5 Comparison and Development Status of CSP

Selecting a technology among the four different options is one of the key issues for this thesis. Choosing the best technological option for our case study is very complex since lots of factors need to be considered.[58 and 59], compared the differences between to the technologies using many factors such as: investment cost, design options, efficiency, water consumption and land use. However, the selection of the CSP technologies in this work is not only based on the previous papers but even on the commercialization maturity. Table 2.4 illustrates the differences between the CSP technologies [60, 61, 62, 63, and 64].

In this study only technology suitable to hybridization with combined cycle, especially integrating CSP with Rankine power plants, will be considered; in order for the solar field to increase the efficiency of the power generation. That rules out the PDC option due to the lack of maturity and commercialization. Generally investors tend to choose the technologies that are commercially matured.

LFR is less matured than trough and heliostat. It has tested in a few small demonstration projects, the Spanish power plants; Puerto Erado 1(1.4 MW) and Puerto Erado 2 (30MW) based on LFR [34]. In Australia, Areva Solar constructed in 2008, a 5 MW to test the Compact LFR that have been developed by the company [34]. They found that reflector could generate steam at 482°C and 106 bars [51]. Furthermore, one commercial power plant is operating in Australia; Liddell power station with 9MW and another one is planned, Kogan Creek solar boost with 44MW [34].

LFR has many the advantages, however, this technology need to be commercialized for large scale plants [51]. Thus, Fresnel technology is not selected for this work.

Table 2.4: Comparison of CSP technologies [60, 61, 62, 63, and 64]

CSP technology	**Parabolic trough**	**Heliostat**	**Linear Fresnel**	**Parabolic dish**
Solar collector	Line focus	Point focus	Line focus	Focus point
Solar receiver	Mobile	Fixed	Fixed	Mobile
Power conversion cycle	RC[3],NGCC	RC, NGCC, BC[4]	RC	RC,SC[5]
Concentration ratio	70-80	>1000	>60	>1300

[3] RC is Rankine Cycle

[4] BC is Brayton Cycle

[5] SC is Stirling Cycle

Working temperature	Medium	Higher	Relatively lower	Highest
Typical capacity (MW)	10-300	10-200	10-200	0.01-0.025
Storage system	Indirect 2-tank (Molten salt) or Direct 2-tank (molten salt)	Direct 2-tank (molten salt)	Short-term pressurized , Steam storage	No storage, chemical storage under development
Applications	Grid-connected plants, mid to high- process heat (Largest single unit solar capacity to date: 280 MW in the US. Total capacity built: over 4115 MW)	Grid-connected plants, high Temperature process heat (Largest single unit solar capacity to date: 392 MW in the US. Total capacity built: 593 MW)	Grid connected plants, or steam generation for use in conventional thermal power plants (Largest single unit solar Capacity to date:125MW in India. Total capacity built: 179 MW)	Prototype; Total capacity built :1.5 MW (60 units)
Water cooling (L/MWh)	3000 or dry	3000 or dry	850-1000	50-100(Mirror washing)

Land Occupancy Km²/100MWe	2.4–2.6 (no TES) 4–4.2 (7h TES)	2.5–3.5(no TES) 5–6 (10–12 h TES)	1.5–2 (no TES)	1.2-1.6
HTF	Thermal oil, direct steam, Molten salt	Water/steam, Nitrate salts, Air	Water/steam	Hydrogen/helium (Stirling), Air (Brayton)
Annual solar-to electric efficiency (Gross)	14–16%	14-17%	14-19%	20–22%
Investment costs (USD/KW)	4,000–5,000 (no storage) / 6,000–7,000 (7– 8h storage)	3,500–4,500 (no storage)	4,000–5,000 (no storage) / 8,000–10,000 (10th storage)	4,500–8,000 (depending on volume production)
Technology Risk	Low	Medium	Medium	High
Development status	**Commercial proven -** over 16 billion kWh of operational experience; Operating temperature potential up to 500°C (400°C commercially proven)	**Commercial-**(565°C proven at 10 MW scale)	**Pilot project**	**Demonstration stage**

PTC and HFC are the most commercially mature and proven technology. It should be stated that both technologies will generate steam that will be injected directly into the steam turbine (ST) or into the heat recovery steam generator (HRSG). When using ISCC, it is essential to maximize the utilization of both sources of free energy (exhaust gases and solar energy) [39].

CSP technology can be categorized based on the fluid temperature capability; high temperature (>500°C), medium temperature (400°C) and low temperature (250-300 °C). Basically Solar tower systems can generate superheated steam at high pressure (HP) and up to 545°C that could be admit directly into the ST. However, PTC can generate steam up to 380 °C; it is the best to generate saturated HP steam to immerse with the saturated steam generated in the HRSG HP drum [39]. Peterseim et al. [48] assessed the hybridization of CSP steam generators with different Rankine cycle plants using qualitative and quantitative data inputs. They found that trough scores well in the 380-450 °C integration steam range because of the maturity.

Table 2.5: CSP technologies operational experience [64]

Technology type	No. of Solar Thermal Energy plants	Installed capacity (MW)	Annual expected electricity production (GWh)	Approximately capacity under construction (MW)
Parabolic trough	73	4115	10000	719
Heliostat	10	497	1300	410
Linear Fresnel	8	179	350	180

Using existing operational CSP power plant data, it clearly showed that trough scores better than all other technologies in terms of commercialization, PTC is a technology widely deployed today with an installed capacity 8 times larger than other CSP technologies. It should be mentioned that for other studies others options could be more precise to evaluate the technology, for this work the most required factor is the maturity.

2.6 Solar Field

In this part, we will illustrate the orientation, the structure and the size of the PTC power plants based on the direct and indirect steam generation system.

2.6.1 Solar field orientation

PTC can be oriented randomly due to the possibility of tracking the sun. However, there is a preferred orientation, which is the north-south alignment with the respective east-west tracking [33]. The differences between the two alignments are based on different incident angles and the corresponding cosine effect[6].

Basically the orientation depends on the latitude where the power plant is installed; different orientations have different energy output of the power plant. The advantages and disadvantages of each alignment are discussed as follows [33]:

- **East-west alignment**
  - The collector performance over the day is quite dissimilar. Due to large incidence angles differences over the day, the collector performance is reduced considerably in the hours after sunrise and the hours before sunset. At noon, the incidence angle is zero leading to the highest possible thermal peak power of the solar field.

[6] The cosine effect is the cosine of the angle between the solar radiation and a surface normal; if a flat surface faces the sun outside the atmosphere and it is parallel to the earth's surface, a maximal possible solar irradiance is falling on this surface [75].

- The difference in the energy output is small between summer and winter.
- Quite small tracking movements are required during the day.
- The annual energy yield is lower compared to the north-south alignment.

❖ **North-south alignment**

- The collector performance over the day is quite stable. Contrarily the east-west alignment, the cosine loss is higher at noon than in the morning and evening but it could be compensate, hence, the different DNI conditions.
- Large difference in the energy output of the solar field between summer and winter.
- The annual energy yield is higher than for east-west alignment.

2.6.2 Solar field structure

The structure of the solar fields differs based on the capacity of the power plant, the HTF used, and the configuration used. Furthermore, new collectors design may have new structure. Generally, the current solar field of PTC power plants has a rectangular shape, nearly a square. The power block is located in the centre or near the centre to reduce the length of the pipes in order to minimize the thermal losses [33].

There are two pipes lead the HTF. The cold pipe feeds the HTF to the solar field and another one (hot pipe) leads the hot HTF from the solar field to the power block. In many cases, two pairs of these pipes, which are also called cold and hot headers, exist [33].

Generally large PTC power plants have four columns of collector loops and each column has 30 to 40 loops[7]. The length of the raw is generally 300 m, which allows the HTF heated while flowing through the distance of about 600m (one loop). The cold header is connected to one end the loop and another to the hot header [33]. Figure 2.14 illustrates the collector loop.

[7] One loop is two collectors' rows that are connected in series [65]

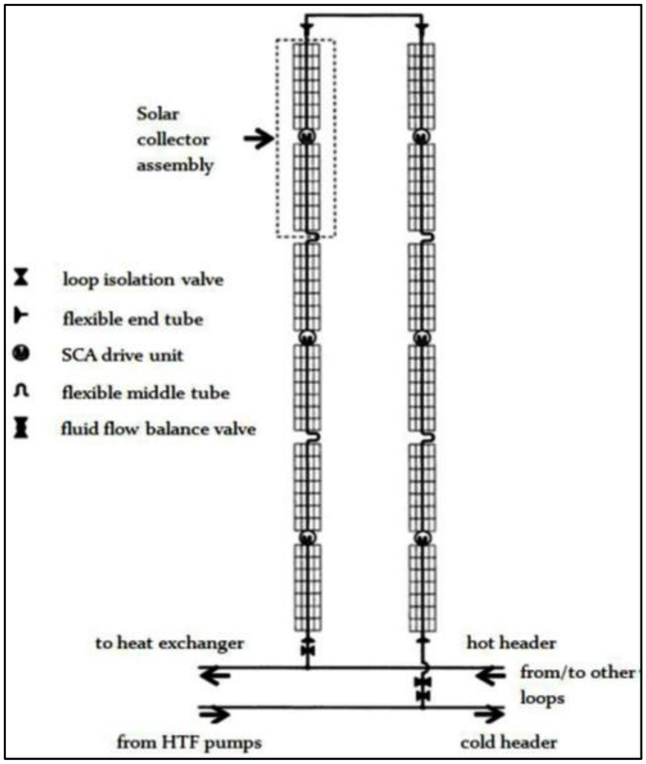

Figure2.14: Collector loop [65]

One collector rows is a combination of many collector modules that are tracked by one common driving unit. Collector assemblies have a length between 100 m and 191 m (Heliotrough). That means that they contain between 8 and 12 modules [33]. The distance between the collector rows, it should be three times the aperture width to avoid the shading between the rows and to reduce the length of the pipes, means minimize the thermal losses as well as the investment cost if the distance is too big[8] [65]

2.6.3 Solar field size

To determine the real size of the solar field is a complex optimization task. However, it can be considered as the total aperture area as well as the total solar field ground area [66]. The approximated solar field ground area depends on the available

[8] Mohr et al. (1999, p. 48) indicate a row distance of 12.5m for the LS-2 collector (aperture width 5.00m) and 16.2m for the LS-3 collector (aperture width 5.76m).

DNI, the power plant capacity, the solar multiple and the efficiency of the solar-to-electricity conversion as well as the economic optimization consideration [33].

- The DNI can be measured or estimated in a specific location and it is an important point to determine the dimensions of the solar fields.
- The power plant capacity is a given value and it is not a problematic.
- The solar-to-electric efficiency is the overall plant efficiency, i.e., the optical of the power plant, the thermal and mechanical efficiencies of the solar field and in the steam generators, generator efficiency, etc. Peak solar-to-electric efficiencies for new PTC power plants are at about 25% or a bit higher (Andasol 28%); annual average solar-to-electric efficiencies are at 12% to 16%.
- The solar multiple is the ratio of the thermal power of the solar field at the design point to the required thermal power for the full-load.
- Economic optimization considerations refer to the radiation conditions as the design point. If a very high DNI is taken, thus, we will not meet the load at certain moments when it is less that value. In contrast, if a weak DNI is taken, the investment cost will be higher due to increasing the solar fields.

The aperture area for a given power plant project (solar only) is approximately calculated as follow [33]:

$$A_{ap} = \frac{P_{el} * SM}{n * G_{b,ap}} \qquad (12)$$

Where:

P_{el} is the rated electric power.

SM is the solar multiple.

n is the solar-to-electric efficiency (related to the irradiance on the aperture).

As mentioned above, the distance between the collector rows is about three times the aperture width, Therefor; the solar field ground area is at least 3.5 to 4 times the aperture area, including the area for the pipes, optimal storage, and the power block [33].

2.6.4 Heat transfer fluid

Heat transfer fluid is a fluid used to transport thermal energy (heat) from the collector to the power block. There are two ways to transfer heat to the power block; either Direct or indirect steam generation.

2.6.4.1 Indirect steam generation:

Indirect steam generation includes two fluids cycles, HFT cycle and the Rankine cycle [33]. DNI is reflected into absorber tubes where it is converted to thermal energy [42]. HTF transfers it to the power block by using a heat exchanger so called Heat Solar Steam Generator (HSSG) [42]. HSSG contains an economizer where feed water is preheated, an evaporator and a superheater [33].

