

# The CSP (Concentrated Solar Power) Plant with Brayton Cycle: A Third Generation CSP System

Huseyin Murat Cekirge<sup>1,2</sup>, Serdar Eser Erturan<sup>1</sup>, Richard Stanley Thorsen<sup>2</sup>

<sup>1</sup>Mechanical Engineering, City College of New York, City University of New York, New York, USA

<sup>2</sup>Mechanical Engineering, New York University, Brooklyn, USA

## Email address:

hmcekirge@nyu.edu (H. M. Cekirge)

## To cite this article:

Huseyin Murat Cekirge, Serdar Eser Erturan, Richard Stanley Thorsen. The CSP (Concentrated Solar Power) Plant with Brayton Cycle: A Third Generation CSP System. *American Journal of Modern Energy*. Vol. 6, No. 1, 2020, pp. 43-50. doi: 10.11648/j.ajme.20200601.16

**Received:** January 28, 2020; **Accepted:** February 17, 2020; **Published:** February 26, 2020

---

**Abstract:** The main goal of this study is that electricity unit price is lower than 6 cents (US) producing in a CSP (Concentrated Solar Power) plant. For this goal, the paper suggests an integrated facility with thermal energy storage. The plant includes heliostat area, air cavity receiver, gas turbine package (compressor, combustion chamber and generator), steam turbine and generator, heat exchanger, sensible thermal energy storage system and condenser. The process details are heated air through SIC (Silicon Carbide) air cavity tube receiver will be sent to the gas turbine (Brayton Cycle) and hot air from output of gas turbine will be source to heat exchanger to steam production. Steam from output of the heat exchanger will be supplied to the TES (Thermal Energy Storage) for its charging and second turbine (Rankine Cycle) for to generate electricity. Thus, the total efficiency of the plant reaches 55% during sunshine. Assumptions that is to calculate unit price are several schedules and interest rates for every year and amortization and taxation are ignored. With these assumptions, the paper's aim is achieving the goal with 5.7 US ¢/kWh<sub>e</sub> for 13 years return time, %3 interest rate without subsidizing.

**Keywords:** CSP, 3rd Generation CSP Plant, SIC, TES, Rankine Cycle, Brayton Cycle, CSP Tower Plant

---

## 1. Introduction

Commonly, steam turbines (Rankine Cycle), Cengel and Boles [1], are used for electricity production in Concentrated Solar Power (CSP) plant Kreith and Goswami [2]; therefore efficiencies are limited. Electricity generation will be done with both gas turbine and steam turbine through this uniquely designed CSP-Tower plant. Combination in the gas turbine (Brayton Cycle), and steam turbine (Rankine Cycle) will increase field efficiency. Also, when the sun does not shine, the thermal energy storage system provides steam to the turbine to produce electricity. If two CSP-Tower plants, Boerema et al. [3] and Law et al. [4, 5], that are having the same number of heliostat and location are compared in terms of efficiency and electricity production, it is seen that this unique facility reaches the target cost.

Another significant point is reduction of carbon emission for the design of CSP-Tower facility. In gas turbines, the air from the compressor is directly burned. However, air came from the compressor is heated in SiC (silicon carbide) Haynes [6] air cavity receiver to higher temperature and

taken to the combustion chamber in this design facility. In this way, it is possible to heat air with reduced consumption of natural gas. Thus, the gas turbine system consumes less fuel and releases lower greenhouse gases.

Concentrated solar energy technology is developing rapidly. However, in order to be expand this technology in electricity generation, it is necessary to develop high efficiency and low cost systems. The purpose of this funding is to demonstrate the reduction of the price below 6 US ¢/kWh<sub>e</sub>. It is also very important to present novel ideas while reaching the targeted cost. There are critical success factors for the target.

One of the most critical success factors is the development of systems which are available and compatible with the grid system. These requirements will be achieved through the integration of energy storage systems. In the paper, it will presented that the implementation of the design of the thermal energy storage for increasing availability in the concentrated solar energy systems. Therefore existing uncertainties preventing the implementation of these systems in a large scale will be overcome. The pilot application will

be developed that concentrated solar power system based on direct steam generation will be supported by innovative thermal energy storage system. This paper's aims will be an example for commercial applications.

Another critical success factor is high efficiency of CSP plants. In conventional CSP technologies, limited efficiencies are achieved with a single turbine cycle. This causes low efficiency in CSP plants. Within the scope of the paper, it is aimed to increase the efficiency by using both gas turbine and steam turbine cycles.

When the success factors are discussed for the targeted price, it will ensure that future designs by the experts in the field will utilize combined steam turbine and gas turbine cycles. Both thermal energy storage and higher efficiency will help to achieve the paper's goals, an acceptable cost and efficiency.

It is evident that future energy sources will be renewable systems and especially CSP tower design for central generation of electric power. The production cost of this energy is the essential to utilization and expansion of the CSP as a dependable energy source. In addition, reduction of carbon emissions will have a positive environmental impact while addressing the unrelenting need for electric power.

## 2. Technical Description, Innovation, and Impact

### 2.1. System Description

- 1) Heated air through SiC air cavity tube receiver to 700°C will be sent to the First Turbine (Brayton Cycle).
- 2) To higher efficiency conditions some limited natural gas will be in complimentary use.
- 3) Hot air (550°C) from output of the turbine (Brayton Cycle) will be source to heat exchanger to steam production. Steam from output of the heat exchanger will be supplied to the Thermal Energy Storage (TES) for its charging and Second Turbine (Rankine Cycle) for to generate electricity.
- 4) While charging Thermal Energy Storage, required steam for steam turbine (Rankine Cycle) will be running the turbine for to generate electricity.
- 5) During the peak hour extra heat will be used to charge the TES.
- 6) Thus, when the sun shines, electricity production will be done together with First Turbine (Brayton Cycle) and Second Turbine (Rankine Cycle), and also the thermal storage system will be charged.
- 7) When the sun does not shine, the thermal storage system will discharge and only the Second Turbine (Rankine Cycle) will produce electricity. While TES charging the Rankine Cycle efficiency will be limited with in turbine capacity.
- 8) Thus, the total efficiency of the plant can reach 3000 h/y for 55%.

