



FEASIBILITY STUDY ON 20 MWe CROSS LINEAR CONCENTRATED SOLAR POWER PLANT

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ABSTRACT

Concentrated solar power (CSP) utilizes solar thermal energy for electric power generation by concentrating the solar radiation with mirrors. The existing solar concentration systems, such as parabolic trough, linear fresnel and tower, have problems of lower concentration efficiency in winter season and high latitude region. Cross linear concentrated solar power (CL-CSP) has been developed to achieve high concentration efficiency even in such conditions. Linear receiver line lies on east-west axis and mirror lines on north-south axis, therefore the both lines are crossed each other at right angles. Since mirrors of CL-heliostat are controlled with dual axes (rotation and elevation) for sun-tracking, high concentration efficiency can be obtained. In order to establish cost competitive and efficient CSP plant, feasibility study on 20 MWe CL-CSP was carried out using computer simulation. Pebbles and air are applied as thermal storage material and working fluid respectively considering the cost competitive system. Heat capacity of the thermal storage tank and the amount of solar concentration were assumed by the estimation of the energy balance of plant operation. The layout of the heliostat field of 20 MWe CL-CSP plant was designed and conversion efficiency from concentrated solar energy to electric power was estimated. High temperature of 600 °C and the conversion efficiency of 24% (recovered heat to electricity) and 19% (electricity from concentrated solar energy) were obtained. Configuration design of thermal storage tank was also conducted. Finally the installation cost of the CL-plant was estimated to be compared with the conventional CSP-plant. The result shows the cost competitiveness of the CL-plant.

Keywords: concentration efficiency, cross linear, heat storage tank, heliostat field, air fluid receiver.

INTRODUCTION

Renewable energy is important for the world's upcoming problem of exhaustion of fossil fuel. Unstable output is one of the most significant issues for renewable energy; condition of photovoltaic generation and wind power generation is limited by whether and time. Concentrated solar power (CSP) is one of the renewable energy which utilize solar thermal energy for electric power generation by concentrating the solar radiation with mirrors. CSP has strong advantages to other renewable energy since the heat energy can be stored in the storage tank for electric generation at night. Since the amount of electricity depends on the concentrated solar radiation, arrangement of mirrors is important. There are mainly three concentration systems as shown Figure-1; parabolic trough, tower and linear Fresnel system [1, 2]. However, existing concentration systems have a problem with low concentration efficiency in winter season and high latitude region due to the low cosine effect [3, 4]. Electrical energy in winter season is 1/4 of that in summer with parabolic trough method [5]. Therefore, cross linear (CL) concentration system has been newly developed in order to reduce the seasonable change of concentration efficiency [6]. The conceptual sketch of CL-plant is shown in Figure-2. Linear receiver line lies on the east-west axis and mirror lines lie on the north-south axis. Mirrors are controlled with dual axis and all the mirrors on one mirror line reflect the solar radiation to the one point of the receiver. Thus, a high temperature of a thermal fluid around can be obtained by the high concentration degree. Linear receiver and point concentration are combined in the CL system.

The purpose of this paper is to evaluate the feasibility for 20 MWe CSP plant with the CL system using computational simulation. A high temperature (600 °C) of thermal fluid could be obtained by the air fluid receiver with CL system, which can get a high concentration degree (high flux of the concentrated sun light). A preliminary CFD study on the air receiver with steel pipes showed that the high temperature of air fluid (600 °C) can be obtained by a parabolic concentration with 15 mirrors of each with a size of 1.5 m × 1.8 m at 1.0 kW/m² DNI. Based on this result, we have applied pebble heat storage system considering a lower cost of CSP plant having a heat storage. The 70% of the thermal efficiency of the air receiver was used in this paper. The heliostat field and thermal storage tank was designed using this thermal efficiency of the air receiver.

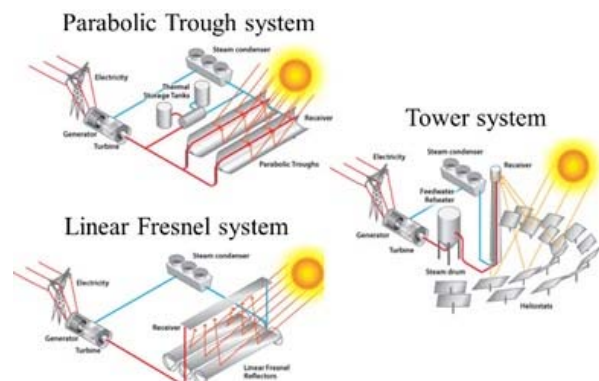


Figure-1. Existing solar concentration systems.