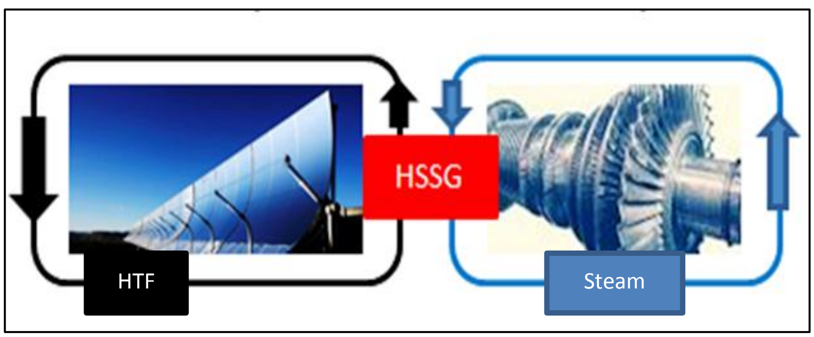

Figure2.15: HTF working cycle

HTF should meet some requirements as follow [33]:

High evaporation and low freezing temperature that ensures no phase change under high and low temperatures that are reached in the solar collectors.

- Sufficient thermal stability that ensure no thermal cracking.
- High specific heat capacity and heat conductivity to have quick heat transfer process.
- Low viscosity to reduce the pump energy.
- Low investment cost and availability in the market.
- Low inflammability and explosivity to ensure the safety of the power plant.

Thermal stability and evaporation temperature are the most important criteria because the steam cycle temperature depends on them which determine the cycle efficiency.

The table 2.6: Properties of different HTF used in parabolic trough power plants [33, 67, and 68]

Medium	**Max. T [°C]**	**Heat Capacity [J/Kg/K]**	**Heat conductivity [W/m/K]**	**Vol. spec. Heat Capacity [KWh/m^3/K]**	**Cost**
Mineral oil	300	2600	0.12	0.55	Low
Synth oil	400	2300	0.11	0.57	High
Silicon oil	400	2100	0.1	0.525	High
Nitride salt	450	1500	0.5	0.75	Moderate
Nitrate salt	565	1600	0.5	0.8	Low
Carbonate salt	850	1800	2	1.05	High
Sodium (liquid)	850	1300	71	0.3	Moderate

2.6.4.2 Direct steam generation

PTC-DSG power plant is one cycle that uses only one fluid (water); meaning that the heat transfer medium in the receiver of the solar field is the same in the Rankine cycle [33]. There are three aspects require a long row of parabolic troughs connected in series of a solar field to execute the complete DSG process (water preheating, evaporation, and steam superheating). The three options are [57]:

- In the once –through process, the feed water becomes superheated steam by passing through the collector rows.

- In the injection process, feed water is injected along the collector row as small fraction. The high controllability of the superheated steam at the field outlet is main advantage.

- Recirculation process uses a water separator at the end of the evaporating section of the collector row, to separate the saturate steam produced as the feed water circulates through the collectors. While the remaining liquid water is recirculated to the solar field inlet by a pump.

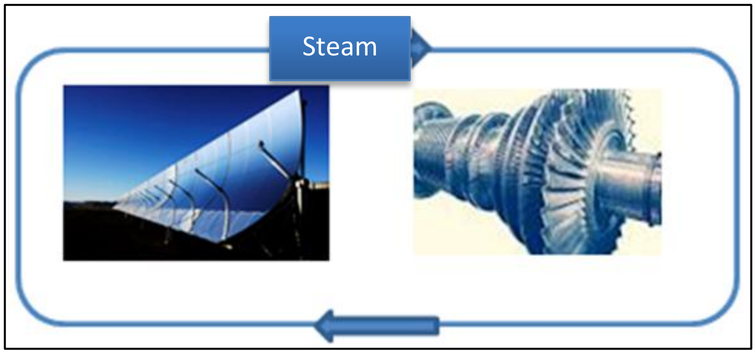

Figure2.16: DSG working cycle

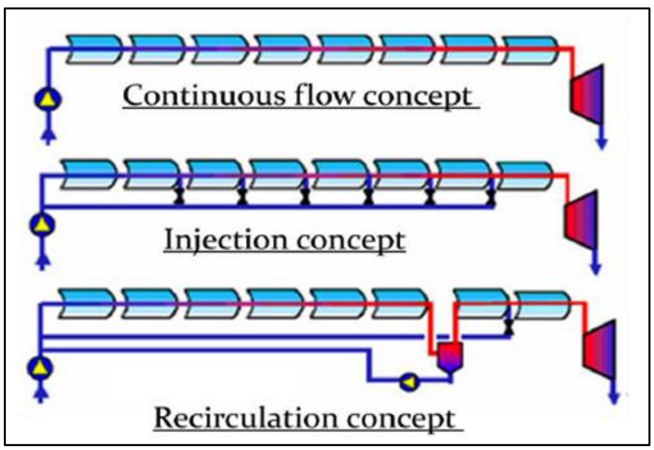

Figure2.17: Difference DSG operation concepts [66]

2.6.4.3 The advantages [33]:

- Steam temperature could reach more 550°C and 120 bars without fluid cracking.

- The power block components can be reduced; no need the heat exchange.

- The use of water is an economic and environmental advantage.

- No thermal losses because there is no heat transfer between two heat transfer fluids.

- The water freezing temperature is lower than the one for salt and thermo oil, means, anti-freeze protection is ensured.

2.6.4.4 The challenges [33]:

- The high pressure of water/steam in the absorber tube is the main challenge in DSG. The water/steam has the pressure of the live steam due to there is no separation between the solar field and the power block. Especially, parabolic trough due to the movability of the receiver.

- Large storage system for DSG is still under development. A large storage system for DSG should be a modular storage with sensible heat storage modules for preheating and superheating and a latent heat storage module for evaporation.

- The complexity of the solar field control compared to indirect HTF and especially for superheated steam generating systems.

The table 2.7: Comparison between direct and indirect steam generation [42, 69, and 70]

	Direct	**Indirect**
Heat exchange	No	Yes
Operating temperature	Promising	Limited

Efficiency	High, promising	Medium, limited
Fluid toxicity	No	Yes
Configuration	Complex	Simple
phase flow	Complex	One phase
Control effort	Higher	Lower
Thermal storage	Expensive, demonstrative stage	Less expensive, commercial
Temperature gradient	Higher	Higher
Technology stage	Demonstrative	Commercial
Scaling up	With additional costs	Easier
Performance enhancement	Promising	Limited
Environmental risks	Low	High
O&M costs	Lower	Higher
Process stability	Less stable	Stable

Leaks	Higher	Low
Solar field size	Smaller	Large
Advancements	**Very promise**	**Limited**

PTCs operating with indirect steam generation achieved the degree of technical maturity [71] to be exploited commercially [72]. However, it has higher environmental risks and temperature limitations due to the matter of HTF used. DSG is the new concept of generating steam with higher temperature level compared to indirect steam generation. It becomes a promising technology for steam production [42].

Bahar et al [42] reviewed ISCCs with PTC in which illustrated the difference integration using DSG and HTF for conventional and non-conventional power plants. They concluded that DSG-ISCC offer better performance in terms of investment cost, O&M costs, thermal efficiency and reduction of greenhouse gas emissions.

Montes [69] analyzed an ISCC with DSG, in which solar field was used for preheating and evaporating part of the HP steam, concluding that 52.2% annual global efficiency and 1.23% annual net electrical solar fraction were obtained with 21.5% annual net solar efficiency. Rivira et al. [8] compared different ISCC configuration, noticing that the only-evaporative DSG configuration is the best choice, since it could benefit of both high system thermal efficiency and low irreversibility at the HRSG. Kelly et al. [73] showed similar conclusion. Li and Yang [74] end up with a solar radiation to electricity efficiency up to 30% by increasing the solar share and using it to generate saturated steam for both high and low pressure (LP) steam turbines.

The objective of this work is to compare the two technics of generating steam in the solar field (DSG and HTF) with PTC working under the Algerian weather. Both technologies are used for preheating and boiling the water to be superheated in the HRSG, and then injected in the steam turbine (ST). The purpose of this work is to clarify which of the different distinctive may be the most efficient and feasible.

CHAPITER 3

METHODOLOGY

Chapter 3: METHODOLOGY

Chapter 3 identifies the reference NGCC power plant. Thereafter, the selections of systems which are applicable to meet the objectives of this research. Energy production, environment and financial modelling were performed to gain an overview of what is available and how these system configurations can be integrated into different locations. To arrive at a nominal cost of electricity generation. The methodology followed is now outlined.

3.1 Reference Combined Cycle Design

In order to evaluate the benefits of the converting a NGCC to an ISCC under the Algerian climate conditions, the Terga combined cycle power plant has been chosen as a reference cycle to be modified to an ISCC power plant. The Terga power plant is a combined cycle gas turbine power plant which has been connected to the Algerian grid since 2012 [78].The power plant consists of one gas turbine and one steam turbine producing 260 MW and 140 MW respectively. The used devices at the Terga power plant are manufactured by Frensh company Alstom. The power plant efficiency is around 58.78 %. Data were obtained from [78].

The GT is a GT26 Alstom type includes a rotor made of a "high pressure" turbine, four "low pressure" turbines, and 22-stage compressor. The exhaust turbine tempeture is 634.2 °C. HRSG consists of three pressure levels; one with reheating [78].

The Alstom ST stage (HP) and the second part of the turbine consists of medium-pressure stages (MP) and low pressure (LP) [78].

The technical parameters of the power plant are summarized in the table 3.1 and the figure 3.1.

Table 3.1: The technical parameters of the power plant [78]

Parameters	**Value**
Natural gas LHV	47.141 MJ/Kg
Natural gas mass flow (m_{gas})	14.48 Kg/s
Gas turbine power	260 MW
Steam turbine power	140 MW

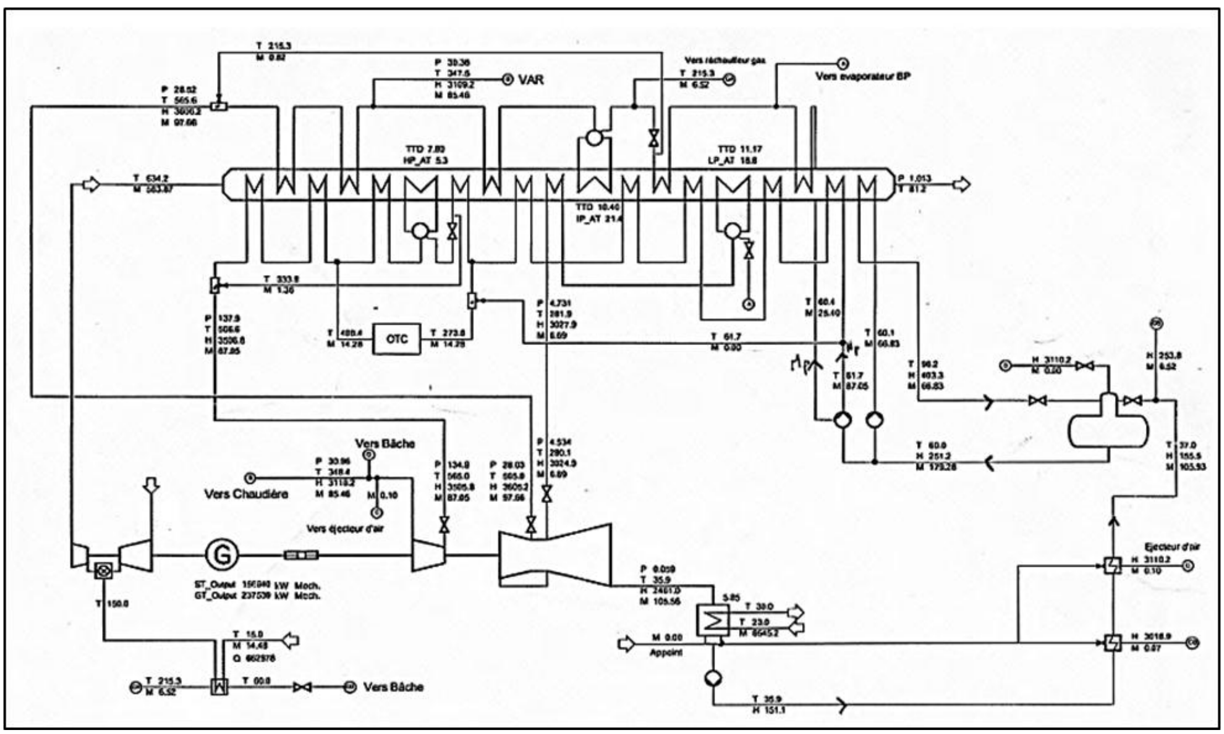

Figure 3.1: Terga NGCC schema [78]

3.2 Meteorological data

After selecting NGCC power plant, meteorological data are required to NGCC and ISCC performance. Hourly datasets of air pressure (p), relative humidity (Rh) and air temperature (Ta) are obtained from Meteonorm Database.