### 2.2. Design Components

Process diagram for CSP facility is shown in Figure 1.

#### 2.2.1. Heliostat Field

- 1) 1500 heliostats each heliostat 16 m<sup>2</sup> total field 24,000 m<sup>2</sup>. Average thermal capacity 10 MW<sub>th</sub>, peak times 12.8 MW<sub>th</sub> (total hours peak solar beam will able to charge 2800 MW<sub>th</sub>/h).
- 2) Main goal is production cost less than 100 US \$/m<sup>2</sup>, including simple site assembly and erections designs including.
- 3) Smart and independent heliostats system within wireless communications, autonomic calibrations.
- 4) Automated interactive heliostat field control management by using auxiliary software.
- 5) Design data of heliostat field for engineering analysis is given in Figure 2.
- 6) The production hours and the power are calculated for the field designed using design data. The calculations made are shown in Figure 3.
- 7) A graph of seasonal production times was created for identified performance points. The generated graph is shown in Figure 4.
- 8) The seasonal average thermal energy production graph was created by taking into consideration the design data and seasonal working hours. The average thermal energy production graph is shown in Figure 5.

#### 2.2.2. Air Cavity Receiver Material SiC Tubes

Although SiC (Silicon Carbide) ceramics have been considered for CSP receiver tubes by the CSP industry in the past, there is reluctance on the part of the commercial CSP industry, and DOE (US Department of Energy) and its labs, to consider SiC for receiver tubes due to concern over the brittle nature of ceramics. This can be mitigated by use of a CMC (Ceramic Matrix Composite) Krenkel [7] as the central layer of its product, using micron sized SiC fibers dispersed within a SiC matrix. This composite layer surrounds an inner monolithic layer providing fluid containment and the state of being airtight. CMCs are not brittle and exhibit a stress strain behavior similar to ductile metals, with a graceful failure mode when overloaded. Testing large SiC CMC components (Channel Boxes for Boiling Water Reactors as examples) have demonstrated an extraordinary tolerance to mechanical shock. Thermal shock testing TRIPLEX clad from 1000°C to room temperature has also demonstrated robust behavior. In addition, independent tests by the Karlsruhe Institute of Technology in Germany demonstrated robust performance under thermal shock from 2000 °C to room temperature. With high temperature, high solar radiation emissivity and light design, the receiver will ensure that the field reaches the desired yield.

#### 2.2.3. Thermal Energy Storage (TES) System

The proposed paper's project will implement the design and pilot scale application of the thermal energy storage system to increase availability in the concentrated solar

energy systems, Mathiesen [8] and Henning and Palzer [9]. One of the most important constraints in solar energy applications is that there are none available and compatible with the grid system. Therefore existing uncertainties prevent the implementation of these systems on a large scale. The pilot application will be developed that concentrated solar power system based on direct steam generation will be supported by innovative thermal energy storage based on steam generation and this paper's project will be an example for commercial applications. CSP (Concentrated Solar Energy) technology is developing rapidly; however, in order to be more used this technology in electricity generation, it has become necessary to develop high efficiency and low cost systems. One of the most important features is the development of systems which are availability and compatibility to the grid system. It is possible only through integration of energy storage systems.

The parabolic trough collector technology is commonly used in concentrated solar energy applications around the world. However, many factors such as temperature limitation, high operating and investment costs, and operating problems are the most important obstacles to the spread of this technology. Alternatively, concentrated solar tower energy systems can reach higher temperatures and increase total energy conversion significantly. In these systems, thermal energy storage has been made by the use of molten salt systems. Therefore, the stored sensory heat is transferred from the molten salt that is circulated between the cold and hot tank to the primary flow through heat exchangers to produce steam. In this type of storage systems, there still remain serious problems in operation due to molten salt circulation.

The proposed paper's project is aimed at a facility that can be an alternative to these systems that are commercially operated but cannot be competitive in the electricity market due to the high cost of operation and investment. In addition to this, it is aimed to develop a novel and innovative design based on sensible heat storage and to perform the performance measurement with the facility to be installed in the real conditions.

The proposed heat storage system consists of combination of evaporator and two super heater units. Hot steam produced by super heaters. Specially designed concrete will be used as heat storage medium because the evaporator can operate at a lower temperature. The desired fluid comes from super heaters to steam drum. When the desired steam is obtained from evaporator section, the steam will be transferred to the super steam production storage with valve control mechanisms. Because of the high temperatures in this unit, molten salt and/or special fillers are used as heat storage medium. In the detailed engineering design work done, it is intended that both evaporator and hot steam storage units are suitable, efficient and low cost operations to the conditions of steam turbine in CSP-tower field. This makes it easier for the operator who operates more economically and smoothly whole system. According to these features, a heat storage system based on high temperature and direct steam production will be designed. In addition, a storage system will be designed which does not currently exist commercially and cannot be found a similar example in the scientific literature. In this regard, concentrated solar energy technology also complies with the development of innovative industrial applications and the development of high temperature thermal storage system.

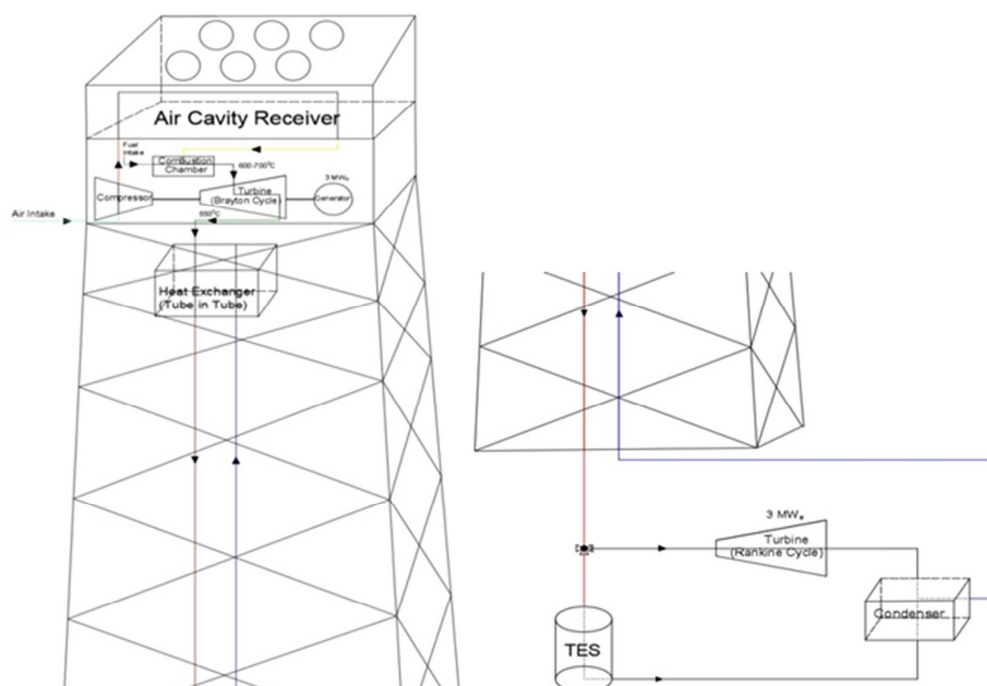


Figure 1. Process diagram top (left) and bottom (right).

| CSP POWER PLANT                                |        |                   |                               |
|--|--------|-------------------|-------------------------------|
| Engineering Analysis                           | Inputs | Outputs           |                               |
| INPUT Calculation Summary                      | Value  | Unit              |                               |
| FIELD SIZE PARAMATER                           |        |                   |                               |
| Number of Heliostat                            | 1500   | Piece(s)          | matlab modelling              |
| Single Heliostat Surface Area                  | 16     | m <sup>2</sup>    | ref size                      |
| Total Mirror Surface Area                      | 24000  | m <sup>2</sup>    |                               |
| WEATHER PARAMETERS                             |        |                   |                               |
| DNI Threshold                                  | 400    | Wh/m <sup>2</sup> |                               |
| Direct Normal Irradiation For Production limit | 950    | Wh/m <sup>2</sup> |                               |
| Wind Threshold                                 | 0      | m/s               |                               |
| PEAK EFFICIENCY PARAMATERS                     |        |                   | Average Efficiency Parameters |
| Reflectivity Efficiency                        | 92,0%  |                   | 92,0%                         |
| Cosine Efficiency                              | 79,7%  |                   | 76,1%                         |
| Atmospheric Attenuation Efficiency             | 95,5%  |                   | 94,1%                         |
| Blocking & Shadowing Efficiency                | 97,3%  |                   | 93,2%                         |
| Total Field Efficiency                         | 68,1%  |                   | 61,4%                         |
| Mirror Cleanliness                             | 95,0%  |                   | 95,0%                         |
| Pipe & Thermal Efficiency                      | 98,0%  |                   | 98,0%                         |
| Boiler Efficiency                              | 87,0%  |                   | 87,0%                         |
| Thermal Efficiency                             | 55,1%  |                   | 49,7%                         |

Figure 2. Engineering analysis.

|   |        |                 |        |                              |      |                               |      |
|---|--------|-----------------|--------|------------------------------|------|-------------------------------|------|
| CALCULATION OF OPERATING HOURS & ENERGY PRODUCTIC | Value  | Unit            |        |                              |      |                               |      |
| Sample Year Production Hour                       | 3029   | Hour            |        |                              |      |                               |      |
| Hourly Thermal Energy (Without Losses)            | 22,80  | MW              |        |                              |      |                               |      |
| Hourly Thermal Energy Production (peak)           | 12,57  | MW              |        |                              |      |                               |      |
| Turbine Efficiency                                | 22,0%  |                 |        |                              |      |                               |      |
| Electricity Production (peak)                     | 2,77   | MWh             |        |                              |      |                               |      |
| Operating Hours For:                              | Summer | Spring & Autumn | Winter | Total annual operating hours | Unit |                               |      |
| Operational Capacity (% of total) 20%             | 30     | 44              | 51     | 125                          | h    |                               |      |
| Operational Capacity (% of total) 40%             | 70     | 159             | 48     | 277                          | h    |                               |      |
| Operational Capacity (% of total) 60%             | 196    | 300             | 95     | 591                          | h    |                               |      |
| Operational Capacity (% of total) 80%             | 305    | 430             | 180    | 915                          | h    |                               |      |
| Operational Capacity (% of total) 100%            | 334    | 575             | 212    | 1121                         | h    |                               |      |
| Total operating hours (yearly)                    | 935    | 1508            | 586    | 3029                         | h    |                               |      |
| Thermal Power Production:                         | Summer | Spring & Autumn | Winter | Thermal Power produced       | Unit | Total Thermal Energy produced | Unit |
| Operational Capacity (% of total) 20%             | 2,53   | 2,39            | 1,74   | 2,16                         | MW   | 0,27                          | GWh  |
| Operational Capacity (% of total) 40%             | 5,44   | 5,32            | 5,06   | 5,31                         | MW   | 1,47                          | GWh  |
| Operational Capacity (% of total) 60%             | 7,64   | 7,66            | 7,66   | 7,65                         | MW   | 4,52                          | GWh  |
| Operational Capacity (% of total) 80%             | 10,13  | 10,16           | 10,09  | 10,14                        | MW   | 9,28                          | GWh  |
| Operational Capacity (% of total) 100%            | 12,20  | 12,19           | 12,11  | 12,18                        | MW   | 13,65                         | GWh  |
| Average Thermal Power Production                  | 9,75   | 9,70            | 9,29   | 9,64                         | MW   | 29,19                         | GWh  |