In addition, the DNI values in the selected locations are estimated using Hottel's method. Hottel has introduced correlations to estimate the atmospheric transmittance for four climate types, which are valid for altitudes lower than 2.5 km [79].

$$\tau_b = a_0 + a_1 * e^{\left(-\frac{k_s}{cos(\theta_z)}\right)} \quad (13)$$

$$a_0 = r_0[0.4237 - 0.00821(6 - Z)^2] \quad (14)$$

$$a_1 = r_1[0.5055 - 0.00595(6.5 - Z)^2] \quad (15)$$

$$k_s = r_k[0.2711 - 0.01858(2.5 - Z)^2] \quad (16)$$

Where:

τ_b: atmosphere transmittance for clear sky beam radiation.

$a_0, a_1 and\ k_s$ are constants for the standard atmosphere.

Z is the observer altitude expressed in km.

$r_0, r_1 and\ r_k\ are\ adimensional\ corrective\ coefficients$

Table 3.2: Correction coefficients of Hottel's correlation [79]

Kind of the weather	r_0	r_1	r_k

Tropical	0.95	0.98	1.02
Summer (average latitude)	0.97	0.99	1.02
Summer (lal. Sub-Arctic)	0.99	0.99	1.01
Winter (average latitude)	1.03	1.01	1.00

Table 3.3: Geographical location parameters [80]

Location	Latitude (degrees)	Longitude (degrees)	Height above the sea level (m)
Annaba	36.83 N	7.82 E	3
Bechar	31.64 N	2.25 W	777

The locations selected are Annaba and Bechar, with two different climates. Annaba is located in the North-East part of Algeria, means; it has a Mediterranean climate condition. The ambient air is humid compared to the author climates. Bechar is the second selected location, located in west Sahara with an arid clime. The temperature is higher than the north part and the air is drier. Furthermore, the fact that those regions are in the Algerian interconnected network makes the electricity produced easier to be injected in the network.

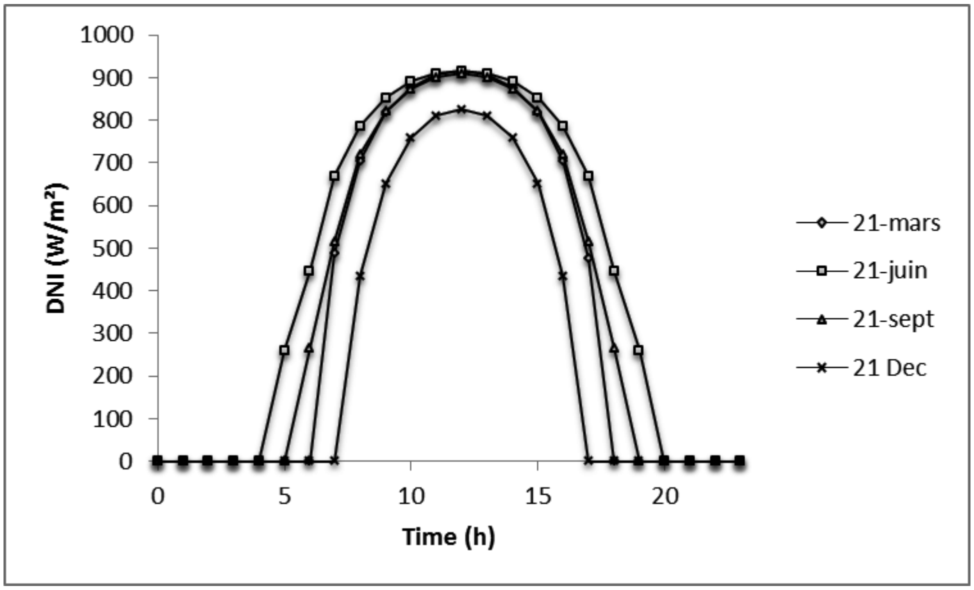

Figure 3.2: DNI at four selected days (Bechar)

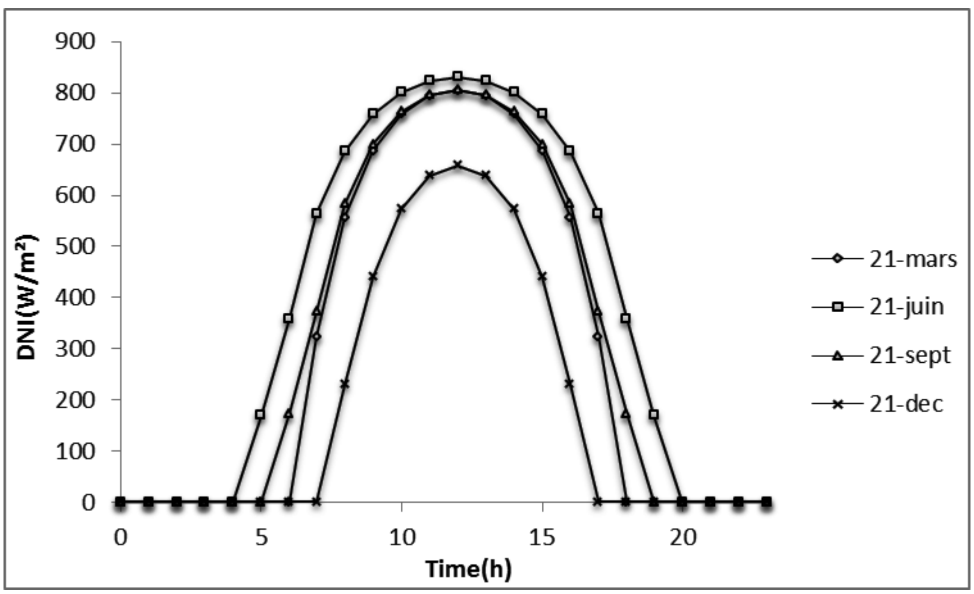

Figure 3.3: DNI at four selected days (Annaba)

3.3 ISCC Configurations

The integration of a solar field into an existing NGCC is a way to minimize the yield loss and to boost the power production [41]. The ISCC configuration is based on the reference NGCC by keeping the same sizes of the GT, HRSG and ST to save incremental costs of oversizing the power plant [67]. This integration is one of the solutions that help the environment to produce energy and reduce harmful emissions together, but, it limits the amount of the solar steam that can be injected [41]. Figure 3.4 represents a typical ISCC with PT-HFT.

The solar field contains different loops of parabolic trough collectors assemblies arranged in parallel and oriented on a north-south axis thus tracking the solar energy from east to west.

- The first Configuration is based on HTF technology includes SSG in which HTF is heated in the solar field and transfers the thermal energy to the feed water from the dearator. HTF used is Therminol VP-1 [81].The temperature of HTF is limited to 393 °C to avoid decomposition [23]. Water valves between the SSG and the HRSG are kept shut until the HTF reaches its nominal working temperature. Thereafter, the water star flowing to exchange the heat with HTF [23]. As the solar fields usually used for replace latent heat in the HRSG [23], preheated feed water is drawn from the HP preheater, evaporated and lightly superheated in the solar field and together with the steam from the conventional system superheated in the HRSG to be injected to ST. Similar configuration is already studied and used by the authors in [41]
- The second configuration is based on DSG technology does not include any SSG because the steam is produced directly in the collectors, resulting in lower investments. The design parameters of the solar field are very similar to that use the HFT. The only difference is the absorber tube thickness, which is thicker for DSG due to high working pressure [71]. A similar configuration is studied in [67]. In this study, the collector trough used is the same for [67]. The inlet steam is extracted from ST, and it is directed to the deareator. Liquid water from the deareator is pumped to the economizers of the HRSG, and to the solar field. DSG-PTC plant is coupled to the HP level in the HRSG to reduce the

pressure drops in the solar collector [47] that improve the overall efficiency. The solar field is used to produce HP steam (95 bar) with the aims of reducing thermal losses [67]. This steam pressure is optimum to be mixed with the steam from the conventional system. The collectors are used for preheating and evaporating the feed water which pumped from the deareator. The steam produced in the solar field is injected in the HP drum in the steam cycle where it is combined with the steam from the conventional system. The steam from the HP drum is superheated in the HRSG to be injected in the HP-ST.

- Both of the configurations can work as a NGCC during the night or cloudy days and as a hybrid system during the sunshine hours.

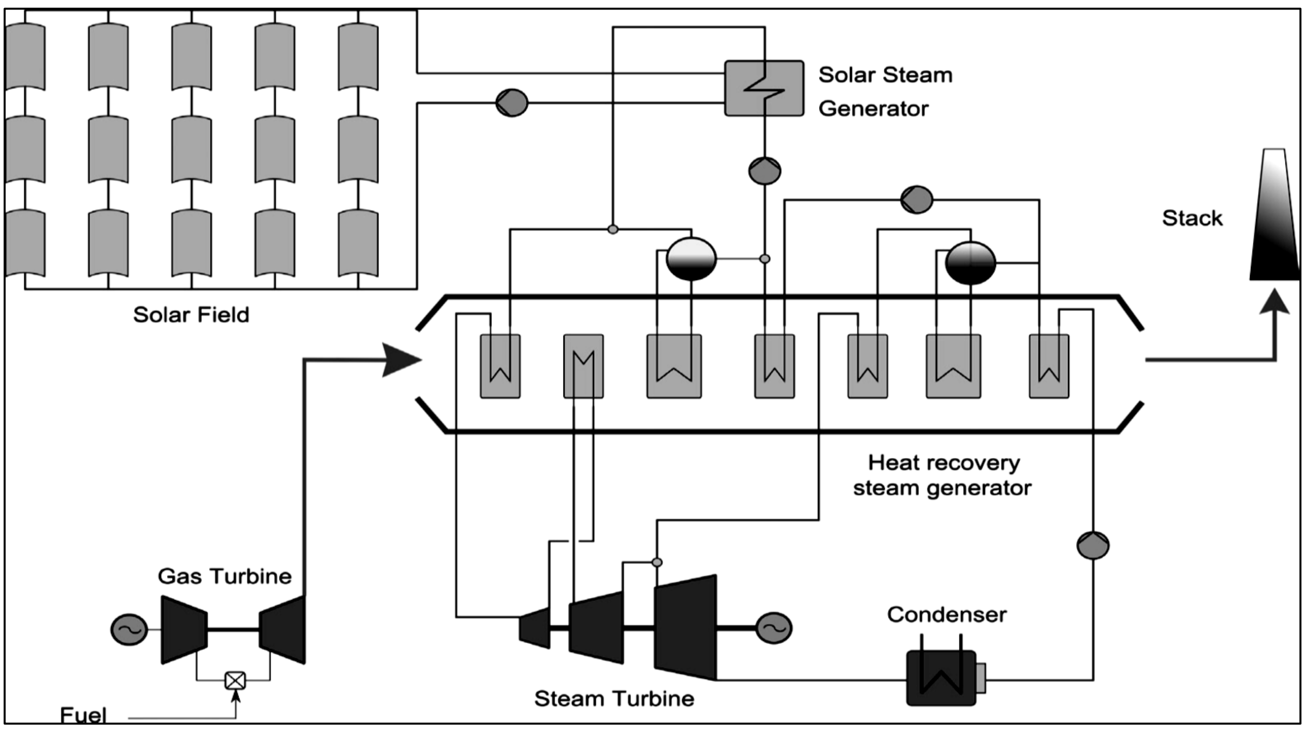

Figure 3.4: ISCC schema with solar field using PT-HTF [41]

3.4 Performance Evaluation

3.4.1 Power production metrics

For ISCC a number of metrics are used to evaluate cycle performance. These metrics can be grouped into efficiency or power production metrics, economic metrics, and environment metrics. The metrics can be either defined instantaneously or for a period of time (annualized).

3.4.1.1 Combined cycle evaluation

The performance of NGCC is considerably influenced by the ambient conditions therefore, ISCC performance is also influenced. This methodology has been previously presented by [82] and [41] for 400MW NGCC.

The assessment of the reference combined cycle is based on the ISO 2314: 2009 design conditions with T_a=15°C, P=1013 mb, and Rh=60% [41]. Those design conditions for the NGCC are not simultaneously reached at any time [67].