Figure 3. Calculation of production hours and power.

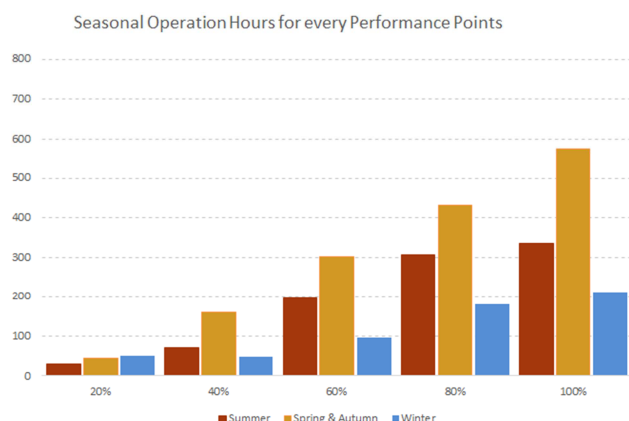


Figure 4. Seasonal operation hours for every performance points.

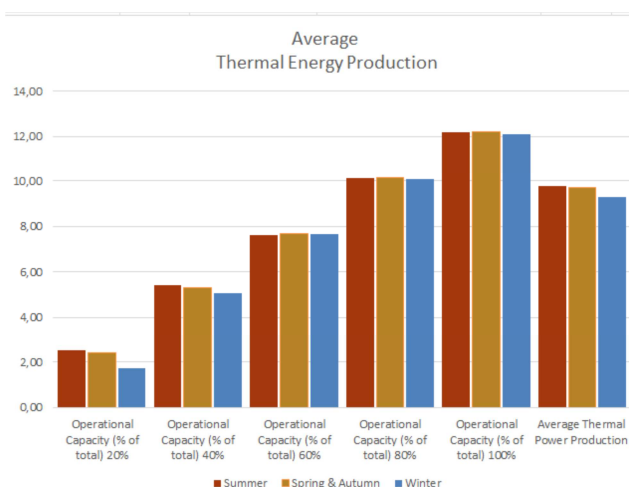


Figure 5. Average thermal energy production.

The CSP plant with considerable innovations will be designed and the technologies described above are important processes in achieving the paper's stated goals.

### 2.3. Feasibility

Detailed feasibility studies were made for the proposed CSP facility within the scope of the paper's project. In particular, if the field is built in Nevada, the operation hours there will be over 3000 available solar hours per year. The number of heliostats to be used for the corresponding CSP field is 1500 when looking at the DNI data in the relevant area. This will correspond to 24000 square meters. Also the height of the tower is 50 m. In electricity generation, both gas turbine and steam turbine will be used and the efficiency is aimed to be 55% and 6 MWe will be generated; 4 MWe from the gas turbine and 2 MWe from the steam turbine. In addition, the storage of thermal energy will begin when the production of steam is peaking and electricity generation from the steam turbine will continue through thermal energy storage when the sun does not shine.

When all these design data and perfect field design are taken into account, the scenario for reaching the target cost has been created. All details for the scenarios are taken into consideration. The way to follow the scenario is explained

below:

- 1) Firstly, the cost of equipment and other components (cabling, electrical components, piping, etc.) to be used for the installation of the CSP plant has been calculated.
- 2) The generated amount of electricity is calculated when the sun shines and does not shine (using the proposed TES).
- 3) While the plant was being constructed, 80% of the cost is bank load and the rest (20%) is organizations equity.
- 4) It is accepted that the credit will have a return time of 5, 10, 13 and 20 years.
- 5) At each return time, 3 different interest rates were settled. These ratios are: 0.03, 0.04 and 0.05.
- 6) For each return time and the interest rate within it, a unit price of 1 to 6 US ¢/kWh<sub>e</sub> was given.
- 7) Income is calculated for each payback time, interest rate and unit price.
- 8) OPEX cost was assumed by using an operating CSP field data.
- 9) For the accepted 4 years and 3 different interest rates, the interest and principal payment was determined based on the relevant return time. Also, equal equity payments are calculated for equity.
- 10) If the difference between income and expenses is negative as the results of all the optimization calculations, it is determined that the field cannot reach the target price of electricity with by considering above assumptions. However, if the difference between income and expenses is positive as a result of all the calculations, it was determined that the field would reach the target cost with these constraints.
- 11) Amortization and taxation are ignored in all calculations made. In addition, no subsidizing has been considered when calculating the lowest cost.

The assumptions can be change according to agreements between banks and the organization management. The methodology LCOE (Levelized Cost of Electricity) is used by considering zero CAPEX after payback period with zero fuel costs, MLCOE (Modified Levelized Cost of Electricity), Herná'ndez-Moro and Marti'nez-Duart [10], Aldersey-Williams and Rubert [11], Dale [12], Joskow [13] and Cekirge and Erturan [14].

The information used for the scenarios is shown in Table 1. Scenarios with 3 different interest rates for the 5-year, 10-year, 13-year and 20-year return time are shown in Tables 2, 3, 4 and 5, respectively.

Table 1. Data for scenarios.

| DATA  |            |
|---|------------|
| Production Hours (h/year)                             | 3487       |
| Electricity Production, Power (MW <sub>e</sub> )      | 6          |
| Total Electricity Production (kWh <sub>e</sub> /year) | 2,092,2000 |
| Total Cost (\$)                                       | 980,0000   |
| OPEX (\$/year)  | 310,000    |
| Loan Share  | 0,8        |



*Table 2. Scenarios for 5-year return time.*

| Expenses            |               |                                      |                |              |                  |                   |                        |               |              |
|---------------------|---------------|--------------------------------------|----------------|--------------|------------------|-------------------|------------------------|---------------|--------------|
| Return Time (years) | Interest Rate | Unit Price (US \$/kWh <sub>e</sub> ) | Income (US \$) | OPEX (US \$) | Interest (US \$) | Principle (US \$) | Equity Payment (US \$) | Total (US \$) | Decision     |
| 5                   | 0,03          | 0,01                                 | 1046100        | 1550000      | 705600           | 7840000           | 1960000                | -11009500     | NOT POSSIBLE |
|                     |               | 0,02                                 | 2092200        | 1550000      | 705600           | 7840000           | 1960000                | -9963400      | NOT POSSIBLE |
|                     |               | 0,03                                 | 3138300        | 1550000      | 705600           | 7840000           | 1960000                | -8917300      | NOT POSSIBLE |
|                     |               | 0,04                                 | 4184400        | 1550000      | 705600           | 7840000           | 1960000                | -7871200      | NOT POSSIBLE |
|                     |               | 0,05                                 | 5230500        | 1550000      | 705600           | 7840000           | 1960000                | -6825100      | NOT POSSIBLE |
|                     |               | 0,06                                 | 6276600        | 1550000      | 705600           | 7840000           | 1960000                | -5779000      | NOT POSSIBLE |
|                     | 0,04          | 0,01                                 | 1046100        | 1550000      | 940800           | 7840000           | 1960000                | -11244700     | NOT POSSIBLE |
|                     |               | 0,02                                 | 2092200        | 1550000      | 940800           | 7840000           | 1960000                | -10198600     | NOT POSSIBLE |
|                     |               | 0,03                                 | 3138300        | 1550000      | 940800           | 7840000           | 1960000                | -9152500      | NOT POSSIBLE |
|                     |               | 0,04                                 | 4184400        | 1550000      | 940800           | 7840000           | 1960000                | -8106400      | NOT POSSIBLE |
|                     |               | 0,05                                 | 5230500        | 1550000      | 940800           | 7840000           | 1960000                | -7060300      | NOT POSSIBLE |
|                     |               | 0,06                                 | 6276600        | 1550000      | 940800           | 7840000           | 1960000                | -6014200      | NOT POSSIBLE |
|                     | 0,05          | 0,01                                 | 1046100        | 1550000      | 1176000          | 7840000           | 1960000                | -11479900     | NOT POSSIBLE |
|                     |               | 0,02                                 | 2092200        | 1550000      | 1176000          | 7840000           | 1960000                | -10433800     | NOT POSSIBLE |
|                     |               | 0,03                                 | 3138300        | 1550000      | 1176000          | 7840000           | 1960000                | -9387700      | NOT POSSIBLE |
|                     |               | 0,04                                 | 4184400        | 1550000      | 1176000          | 7840000           | 1960000                | -8341600      | NOT POSSIBLE |
|                     |               | 0,05                                 | 5230500        | 1550000      | 1176000          | 7840000           | 1960000                | -7295500      | NOT POSSIBLE |
|                     |               | 0,06                                 | 6276600        | 1550000      | 1176000          | 7840000           | 1960000                | -6249400      | NOT POSSIBLE |