- **Influence of the temperature**

Temperature is the main factors affecting the performance of the NGCC [41]. When T_a rises, the mass flow of the air entering the GT decreases (the low of ideal gases) as a result a net energy yield losses implied [82]. Equations 17 and 18 illustrate the empirical relationship between the relative power output (RPO) and the inlet air temperature of the GT and the ST respectively [41]:

$$RPO_{GT-T} = -0.005024\, T_a + 1.07536 \quad (17)$$

$$RPO_{ST-T} = 6.10^{-6}\, T_a^2 - 0.001579\, T_a + 1.0224 \quad (18)$$

- **Influence of the pressure**

Atmospheric pressure is the second factor affecting the performance of the NGCC. A decrease in the pressure has an effect on the net energy of the GT. Equation 19 evaluates the relative power output of the GT [41].

$$PRO_{GT-P} = 1.08\ \frac{P}{P_{design}}\ - 0.08 \qquad (19)$$

- **Influence of the relative humidity**

Relative humidity (Rh) has a minor effect on the NGCC performance. Equation 20 illustrates the variation of the relative power output of the GT [41]:

$$RPO_{GT-Rh} = 0.00116\ Rh + 0.993 \quad (20)$$

3.4.1.2 Solar field evaluation

- **HTF technology**

The method used in this study has been used by the authors in [41]. The solar energy production is evaluated by considering the DNI irradiances for each location. The solar field is designed with Euro-trough collector modules (ET-150). Table3.4 shows the technical specifications of the collector. Some of the parameters are provided by the manufacturers for an incidence angle of (¢) of 0°C. The parameters must be corrected due to the changing in the incidence angle during the day with equation 21.this equation takes into consideration all the optic and geometric losses [41].

$$k(¢) = 1 - 2.23073 * 10^{-4}¢ - 1.1 * 10^{-4}¢^{2} + 3.18596 * 10^{-6}¢^{3} - 4.85509 * 10^{-8}¢^{4} \qquad (21)$$

K(¢) is the modifier of incidence angle.

This equation is valid for ¢ between 0 and 80 °C. Other ways, *k(¢)* is null.

The optical efficiency of the collector also has to be modified:

$$\varepsilon = k(\not{c}).\, \eta_{opt,0^\circ} \quad (22)$$

$$\eta_{opt,0^\circ} = \zeta\tau\alpha\sigma \quad (23)$$

Where

ζ is glass transmissivity

α is the solar absorptivity

τ is the mirror reflectivity

σ is the interception factor

The surface losses of the collectors are taken in account due to a part of sunlight is reflected out of the absorber:

$$A_{loss} = b * \left(d_f + \frac{b^2}{48.\, d_f}\right).\tan\not{c} \quad (24)$$

Where

b is the collector width

d_f is the focal distance of the collector.

The heat losses from the fluid to the environment by radiation are calculated as:

$$P_{Q,col-env} = (0.00154 * \Delta T^2 + 0.2021.\Delta T - 24.899 + [(0.0036.\Delta T^2 + 0.2029.\Delta T + 24.899)(\frac{E}{900}\cos\not{c})]).\, L \quad (25)$$

Where:

ΔT is the difference temperature between the fluid and the environment

L is the length of the collector

Finally, the thermal power transmitted to the working fluid is:

$$P_{Q,col-fluid} = (A_c - A_{loss}).DNI.\cos\phi.k(\phi).\eta_{opt,0°}.F_e - P_{Q,col-env} \quad (26)$$

Where:

A_c is the opening area of the collector

DNI is the hourly direct normal irradiance

F_e is the collector fouling factor.

- **DSG technology**

The aims of the use both technologies are to compare which technology is more efficient and more productive. To evaluate DSG technology, the same strategy proposed by [67], is followed. In which, the authors made several simulations with different outlet pressure to match DSG with NGCC. The results show that the net heat gain by the collector loop depends on the DNI and the outlet pressure:

$$Q_{DSG\ net,loop} = 3.4 * 10^3.DNI_{inc} + \left(\frac{100 - P_{out}}{2}\right) - 105 \quad (27)$$

Where

DNI_{inc} is the incidence DNI normal to the collector aperture area (kW)

P_{out} is the fluid pressure at the outlet of the solar field (bar)

Table 3.4: Technical parameters of the collector loops [82 and 71]

Geometrical parameters for the collector loop	
Absorber tube outer diameter(m)	0.07
Absorber tube inner diameter(m)	0.065 (HTF) / 0.055 (DSG)
Glass envelope outer diameter(m)	0.115
Glass envelope inner diameter(m)	0.109
Module length(m)	12.27
Mirror length in every module (m)	11.9
Collector Length (m)	99
Width (m)	5.76
Number of collector modules/loop	8
Focal distance (m)	1.71
Opening area (m^2)	828
Optical parameters for the collector ET-150	
Intercept factor	0.92
Mirror reflectivity	0.92
Glass transmissivity	0.945
Solar absorptivity	0.94
Peak optical efficiency	0.75

Thermal emissivity	0.04795+0.002331 T(°C)

The efficiency of the steam generation process and the instantaneous parasitic consumption of the solar field are assumed 92% and 6% respectively.

- **Scenarios operating and power production**

- **Scenario 0**

In this scenario the ISCC is operating as a NGCC, means, no solar energy is used. This scenario is considered as a benchmarked for scenario 1. The variation of the power output is calculated as:

$$P_{cc} = \left(ROP_{st-T} * P_{st,design}\right) + \left(ROP_{GT} * P_{GT,Design}\right) \quad (28)$$

$$ROP_{GT} = ROP_{GT-T} * ROP_{GT-P} * ROP_{GT-Rh} \quad (29)$$

Where

P_{cc} is the total combined cycle power output.

$P_{GT,Design}$ is the gas turbine power output at the design conditions.

$P_{st,Design}$ is the steam turbine power output at the design conditions.

- **Scenario 1**

In this scenario, the number of loops set to be 5 loops for both technologies, so the solar field size is the same for both locations. This operating mode is known as solar boosting [41]. The NGCC is operated under the full load. However, the NGCC production drops due to the variation of the weather conditions. The solar field is designed to replace the power drops. The problem with this operating mode is the power dumping. This power dumping is an extra power for the capacity of the ST [41]. So that the turbine operates in the nominal conditions, the solar dumping could be stored or taking some collectors out of the focus [69].

Power of solar field of HTF and DSG technologies:

$$P_{int-sol-sc1} = (1 - ROP_{st-T}).P_{st,design} \quad (30)$$

The net solar energy produced of HTF technology:

$$P_{sol\_ele,HTF} = ŋ_1.ŋ_2.(1 - ŋ_3).n_1.n_2.Q_{net} \quad (31)$$

The net solar energy produced of DSG technology:

$$P_{sol\_ele,DSG} = ŋ_1.ŋ_2.(1 - ŋ_3).n_1.Q_{DSG\ net,loop} \quad (32)$$

Where

$Ŋ_1$ is the process efficiency

$Ŋ_2$ is the steam turbine efficiency

$Ŋ_3$ is percent of energy consumed by the solar field

n_1 is the number of loops

n_2 is the number of collectors per loop

The total power of HTF and DSG:

$$P_{tot,sc1} = P_{int-sol-sc1} + \left(ROP_{st-T} * P_{st,design}\right) + \left(ROP_{GT} * P_{GT,Design}\right) \quad (33)$$

Power dumping of HTF and DSG:

$$P_{dumping} = P_{sol\_ele} - P_{int-sol-sc1} \qquad (34)$$

- **Scenario 2**

In this scenario, all the steam produced by the solar field is injected in the steam turbine. This mode is known as displacing mode. In this mode, the solar dumping is limited and the load of the GT is reduced to adapt the steam flow in the steam turbine, means; the mass flow of fuel used in the GT will be reduced. However, with changing the mass flow, there is a load yield losses [41]. This scenario has more environmental and economic significances because the amount of the energy generated from the solar field increases by increasing the number of solar loops therefor, the comparison between the two technologies will be done in terms of the most economic. For this operating mode, we calculate the number of loops that gives R values of 0 %, 30 % and 80 %.

Percentage of natural gas mass flow consumption:

$$R = 100 * \frac{\left(ROP_{st-T} * P_{st,design} - P_{sol_{ele}}\right)}{ROP_{st-T} * P_{st,design}} \qquad (35)$$

The power output of the GT:

$$P_{GT,sc2} = R * ROP_{GT} * P_{GT,Design} * (1 - R_{ch}) \qquad (36)$$

Where

R_{ch} is the load yield losses and it is assumed to be 7%.

The power output of the ST:

$$P_{ST,sc2} = P_{sol_{ele}} + R * ROP_{st-T} * P_{st,design} \qquad (37)$$

The total power of the ISCC:

$$P_{issc,sc2} = P_{GT,sc2} + P_{ST,sc2} \qquad (38)$$

The overall efficiency for scenario 1 and scenario 2:

The ISCC efficiency could be calculated using two laws [37]. The first law is defined as

$$\eta_1 = \frac{W}{Q_{fuel}+Q_{solar}} \qquad (39)$$

Where W is the electricity production of the cycle, Q_{fuel} is the " heating rate" input from the fuel, and Q_{solar} is the energy rate input from the solar. If the GT is not working, this efficiency is the so called solar to electric efficiency.

The heating rate is defined as $Q_{fuel}=m_{fuel}.LHV$ where the lower heating value of the fuel (per unit mass) and m_{fuel} is the mass flow rate of the fuel used in the cycle.

The energy rate input from the solar is defined as $Q_{solar}=q.A_a$ where q is the incident solar radiation and A_a is the collector area.

The second law efficiency for an ISCC is defined as

$$\eta_2 = \frac{w}{E_{fuel} + E_{solar}} \qquad (40)$$

Where E_{fuel} is the exergy rate of the fuel and E_{solar} is the exergy rate of the solar input.

3.4.2 Economic and environmental metrics

3.4.2.1 CO_2 emissions

The main environmental indicator to design a sustainable electricity generation systems, is to reduce the worldwide CO_2 emissions. They are many publications compare and quantify the amounts of the CO_2 emissions associated with the production of electricity of each technologies collected at Open Energy Information (EI).The chart below shows and compares the median value of equivalent carbon dioxide (CO_2 eq).

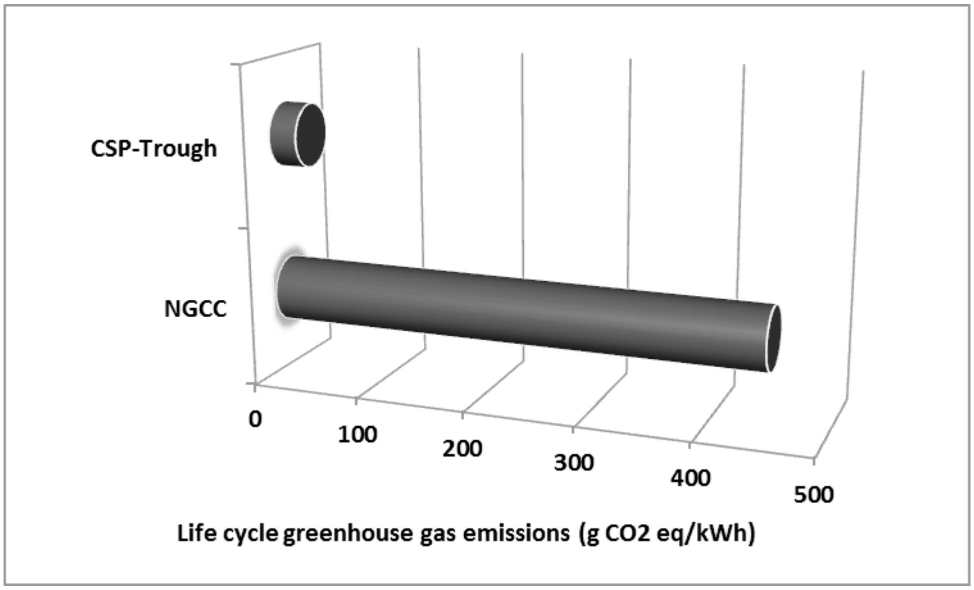

Figure 3.5: Median value of life-cycle of greenhouse gas emissions (gCO_2 eq/ kWh) [84]

From the figure 3.5, the median value of equivalent carbon dioxide (CO_2 eq) emissions for the electricity produced from the CSP-PTC technology is 26 gCO_2 eq/kWh. While the median value for electricity produced from NGCC is 449 gCO_2 eq/kWh [84]. The difference of CO2 eq for the production of a kilowatt hour between the two technologies is 443 gCO_2 eq.