*Table 3. Scenarios for 10-year return time.*

| Expenses            |               |                                      |                |              |                  |                   |                        |               |              |
|---------------------|---------------|--------------------------------------|----------------|--------------|------------------|-------------------|------------------------|---------------|--------------|
| Return Time (years) | Interest Rate | Unit Price (US \$/kWh <sub>e</sub> ) | Income (US \$) | OPEX (US \$) | Interest (US \$) | Principle (US \$) | Equity Payment (US \$) | Total (US \$) | Decision     |
| 10                  | 0,03          | 0,01                                 | 2092200        | 3100000      | 1293600          | 7840000           | 1960000                | -12101400     | NOT POSSIBLE |
|                     |               | 0,02                                 | 4184400        | 3100000      | 1293600          | 7840000           | 1960000                | -10009200     | NOT POSSIBLE |
|                     |               | 0,03                                 | 6276600        | 3100000      | 1293600          | 7840000           | 1960000                | -7917000      | NOT POSSIBLE |
|                     |               | 0,04                                 | 8368800        | 3100000      | 1293600          | 7840000           | 1960000                | -5824800      | NOT POSSIBLE |
|                     |               | 0,05                                 | 10461000       | 3100000      | 1293600          | 7840000           | 1960000                | -3732600      | NOT POSSIBLE |
|                     |               | 0,06                                 | 12553200       | 3100000      | 1293600          | 7840000           | 1960000                | -1640400      | NOT POSSIBLE |
|                     | 0,04          | 0,01                                 | 2092200        | 3100000      | 1724800          | 7840000           | 1960000                | -12532600     | NOT POSSIBLE |
|                     |               | 0,02                                 | 4184400        | 3100000      | 1724800          | 7840000           | 1960000                | -10440400     | NOT POSSIBLE |
|                     |               | 0,03                                 | 6276600        | 3100000      | 1724800          | 7840000           | 1960000                | -8348200      | NOT POSSIBLE |
|                     |               | 0,04                                 | 8368800        | 3100000      | 1724800          | 7840000           | 1960000                | -6256000      | NOT POSSIBLE |
|                     |               | 0,05                                 | 10461000       | 3100000      | 1724800          | 7840000           | 1960000                | -4163800      | NOT POSSIBLE |
|                     |               | 0,06                                 | 12553200       | 3100000      | 1724800          | 7840000           | 1960000                | -2071600      | NOT POSSIBLE |
|                     | 0,05          | 0,01                                 | 2092200        | 3100000      | 2156000          | 7840000           | 1960000                | -12963800     | NOT POSSIBLE |
|                     |               | 0,02                                 | 4184400        | 3100000      | 2156000          | 7840000           | 1960000                | -10871600     | NOT POSSIBLE |
|                     |               | 0,03                                 | 6276600        | 3100000      | 2156000          | 7840000           | 1960000                | -8779400      | NOT POSSIBLE |
|                     |               | 0,04                                 | 8368800        | 3100000      | 2156000          | 7840000           | 1960000                | -6687200      | NOT POSSIBLE |
|                     |               | 0,05                                 | 10461000       | 3100000      | 2156000          | 7840000           | 1960000                | -4595000      | NOT POSSIBLE |
|                     |               | 0,06                                 | 12553200       | 3100000      | 2156000          | 7840000           | 1960000                | -2502800      | NOT POSSIBLE |

*Table 4. Scenarios for 13-year return time.*

| Expenses            |               |                                      |                |              |                  |                   |                        |               |              |
|---------------------|---------------|--------------------------------------|----------------|--------------|------------------|-------------------|------------------------|---------------|--------------|
| Return Time (years) | Interest Rate | Unit Price (US \$/kWh <sub>e</sub> ) | Income (US \$) | OPEX (US \$) | Interest (US \$) | Principle (US \$) | Equity Payment (US \$) | Total (US \$) | Decision     |
| 13                  | 0,03          | 0,01                                 | 2719860        | 4030000      | 1646400          | 7840000           | 1960000                | -12756540     | NOT POSSIBLE |
|                     |               | 0,02                                 | 5439720        | 4030000      | 1646400          | 7840000           | 1960000                | -10036680     | NOT POSSIBLE |
|                     |               | 0,03                                 | 8159580        | 4030000      | 1646400          | 7840000           | 1960000                | -7316820      | NOT POSSIBLE |
|                     |               | 0,04                                 | 10879440       | 4030000      | 1646400          | 7840000           | 1960000                | -4596960      | NOT POSSIBLE |
|                     |               | 0,05                                 | 13599300       | 4030000      | 1646400          | 7840000           | 1960000                | -1877100      | NOT POSSIBLE |
|                     |               | 0,057                                | 15503202       | 4030000      | 1646400          | 7840000           | 1960000                | 26802         | POSSIBLE     |
|                     | 0,04          | 0,01                                 | 2719860        | 4030000      | 2195200          | 7840000           | 1960000                | -13305340     | NOT POSSIBLE |
|                     |               | 0,02                                 | 5439720        | 4030000      | 2195200          | 7840000           | 1960000                | -10585480     | NOT POSSIBLE |
|                     |               | 0,03                                 | 8159580        | 4030000      | 2195200          | 7840000           | 1960000                | -7865620      | NOT POSSIBLE |
|                     |               | 0,04                                 | 10879440       | 4030000      | 2195200          | 7840000           | 1960000                | -5145760      | NOT POSSIBLE |
|                     |               | 0,05                                 | 13599300       | 4030000      | 2195200          | 7840000           | 1960000                | -2425900      | NOT POSSIBLE |
|                     |               | 0,059                                | 16047174       | 4030000      | 2195200          | 7840000           | 1960000                | 21974         | POSSIBLE     |
|                     | 0,05          | 0,01                                 | 2719860        | 4030000      | 2744000          | 7840000           | 1960000                | -13854140     | NOT POSSIBLE |
|                     |               | 0,02                                 | 5439720        | 4030000      | 2744000          | 7840000           | 1960000                | -11134280     | NOT POSSIBLE |
|                     |               | 0,03                                 | 8159580        | 4030000      | 2744000          | 7840000           | 1960000                | -8414420      | NOT POSSIBLE |
|                     |               | 0,04                                 | 10879440       | 4030000      | 2744000          | 7840000           | 1960000                | -5694560      | NOT POSSIBLE |

| Return Time (years) | Interest Rate | Unit Price (US \$/kWh) | Expenses       |              |                  |                   | Equity Payment (US \$) | Total (US \$) | Decision     |
|---------------------|---------------|------------------------|----------------|--------------|------------------|-------------------|------------------------|---------------|--------------|
|                     |               |                        | Income (US \$) | OPEX (US \$) | Interest (US \$) | Principle (US \$) |                        |               |              |
|                     |               | 0,05                   | 13599300       | 4030000      | 2744000          | 7840000           | 1960000                | -2974700      | NOT POSSIBLE |
|                     |               | 0,06                   | 16319160       | 4030000      | 2744000          | 7840000           | 1960000                | -254840       | NOT POSSIBLE |

Table 5. Scenarios for 20-year return time.

| Return Time (years) | Interest Rate | Unit Price (US \$/kWh) | Expenses       |              |                  |                   | Equity Payment (US \$) | Total (US \$) | Decision     |
|---------------------|---------------|------------------------|----------------|--------------|------------------|-------------------|------------------------|---------------|--------------|
|                     |               |                        | Income (US \$) | OPEX (US \$) | Interest (US \$) | Principle (US \$) |                        |               |              |
| 20                  | 0,03          | 0,01                   | 4184400        | 6200000      | 1822800          | 7840000           | 1960000                | -13638400     | NOT POSSIBLE |
|                     |               | 0,02                   | 8368800        | 6200000      | 1822800          | 7840000           | 1960000                | -9454000      | NOT POSSIBLE |
|                     |               | 0,03                   | 12553200       | 6200000      | 1822800          | 7840000           | 1960000                | -5269600      | NOT POSSIBLE |
|                     |               | 0,043                  | 17992920       | 6200000      | 1822800          | 7840000           | 1960000                | 170120        | POSSIBLE     |
|                     |               | 0,05                   | 20922000       | 6200000      | 1822800          | 7840000           | 1960000                | 3099200       | POSSIBLE     |
|                     |               | 0,06                   | 25106400       | 6200000      | 1822800          | 7840000           | 1960000                | 7283600       | POSSIBLE     |
|                     | 0,04          | 0,01                   | 4184400        | 6200000      | 3292800          | 7840000           | 1960000                | -15108400     | NOT POSSIBLE |
|                     |               | 0,02                   | 8368800        | 6200000      | 3292800          | 7840000           | 1960000                | -10924000     | NOT POSSIBLE |
|                     |               | 0,03                   | 12553200       | 6200000      | 3292800          | 7840000           | 1960000                | -6739600      | NOT POSSIBLE |
|                     |               | 0,047                  | 19666680       | 6200000      | 3292800          | 7840000           | 1960000                | 373880        | POSSIBLE     |
|                     |               | 0,05                   | 20922000       | 6200000      | 3292800          | 7840000           | 1960000                | 1629200       | POSSIBLE     |
|                     |               | 0,06                   | 25106400       | 6200000      | 3292800          | 7840000           | 1960000                | 5813600       | POSSIBLE     |
|                     | 0,05          | 0,01                   | 4184400        | 6200000      | 4116000          | 7840000           | 1960000                | -15931600     | NOT POSSIBLE |
|                     |               | 0,02                   | 8368800        | 6200000      | 4116000          | 7840000           | 1960000                | -11747200     | NOT POSSIBLE |
|                     |               | 0,03                   | 12553200       | 6200000      | 4116000          | 7840000           | 1960000                | -7562800      | NOT POSSIBLE |
|                     |               | 0,04                   | 16737600       | 6200000      | 4116000          | 7840000           | 1960000                | -3378400      | NOT POSSIBLE |
|                     |               | 0,049                  | 20503560       | 6200000      | 4116000          | 7840000           | 1960000                | 387560        | POSSIBLE     |
|                     |               | 0,06                   | 25106400       | 6200000      | 4116000          | 7840000           | 1960000                | 4990400       | POSSIBLE     |

The scenario that catches the target, which is positive, is a scenario with only 5.7 US ¢/kWh<sub>e</sub> and a payback time of 13 years with 3% interest rate.

#### 2.4. Innovation and Impacts

A virtue of this paper is that the cost of the heliostats and wireless communication based intelligent design, which is one of the facility major components, is reduced by virtue of a elaborate CSP design. The thermal energy storage system, another critical component, is also developed at low cost. Moreover, one of the most important constraints in solar energy applications is unavailability and incompatibility with grid systems. Therefore existing uncertainties prevent the implementation of these systems on a large scale. With sensible TES (Thermal Energy Storage) system in an integrated facility design, availability of concentrated solar energy systems increases. Another critical factor is high efficiency for CSP plants. For most of the CSP technologies, the limited efficiency is achieved with a single turbine cycle. This causes low efficiency in CSP plants. Within the scope of the paper, it is aimed to increase the efficiency by using both gas turbine and steam turbine.

### 3. Work Plan of the Study

#### 3.1. Study's Objectives

There is considerable evidence that carbon emissions are a major potential contributor to global warming. For this reason many technologies are seeking innovations that will

reduce carbon emissions. In the energy sector the search for innovation has begun in energy markets. Investigations on renewable energy sources have been increased with respect to other energy sources such as coal, fuel oil or natural gas. As a result, solar and wind power plants have been installed and countries have started to set new targets. In this new CSP tower system design, gas turbine and steam turbine, new receiver materials and new sensible TES system are combined for high efficient low cost electric production systems. The other important issue is the water usage in CSP plants. This paper aims to reduce water consumption by 90% using the Brayton Cycle. This is particularly important in arid climates which often coincide with the greatest availability of solar radiation.

Specific objectives for this study are:

- 1) To decrease carbon emission.
- 2) To add value to existing conventional power generating equipment's.
- 3) To demonstrate high efficiencies for small CSP tower plants.
- 4) To increase overall CSP plant efficiency.
- 5) To low cost and maintains free TES system design.
- 6) To provide electricity when the sun does not shine.
- 7) To reduce CAPEX (Capital Expenditures) and OPEX (Operating Expenses).
- 8) To test SiC tube air cavity receiver at high temperature.
- 9) To increase solar beam emissivity and lightweight design criteria.
- 10) To minimize water consumption in CSP systems.
- 11) Existing thermal cycle equipments (steam and gas turbines) will be valued.