3.4.2.2 Levelised cost of electricity

The levelised cost of electricity (LCOE) is the concept used to evaluate the cost of the electricity generated by a power plant. It is known as the sale price of the electricity produced that incorporates both the initial investment cost and the on-going operation costs. Basically, it is used by the practitioners in the field of energy to compare different options for delivering energy to the customers. Many prices included in the on-going operation costs depends on the market what makes a gap between LCOE and the real financial costs [24]. The main assumption that could be variable in the definition of the LCOE is:

- The interest rate "r" that is assumed constant during the lifetime of the plant.

The price to sell the electricity produced is constant over the whole lifetime of the plant.

The levelised cost of electricity can be calculated by equation 41, where C_0 is the total investment cost including contingencies, C_{dec} is the cost for decommissioning, C_{fuel} is the annual fuel cost, $C_{O\&M}$ is the annual operation and maintenance costs and E_{net} is the net annual electricity production.

$$LCOE = \frac{C_0 * CRF + C_{dec} * G + C_{fuel} + C_{O\&M}}{E_{net}} \qquad (41)$$

The term *CRF* is the capital recovery factor. It is used to transform the capital cost into an annual payment over the lifetime of the plan. It is defined by:

$$CRF = \frac{r * (1 + r)^n}{(1 + r)^n - 1} + r_{ins} \qquad (42)$$

The term r_{ins} is the annual insurance rate. It reduces the gap between LCOE and the true financial costs.

The terms *G* is used to transform the fixed cost of decommissioning that is paid in the end of the project into constant annual payment over the lifetime of the plant. It is defined by:

$$G = \frac{r}{(1 + r)^{n+1} - (1 + r)} \qquad (43)$$

However, according to the Organisation for Economic Co-operation and Development (OECD) report in 2010, the cost of CO_2 emissions to the atmosphere must be included in the LCOE equation [85]. LCOE becomes as:

$$LCOE = \frac{C_0 * CRF + C_{dec} * G + C_{fuel} + C_{O\&M} + C_c}{E_{net}} \qquad (44)$$

Where C_c is the carbon cost.

The LCOE will be influenced in the near future by two main factors are:

- **Influence of natural gas price**

Algeria owns one of the highest reserves of the natural gas, means it can be classified on the high resources trajectory. The share of fuel cost over the total LCOE increases due to the constant formula of the LCOE. The cost of the natural gas is between 4 to 9 \$/MM Btu. By increasing the price of the natural gas, LCOE will increase.

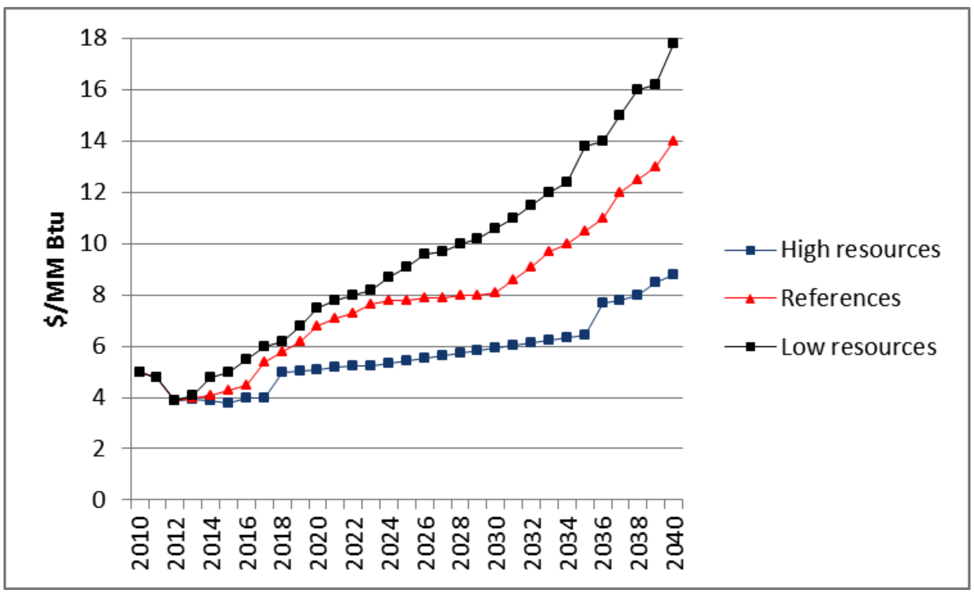

Figure 3.6: AEO 2014 projections of natural gas prices till 2040 [86]

- **Influence of CO_2 emissions price**

According to the Synapse's 2015 CO_2 price forecast, the price of CO2 emitted from a power plant electricity generation will continuous increasing from 2020 to 2050 significantly. Furthermore, this report evaluated the price in three categories. The figure 3.6 illustrates the CO_2 emissions price trajectories [86].

- The **Low case** forecasts a CO_2 price that starts in 2020 at 15 $/ton to achieve 45 $/ton in 2050. This forecast represents a scenario in which the clean power plan is relatively lenient and excludes the state policies control.
- The **Mid case** forecasts a CO_2 price that starts in 2020 at 20 $/ton to achieve 85 $/ton in 2050. This scenario includes reasonable state policies' implementations.
- The **High case** forecasts a CO_2 price that starts in 2020 at 25 $/ton to achieve 120 $/ton in 2050. This scenario includes more stringent state policies.

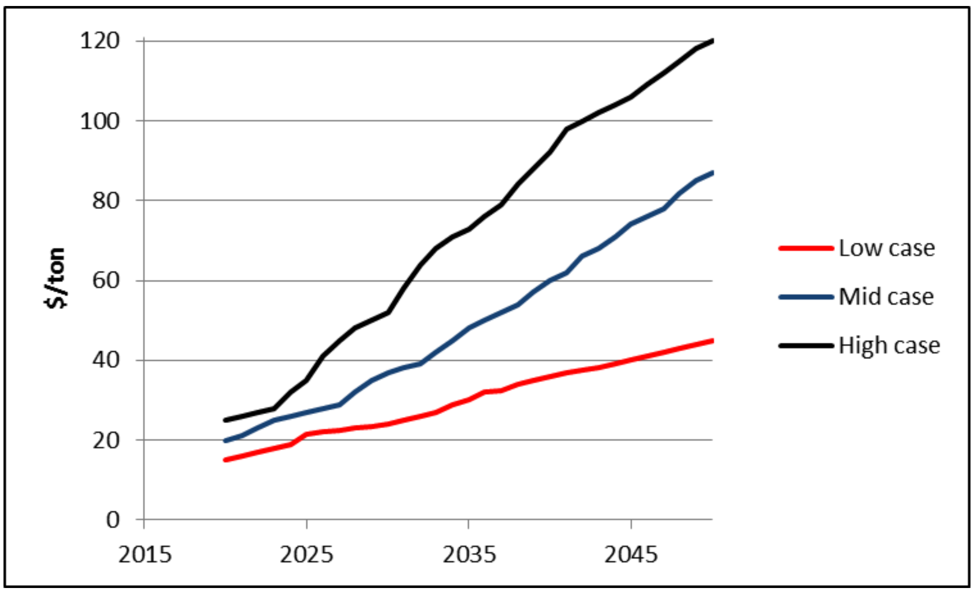

Figure 3.7: Synapse 2015 CO_2 price trajectories [86]

After COP 21 in Paris, the cost of CO_2 emissions will increase significantly in the future that affect the LCOE. The assessment of renewable energies costs ignore the fuel cost because of the resources are free. Secondly, using renewable energies, the CO_2 emissions are considerably reduced due to the lack of using fossil fuels in the electricity generation; only emissions from construction and manufacturing materials used to transform the row materials into final products (renewable energies devices) [88]. Thus, the carbon cost is reduced significantly.

3.5 Economic data

For this study, the economic data are taken from the previous publications. In addition, some costs are assumed.

3.5.1 Combined cycle assumption

The capital cost of the combined cycle power plant is assumed to be between 876 and 1050 $/kW of net installed capacity while the fixed O&M cost is estimated to be 13.1-14.91 K$/MW annually [87]. The capacity factor of the natural gas combined cycle power plant is assumed to be 61.8 % and 87 % for the ISCC power plant [38]. The price of the natural gas would be raised according to Annual Energy outlook 2014 (AEO) [87].

3.5.2 CSP assumption

The capital cost of a CSP plant without energy storage based on the references, is estimated to be between 3000 and 5067 $/kWe [87]. In this study the installation cost is obtained from IRENA report and it is estimated to be 4600 $/kW [89]. Since the ISCC has two sources of heat (fossil and water) and operates independently, it is decisive to ensure the quality of water that the solar field will not be affected in the long terms [39]. The capacity factor for the CSP plant is estimated 30%.

Table 3.5: Parameter and data used in economic analysis

Economic parameter	Value	Units	References
Investment			
CC installation cost	900	k$/MW	[87]
SF installation cost without power block	4600	$/kW	[89]
Land cost (SF)	0.1-1	$/m²	-
Surcharge for engineering (SF,CC)	7	%	[90]
Site supervision and project management (SF,CC)	4	%	[90]

Operation and maintenance			
Annual Fixed O&M (CC)	14	k$/MW	[87]
Annual variable O&M (CC)	2	$/MWh	[87]
Annual Fixed O&M (SF)	49.9	$/kW	[89]
Annual O&M equipment cost (SF)	1	%	-
Financial parameter			
Interest rate	7	%	-
Plant lifetime	25	Year	[38]
Insurance rate	3	%	-
Fuel cost			
Natural gas cost	5	$/MM Btu	[88]
Water cost	0.1(HTF)-2(DSG)	$/MWh	-
Emission cost			
CO_2 cost	5	$/ton/year	[88]

CHAPITER 4

RESULTS & DISCUSSION

Chapter 4: RESULTS & DISCUTION

Chapter 4 presents and discuss the results obtained from the configurations proposed in term of power generation, LCOE and annual CO_2 saving.

4.1 Results of Scenario 1 & 0

As the weather conditions parameters vary from summer to winter and represent the maximum and the minimum values, two particular days are selected for the simulations and they are 21st Jun and 21st December. The most important parameters of the weather conditions are shown in the figures below.

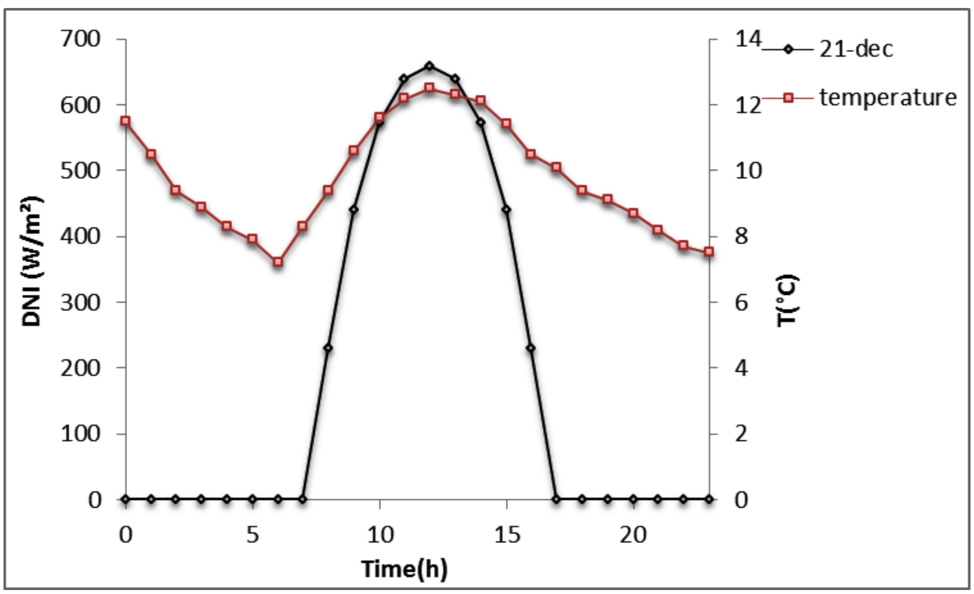

Figure 4.1: Daily ambient temperature and DNI at Annaba (21 Dec)

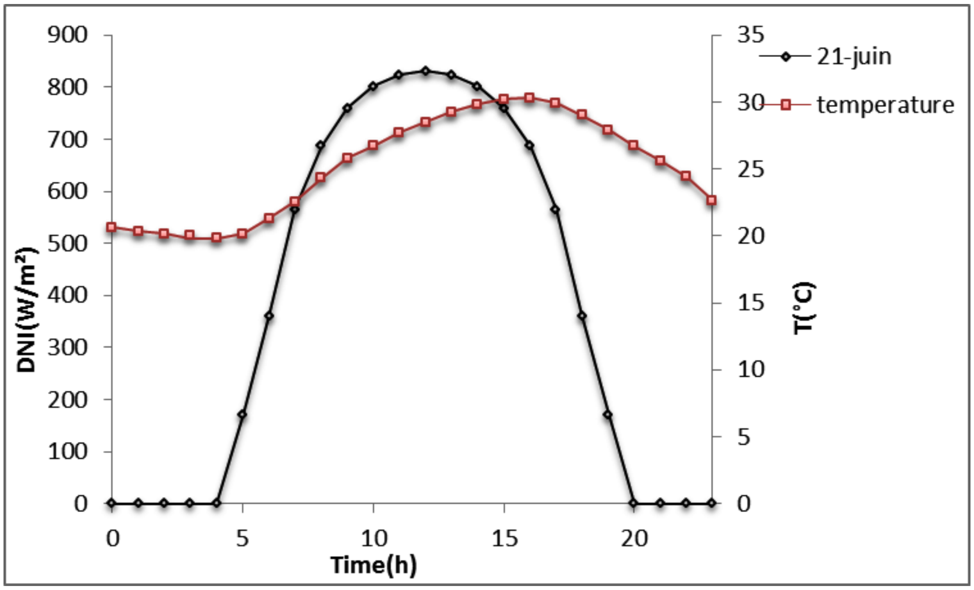

Figure 4.2: Daily ambient temperature and DNI at Annaba (21Jun)

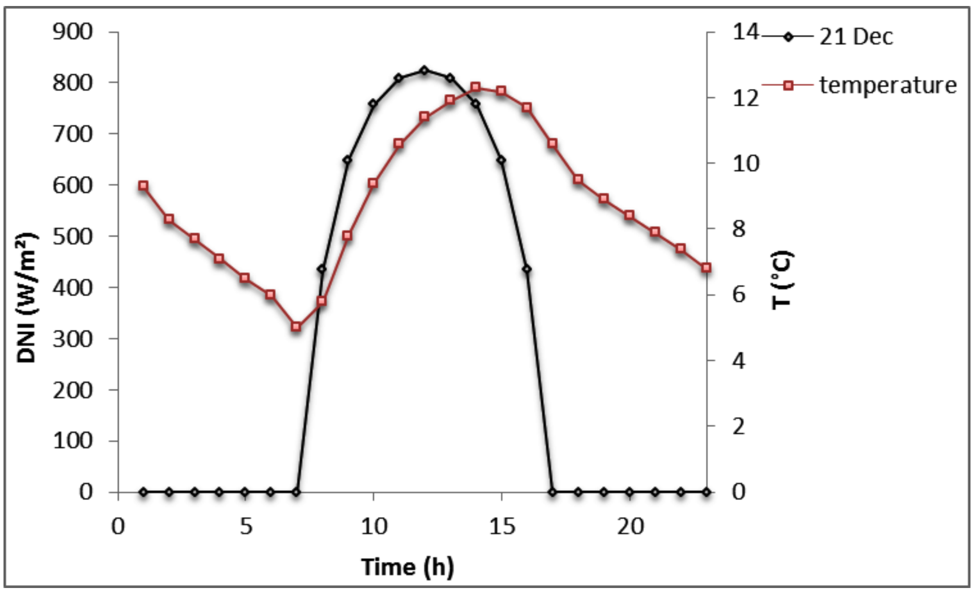

Figure 4.3: Daily ambient temperature and DNI at Bechar (21 Dec)

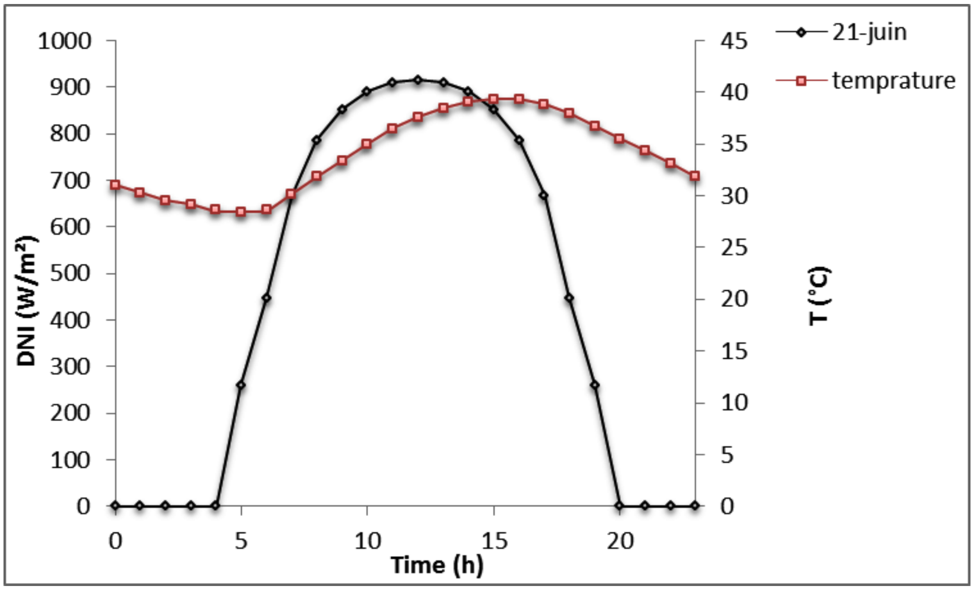

Figure 4.4: Daily ambient temperature and DNI at Bechar (21 Jun)

It can be observed that the ambient temperature reaches coincidentally almost the maximum value when the DNI is on the top. This makes the power produced from the solar field an improvement of the NGCC power plant to boost the total ISCC power plant generation. Daily simulations have been figured out for both locations and for the three configurations with 5 loops: the NGCC, the ISCC with HTF and the ISCC with DSG.

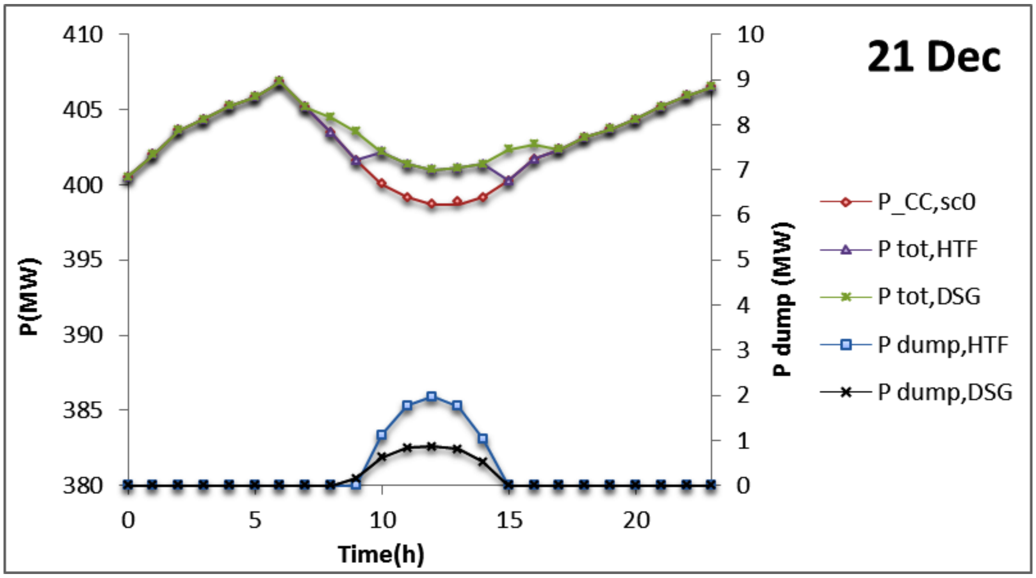

Figure 4.5: Assessment of ISCC with 5 loops at Annaba (21 Dec) for scenario 0 and 1

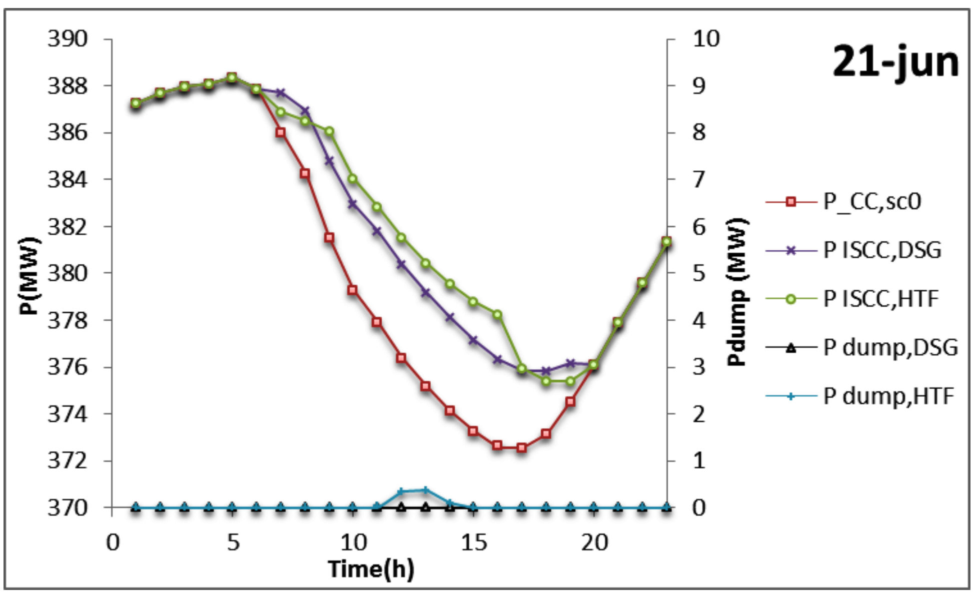

Figure 4.6: Assessment of ISCC with 5 loops at Annaba (21 Jun) for scenario 0 and 1

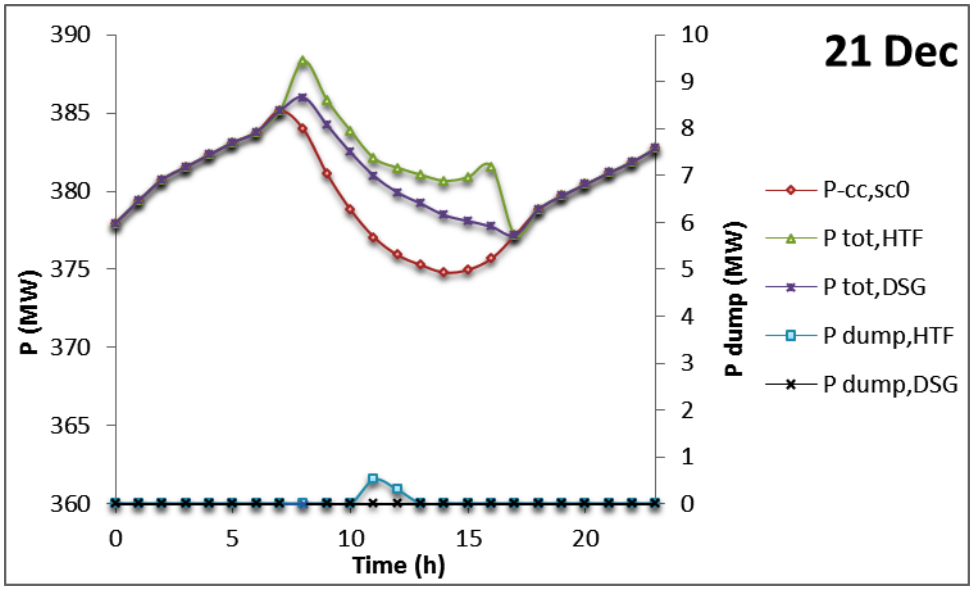

Figure 4.7: Assessment of ISCC with 5 loops at Bechar (21 Dec) for scenario 0 and 1

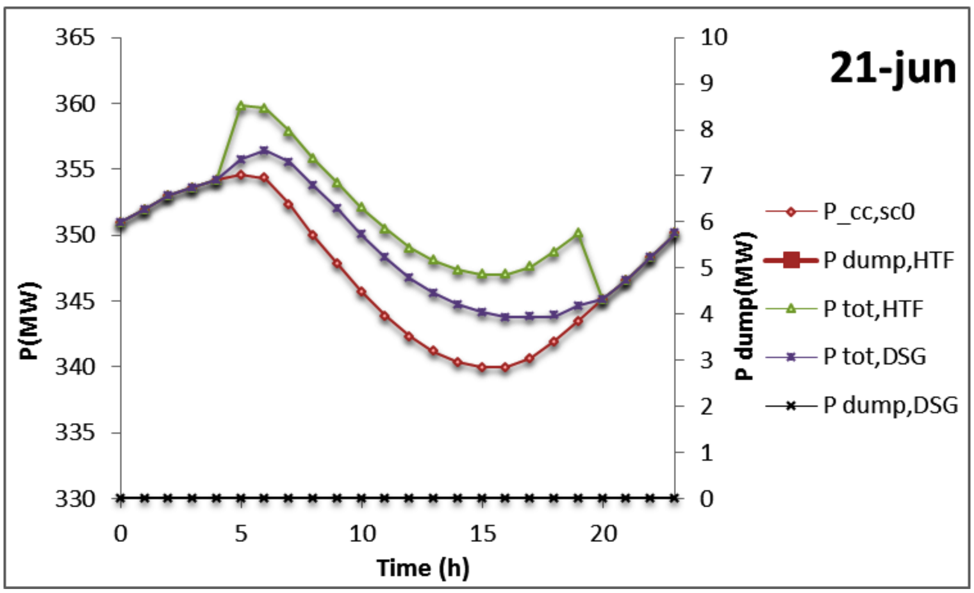

Figure 4.8: Assessment of ISCC with 5 loops at Bechar (21 Jun) for scenario 0 and 1

Figures 4.5, 4.6, 4.7 and 4.8 represent the power production of the NGCC and ISCC for scenario 0 and 1. The objective of those graphs is to show the effect of the variation of ambient conditions. It is well shown that the performance of the NGCC decrease significantly in summer compared to winter season due to the big gap between the design conditions and the ambient conditions. Instead of that, the power production of the CSP is much higher in summer what makes ISCC power plant an important hybridization.