### 3.2. Technical Scope Summary

The target duration of paper's project is 2 years. The work presented in the paper is divided three periods:

STAGE 1: Initiate Phase Activities: The main task is legal obligations and other relevant documents are being investigated.

STAGE 2: CSP System Design and Engineering Phase Activities: The main tasks are finalizing plant design and procurement and transport phase activities.

STAGE 3: Installation Phase Activities: The tasks are paper management, site works, ground and civil works, mounting structure, electrical works, general construction, grid connection phase activities, commissioning phase activities, acceptance phase activities and close phase activities.

## 4. Conclusion

The end of project goal:

- 1) Producing electricity at the cost of 0.06 US \$/kWh<sub>e</sub> and/or lower. This objective can be reached and furthermore, the price of kWh will be far further down after CAPEX expenses are paid, [15, 16].
- 2) Connection to local and national grids with minimum carbon emissions.
- 3) The hybrid power plants, (solar, photovoltaic or CSP) and thermal and/or combined cycles can be built without economic considerations to meet objectives and regulations of carbon emission standards, [17] and Soria et al. [18].

The above targets may be achieved by considering project objectives. If, according to market situations, lower or zero interest rates are considered, the values of LCOE or MLCOE will be lower and the payback period will be shorter.

## References

- [1] Cengel, Yunus A. and Boles Michael A., *Thermodynamics, An engineering Approach, Eight Ed.*, McGraw Hill, 2015.
- [2] Kreith, Frank and Goswami, D. Yogi ed., *Handbook of Energy Efficiency and Renewable Energy*, CRC Press, 2007.
- [3] Boerema, Nicholas, Morrison, Graham, Taylor, Robert and Rosengarten, Gary, *High temperature solar thermal central-receiver billboard design*, Solar Energy. 97: 356–368. doi: 10.1016/j.solener.2013.
- [4] Law, Edward W., Prasad, Abhnil A., Kay, Merlinde and Taylor, Robert A., *Direct normal irradiance forecasting and its application to concentrated solar thermal output forecasting – A review*, Energy. 108: 287– 307, doi: 10.1016/j.solener.2014.
- [5] Law, Edward W., Kay, Merlinde; Taylor and Robert A., *Calculating the financial value of a concentrated solar thermal plant operated using direct normal irradiance forecasts*, Solar Energy. 125: 267–281, doi: 10.1016/j.solener.2015.
- [6] Haynes, William M., ed., *CRC Handbook of Chemistry and Physics*, CRC Press, 2011.
- [7] Krenkel, Walter, ed, *Ceramic Matrix Composites: Fiber Reinforced Ceramics and their Applications 1st Ed.*, Wiley VSH, 2008.
- [8] Mathiesen, B. V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P. A., Möller, B., Nielsen, S., Ridjan, I., Karnøe, P., Sperling, K. and Hvelplund, F. K., *Smart Energy Systems for coherent 100% renewable energy and transport solutions*, Applied Energy. 145: 139–54, doi: 10.1016/j.apenergy.2015.
- [9] Henning, Hans-Martin and Palzer, Andreas, *A comprehensive model for the German electricity and heat sector in a future energy system with a dominant contribution from renewable energy technologies—Part I: Methodology*, Renewable and Sustainable Energy Reviews. 30: 1003–18. doi: 10.1016/j.rser.2013.
- [10] Herna'ndez-Moro J. and Marti'nez-Duart J. M., *Analytical model for solar PV and CSP electricity cost: Present LCOE values and their future evolution*, Renewable and Sustainable Energy Reviews, 20 (4): 119-32, 2013.
- [11] Aldersey-Williams, J. and Rubert, T., *Levelised cost of energy – A theoretical justification and critical assessment*, Energy Policy, vol. 124, issue C, 169-179, 2019.
- [12] Dale, M. A., *Comparative Analysis of Energy Costs of Photovoltaic, Solar Thermal, and Wind Electricity Generation Technologies*. Appl. Sci., 3, 325–337, 2013.
- [13] Joskow, Paul L., *Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies*, American Economic Review, 101 (3): 238-41. doi: 10.1257/aer.101.3.238, 2011.
- [14] Cekirge, H. M. and Erturan, S., *Modified Levelized Cost of Electricity or Energy, MLOCE and Modified Levelized Avoidable Cost of Electricity or Energy, MLACE and Decision Making*, American Journal of Modern Energy, 5 (1): 1-4, doi: 10.11648/j.ajme.20190501.11, 2019.
- [15] Thomas, J., *6 Cents Per kWh: World's Largest Solar Project Unveiled*, Energy, Renewable Energy, <https://www.treehugger.com/renewable-energy/6-cents-per-kwh-worlds-largest-solar-project-unveiled.html>, August 14, 2006.
- [16] Geuss, M., *Solar now costs 6¢ per kilowatt-hour, beating government goal by 3 years*, SCIENCE, <https://arstechnica.com/science/2017/09/solar-now-costs-6-per-kilowatt-hour-beating-government-goal-by-3-years/>, 9/13/2017.
- [17] *World's largest hybrid solar/thermal plant is switched on in Burkina Faso*, <https://www.mining.com/web/worlds-largest-hybrid-solar-thermal-plant-switched-burkina-faso/>, 19 March 2018.
- [18] Soria, R., Portugal-Pereira, J., Szklo, A., Milani, R. and Schaeffer, R., *Hybrid concentrated solar power (CSP)–biomass plants in a semiarid region: A strategy for CSP deployment in Brazil*, Energy Policy, Volume 86., Pages 57-72, <https://doi.org/10.1016/j.enpol.2015.06.028>, November 2015.