From the figures, it is clearly pointed out that the performance of the NGCC in Bechar is inefficient compared to Annaba. However, it is totally opposite for the CSP power production. Furthermore, Annaba has the highest power dumping that is explained as the limits of the ST to absorb more solar steam.

Table 4.1: Assessment of LCOE and power capacity at Bechar (21 Jun at 12:00 h) for scenario 0 and 1

	NGCC	CSP		ISCC	
		HTF	DSG	HTF+NGCC	DSG+NGCC
Power capacity (MW)	342.25	6.33	4.46	348.58	346.71
LCOE (c$/kWh)	2.9	22.56	23.20	3.076	3.028

Table 4.2: Assessment of LCOE and power capacity at Bechar (21 Dec at 12:00 h) for scenario 0 and 1

	NGCC	CSP		ISCC	
		HTF	DSG	HTF+NGCC	DSG+NGCC
Power capacity (MW)	375.26	5.56	3.92	380.82	379.18
LCOE (c$/kWh)	2.9	22.56	23.18	3.041	3.002

Table 4.3: Assessment of LCOE and power capacity at Annaba (21 Jun at 12:00 h) for scenario 0 and 1

	NGCC	CSP		ISCC	
		HTF	DSG	HTF+NGCC	DSG+NGCC
Power capacity (MW)	375.13	5.65	4.03	380.78	379.19
LCOE (c$/kWh)	2.9	23.29	23.33	3.048	3.006

Table 4.4: Assessment of LCOE and power capacity at Annaba (21 Dec at 12:00 h) for scenario 0 and 1

	NGCC	CSP		ISCC	
		HTF	DSG	HTF+NGCC	DSG+NGCC
Power capacity (MW)	398.72	4.26	3.16	402.98	401.88
LCOE (c$/kWh)	2.9	23.33	23.39	3.005	2.979

LCOE of the NGCC is constant for both locations and it is 2.9 c$/kWh where the cost of electricity from conventional system in Algeria, is fixed and well known (2.2 Dinar/kWh) equivalent to 2 c$/kWh, means, the estimations taken are in the norms. Furthermore, LCOE from the solar field varies in Bechar from 23.18 to 23.20 c$/kWh for DSG and 22.56 c$/kWh for HTF, and in Annaba from 23.33 to 23.39 c$/kWh for DSG and 23.29 to 23.33 for HTF. According to IRENA, LCOE from CSP-PTC is currently in the range of 20 to 36 c$/kWh [89], means, those results are in the norms.

Instead LCOE of NGCC, LCOE of ISCC is variable for each location and depends on the local solar thermal potential. It is slightly less in Annaba with the range of 2.979 to 3.006 c$/kWh for ISCC-DSG.

4.2 Results of Scenario 2

Table 4.5 and 4.6, show the number of loops needed to replace the power from GT. Generally, the number is higher in winter due to the limitation of the DNI.

Table 4.5: Number of loops (21 Jun at 12:00 h) for scenario 2

	Bechar		Annaba	
R (%)	HTF	DSG	HTF	DSG
0	114	159	125	174
30	80	111	87	122
80	23	32	25	35

Table 1: Number of loops (21 Dec at 12:00 h) for scenario 2

	Bechar		Annaba	
R (%)	HTF	DSG	HTF	DSG
0	126	179	165	222
30	89	126	116	156

80	26	36	33	45

ISCC performance is variable because of the influence of the ambient conditions. Thus, it is necessary to take the biggest number of loops to ensure the sufficient power plant generation over the whole year.

Table 4.7: total results of power capacity against the ratio of natural gas consumption (Bechar, 21 Jun at 12:00 h) for scenario 2

R (%)	P_s (MW)		P_{st} (MW)		P_{GT} (MW)	P_{dump} (MW)		P_{iscc} (MW)	
	HTF	DSG	HTF	DSG	-	HTF	DSG	HTF	DSG
0	154.98	158.41	154.98	158.41	0	14.98	18.41	154.98	158.41
30	108.49	110.89	148.41	150.81	58.03	8.41	10.81	206.44	208.84
80	31	31.68	137.47	138.15	154.75	0	0	292.22	292.9

Table 4.8: total results of power capacity against the ratio of natural gas consumption (Annaba, 21 Jun at 12:00 h) for scenario 2

R (%)	P_s (MW)		P_{st} (MW)		P_{GT} (MW)	P_{dump} (MW)		P_{iscc} (MW)	
	HTF	DSG	HTF	DSG	-	HTF	DSG	HTF	DSG

0	186.29	179.02	186.29	179.02	0	46.29	39.02	186.29	179.02
30	130.39	125.31	170.8	165.72	67.09	30.8	25.72	237.89	232.81
80	37.26	35.80	145.26	143.57	178.93	15.26	3.57	324.19	322.5

Table 4.9: Total results of power capacity against the ratio of natural gas consumption (Bechar, 21 Dec at 12:00 h) for scenario 2

R (%)	P_s (MW)		P_{st} (MW)		P_{GT} (MW)	P_{dump} (MW)		P_{iscc} (MW)	
	HTF	DSG	HTF	DSG	-	HTF	DSG	HTF	DSG
0	139.86	140.34	139.86	140.34	0	0	0.34	139.86	140.34
30	97.90	98.23	139.24	139.58	66.24	0	0	205.48	205.82
80	27.97	28.07	138.23	138.33	176.64	0	0	314.67	314.77

Table 4.10: Total results of power capacity against the ratio of natural gas consumption (Annaba, 21 Dec at 12:00 h) for scenario 2

R (%)	P_s (MW)		P_{st} (MW)		P_{GT} (MW)	P_{dump} (MW)		P_{iscc} (MW)	
	HTF	DSG	HTF	DSG	-	HTF	DSG	HTF	DSG
0	140.58	140.53	140.58	140.53	0	0.58	0.53	140.58	140.53
30	98.41	98.37	139.72	139.67	72.54	0	0	212.21	212.17
80	28.12	28.11	138.28	138.27	193.44	0	0	331.72	331.71

From the table 4.8 and 4.7, the power dumping is present in summer (21st Jun) due to the extra loops taken in account while there is no solar power dumping in winter (21st Dec). This extra power could cause problems in ST. The only solution is to oversize the ST power.

Next, the total ISCC power is decreasing by increasing the solar share because the power abducted from the GT could not be replaced by the solar field and even the ST is designed to be the same of the CCGT.

Table 4.11: Assessment of LCOE and annual CO_2 emissions saving (21 Jun at 12:00 h)

R	LCOE (c$/kWh)				Annual CO_2 saving (Tonne)			
	Bechar		Annaba		Bechar		Annaba	
	HTF	DSG	HTF	DSG	HTF	DSG	HTF	DSG
0	22.55	23.19	23.26	23.30	601.428	614.728	679.037	706.612
30	9.77	10.09	10.44	20.17	421.014	430.328	475.311	494.579
80	3.97	4.03	4.10	4.06	120.301	122.939	135.792	141.330

Table 4.12: Assessment of LCOE and annual CO2 emissions saving (21Dec at 12:00 h)

R	LCOE (c$/kWh)				Annual CO_2 saving (Tonne)			
	Bechar		Annaba		Bechar		Annaba	
	HTF	DSG	HTF	DSG	HTF	DSG	HTF	DSG

0	22.56	23.20	23.33	23.38	530.5	532.32	533.231	533.042
30	8.92	9.13	8.94	8.95	371.342	372.594	373.277	373.125
80	3.79	3.82	3.78	3.78	106.092	106.471	106.661	106.623

From table 4.11 and 4.12, the LCOE of the ISCC and the annual amount of CO_2 emissions decrease by minimizing the share of the solar field. The LCOE of ISCC in both locations with 20% share is a legitimate price comparing to the feet in tariff set by the government that is 7.64 c$/kWh (see Appendix). To deduce, both technologies in both locations are convenient to be installed. However, using DSG is more suitable solution to reduce CO_2 emissions.

CHAPITER 5

CONCLUSION & FURTHER WORK

Chapter 5: CONCLUSION & FURTHER WORK

This study provides an economic, environmental and performance assessments of a standalone NGCC and integrating solar field (PTC) using both configuration DSG and HTF. The simplicity, deployability, and predicted cost make PTC an edge over other existing technologies.

The performance assessment was done by using equations from the references [41] and [67]. The results show reasonable values for both configurations. The limited solar share is attributed to limitations in the size of the ST, increasing in the loops number of the solar field for scenario 1 causes a power drop and decreases the total ISCC power for scenario 2.

The economic and environmental analysis for both scenarios shows that the ISCC has less LCOE when compared to standalone CSP technologies. The first scenario concluded that ISCC-DSG is the favorable technology and LCOE to be in the range of 2.979-3.006 c$/kWh. The second scenario deduced that both technologies are convenient to be installed, but DSG is more suitable in terms of CO_2 emissions reduction. Besides, only an amount of solar share (20%) can reduce annually at least 106 tons of CO_2 emissions, install more this technology in Algeria could be an alternative solution for the energy transition and shift from conventional to renewable resources.

The results from this thesis show the potential of integrating solar combined cycle power plants, for future work a number of measures can be implemented for further studies:

- It would be interesting to compare other CSP technologies using the identical assumptions.

- It may also be interesting to compare the different model of integrating, especially a model of integrated solar gas-turbine or integrating storage system in ISCC to assess the profitability of using such systems.
- The economic analysis in this thesis is evaluated based on many assumptions. Further work, should be assessed taking into account a detailed capital cost reductions of each component of CSP plants and varying the fuel prices and carbon taxes.

The green message, the ISCC plants can pave the way and would be more competitive than NGCC plants with imposing carbon pricing, increasing natural gas prices and reducing the CSP capital costs in the future.

Genaral recommendation

Algeria has already started to set some policies and develop a national program encouraging the renewable energies. Nevertheless, some lacks still now exist regarding policy awareness, institutional regulatory framework, capacity building. Some suggested recommendations aim to support the promotion of renewable energies are:

- Removing subsidies on electricity prices from fossil fuels sources.
- Removing subsidies from fossil fuels prices because they contribute to the fossil fuel projects and they are harmful to the environment.
- Evaluating energy projects based on the more efficient and less CO_2 emitted.
- Creating a more competitive market for renewable energies by offering credit enhancement and attracting more funds and financial investors .
- Implimenting carbon taxes on the industries and raising in feed-in tariffs of renewable energies to ensure investment in this domain.
- Reinforce internal communication between different actors and responsible authorities on renewable energies implementation.

- Accepting environmental transactions to reduce CO_2 emissions and increasing interest in alternative energy sources (Kyoto Protocol, COP21, etc,.).
- International collaboration and cooperation level with energy research institutions and universities to ensure technological knowledge; for instant Algeria establishes an institute for water and energy including climate change (PAUWES) in collaborations with many German actors for teaching and consulting.

APPENDIX

Appendix A: Legislative and Regulatory Texts of Renewable Energies in Algeria

The adoption of the legal framework conducive to the promotion of renewable energy and the realisation of infrastructures for electricity production based on renewable energies, is defined primarily through the following measures [91]:

- Law N°. 02-01 of 22 Dhu Al Kaada 1422 corresponding to February 5th, 2002 amended and supplemented, on electricity and gas distribution by pipeline (OJ n° 08 of 6 February 2002);
- Law N°. 04-09 of 27 Jumada Ethania 1425 corresponding to August 14th, 2004 on the promotion of renewable energy in the context of sustainable development (OJ n° 52 of 18 August 2004);
- Law N°. 09-09 of 13 Moharram 1431 corresponding toDecember 30th, 2009 Finance Act 2010, in particular Article 64 establishing the National Fund for
Renewable Energies and Cogeneration (OJ n° 78 of 31 December 2009);
- Law N°. 11-11 of 16 Sha'ban 1432 corresponding to July 18th, 2011 supplementary budget law for 2011, in particular Article 40 amending Article 63 of Law No. 09-09 (OJ n°. 40 of July 20 2011);
- Law N°. 14-10 of 8 Rabie El Aouel 1436 corresponding to December 30th, 2014 finance law for 2015, in particular Article 108 which provides for the merger of the two special funds "The National Fund for Energy efficiency and the National Fund for Renewable Energy and Cogeneration "(OJ No 78 of 31 December 2014);

- Executive Decree N°. 13-218 of 9 Sha'ban 1434 corresponding to June18th, 2013 laying down the conditions for granting premiums for the costs of diversification of electricity production. (OJ n° 33 of 26 June 2013);
- Executive Decree N°. 15-69 of 21 Rabie Ethani 1436 corresponding to February 11th, 2015 fixing the origin certification procedures of renewable energy and the use of such certificates; (OJ n°. 09 of February 18th, 2015);
- Executive Decree N°o. 15-319 of Aouel Rabie El Aouel 1437 corresponding to December 13th, 2015 laying down the operating procedures of the trust account n°. 302-131 entitled "National Fund for Energy Efficiency and for Renewable Energy and Cogeneration "

- ❖ Decree of 2 Rabie Ethani 1435 corresponding toFebruary 2nd, 2014 fixing the guaranteed purchase prices in terms of their application for the electricity produced from plants using wind energy (OJ n°23 of April 23th, 2014);
- ❖ Order of 2 Rabie Ethani 1435 corresponding to February 2nd, 2014 setting the feed-in tariffs and conditions of application for electricity produced from plants using photovoltaic solar power (OJ n° 23 of April 23th, 2014) ;
- ❖ Decree of 6 Dhu Al Kaada 1435 corresponding to September 1st, 2014 fixing the guaranteed purchase prices and terms of their application for electricity produced from plants using cogeneration sector (OJ n° 18 of April 8th, 2015);
- ❖ Decree of 14 Safar 1429 corresponding to February 21st, 2008 fixing the technical rules connecting to the electricity transmission network and the rules of conduct of the electrical system (OJ n°. 25 of May 18th, 2008).
- ❖ Interministerial order of April 19th, 2008 on Adoption of the Technical Regulation on "Photovoltaic Module (PV) crystalline silicon terrestrial ".

Appendix B: Electricity selling price from renewable energies [92].

Solar share (%)	Bonus (%)	Electricity selling price (c$/kWh)
25+Cogeneration	360	13.53
100	300	11.76
25	200	8.82
20-25	180	8.24
15-20	160	7.64
10-15	140	7.06
5-10	100	5.88
0-5	---	2.94

Appendix C: Assessment of ST Production

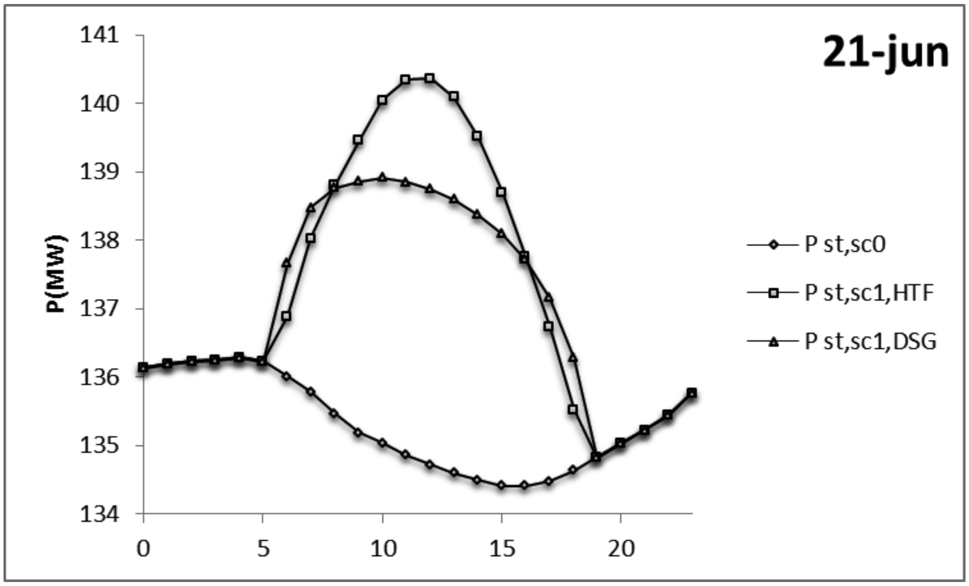

Figure 5.1: Assessment of ST production at Annaba (21 Jun) for scenario 0 and 1

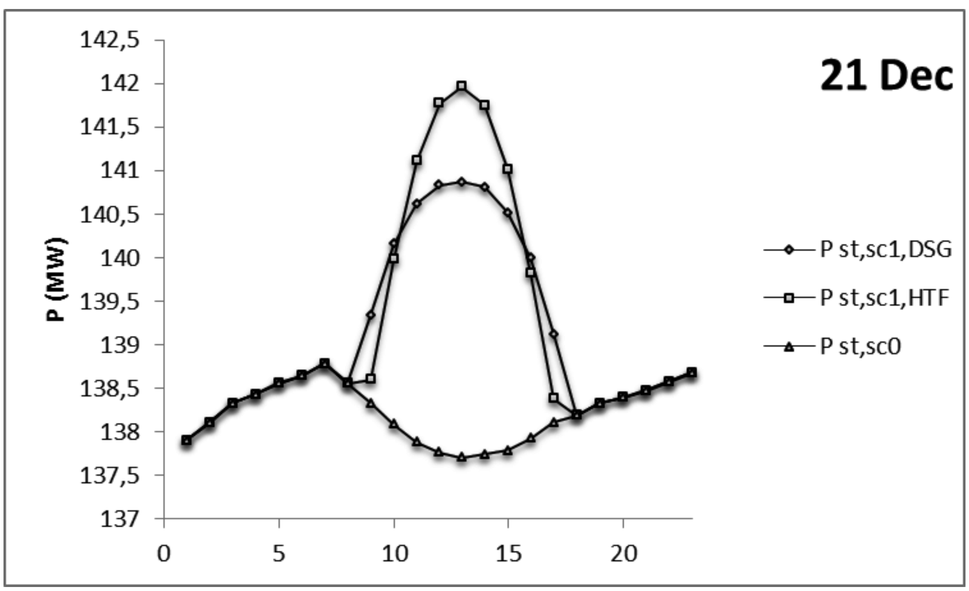

Figure 5.2: Assessment of ST production at Annaba (21 Dec) for scenario 0 and 1

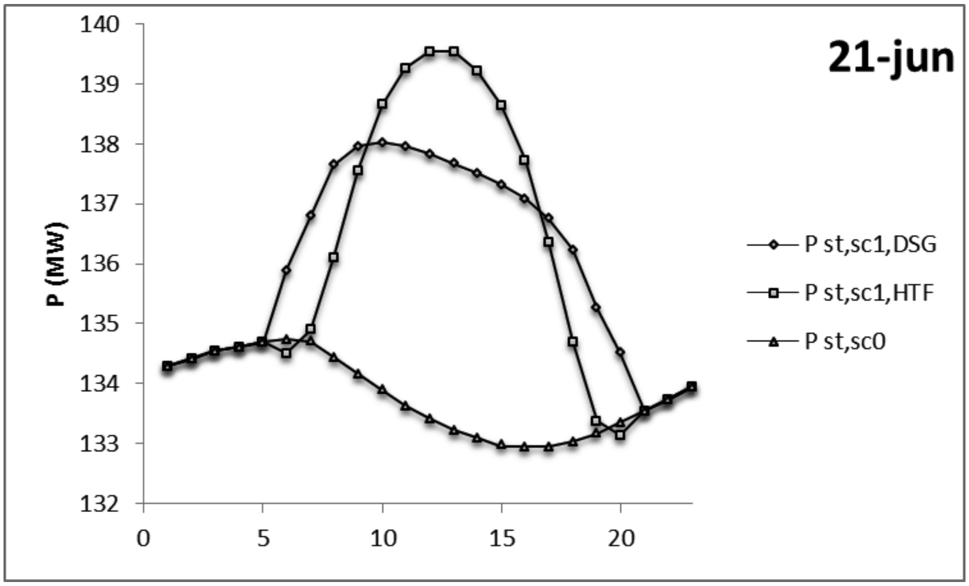

Figure 5.3: Assessment of ST production at Bechar (21 Jun) for scenario 0 and 1

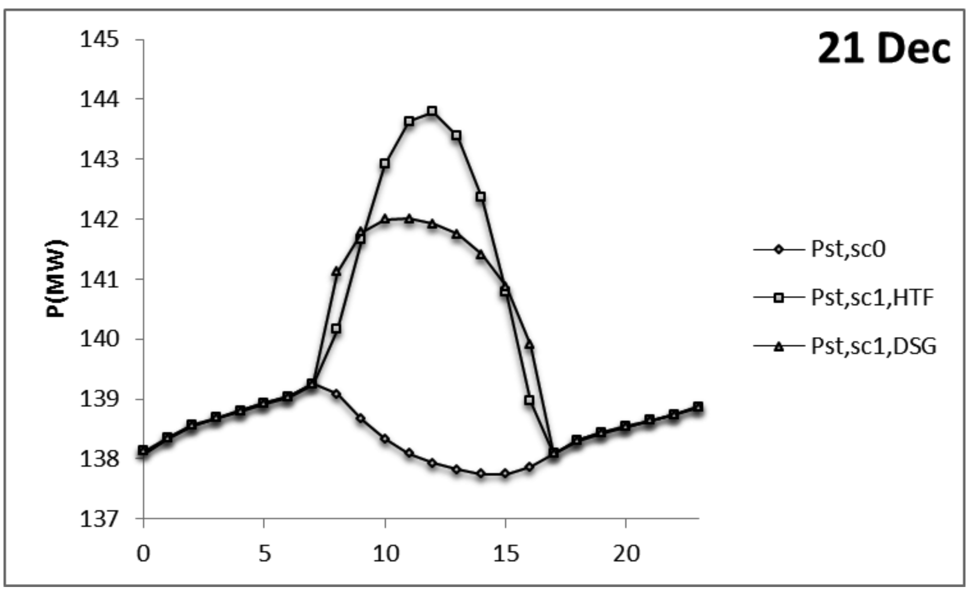

Figure 1: Assessment of ST production at Bechar (21 Dec) for scenario 0 and 1

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Summary:

My final project study is within the field of renewable energies, and particularly solar energy. This project presents a study of Integrated Solar Combined Cycle (ISCC) for an existing Natural Gas Combined Cycle (NGCC) power plant under two different locations in Algeria.

This study consists of three parts:

- The first part: Performance evaluation of the NGCC under two different locations.
- The second part: Performance evaluation of the ISCC using the two configurations; direct steam generation (DSG) and heat transfer fluid (HTF).
- The last part: Assessment of Levelised cost of electricity (LCOE) and the impact on the environment.

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Keywords:
Natural gas combined cycle, Direct steam generation, Heat transfer fluid, Levelised cost of electricity, Carbon reduction.

Résumé :

Mon projet de fin d'étude rentre dans le domaine des énergies renouvelables, et en particulier l'énergie solaire. Ce projet présente une étude d'un cycle combiné solaire intégré pour une centrale thermique existant dans deux endroits différents

Cette étude se compose de trois parties :

- La première partie : Evaluation de la performance d'un cycle combiné à base du gaz naturel dans deux endroits différents.
- La deuxième partie : Evaluation de la performance de l'intégration de l'énergie solaire au cycle combiné en utilisant deux techniques ; la production directe de la vapeur et le fluide de transfert de chaleur.
- La dernière partie : Evaluation du prix de l'électricité produite et l'impact sur l'environnement.

Mots clés :

Cycle combiné, Production directe de la vapeur, Fluide de transfert de chaleur, Prix de l'électricité produite et Réduction du carbone