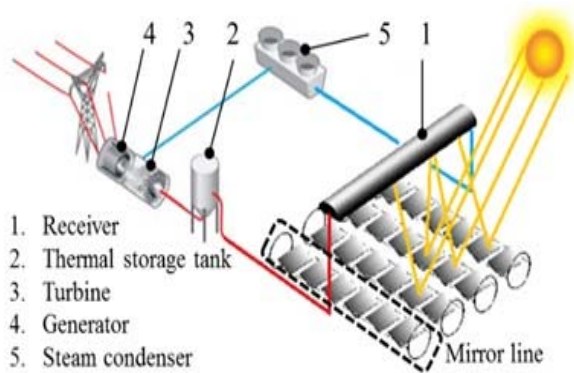


Figure-2. Cross linear concentration system.

METHODOLOGY

The structure of the CL-CSP plant was designed and the total energy balance was estimated in order to determine the parameters of main plant components such as heliostat field and thermal storage tank. In order to optimize the mirror design and heliostat arrangement, optical simulation software is newly developed based on ray tracing and Monte Carlo method. The mirrors are composed of small facets, therefore the inclination of each facet was determined by the simulation. The effect of shadowing and blocking caused by neighbor mirrors, receiver and receiver support was examined. The distance of each mirror and receiver position were optimized as well. Thermal energy which can be obtained by one unit of heliostat field was calculated and thereby total number of heliostat was obtained for 20 MWe electrical energy. The heat storage capacity were calculated and thereby the size of the tank was estimated. The thermal energy needed for 20 MWe electrical generation is 192 MWt, which is mentioned in the chapter of heat storage tank. The conversion efficiency from heat to electricity was set to 23%. The thermal efficiency of the air receiver was set to 70% based on a preliminary CFD study on the air receiver. Finally the installation cost of the plant was estimated to compare with the conventional CSP-plant.

RESULTS AND DISCUSSION

Flow diagram of CL plant

Figure-3 shows the flow diagram of 20 MWe CL-plant. The plant consists of three blocks; solar concentration block, thermal storage block and power block. Sun light is reflected and concentrated to the receiver in the heliostat field and the thermal energy is transported by the air. The receiver inlet temperature of the air is 229 °C and the air is heated up to 600 °C. Steam is generated by the thermal energy and sent to the turbine for electric generation. The conversion efficiency of the power block from heat to electricity was evaluated to be 24% with a conventional power block system. The surplus hot air is sent to the heat storage tank. One of the special features of CL-CSP is the pebble heat storage system. Pebbles are applied in the thermal storage tank for more reliable and cost competitive CSP plant compared to the molten salt heat storage. Generally, oil is applied as working fluid for typical high temperature CSP since heat capacity is high, however, air is applied as working fluid since oil cannot be used due to its decomposition temperature of around 450 °C. Pebble heat storage with air fluid can be achieved by high temperature of 600 °C. The conversion efficiency from concentrated solar energy to electricity was evaluated to be 19%.

Operation mode

Assuming that the operation date is May 21st, 2014 and the place is Almeria, Spain. Energy balance of the CL-plant was estimated as shown in Table-1. Solar irradiation can be obtained at daytime of 08:30-17:15. Operation mode is also 20 MWe at the time ranges of 17:15-22:00 and 08:00-08:30 when the electricity is generated using the stored heat because the sun is down. Since the demand for electric power decreases at 22:00-08:00, the target value is set to 10 MWe at that time. Thermal energy which is required for generation is calculated using the efficiency of 0.24 on each time range. Thermal energy of 192 MWt is required at daytime (08:30-17:15) including 82 MWt for generation and 110 MWt for night generation.

Table-1. Estimation of heat storage capacity.

| Time range | Hour (h) | Electrical generation (MWe) | Thermal energy (MWt) | Heat storage (MWt) | Heat storage (MWh) |
|-------------|----------|-----------------------------|----------------------|--------------------|--------------------|
| 8:30-17:15 | 8.75 | 20 | 82 | +110 | +962.5 |
| 17:15-22:00 | 4.75 | 20 | 83.3 | -83.3 | -395.7 |
| 22:00-8:00 | 10 | 10 | 41.7 | -41.7 | -416.7 |
| 8:00-8:30 | 0.5 | 20 | 83.3 | -83.3 | -41.7 |
| Total | 24 | - | - | - | +108.6 |

The target value of the CL-CSP is shown in Table-2. The heat loss including the loss of transportation pipes and thermal storage is assumed to be 8 %. Also, the

receiver efficiency is assumed to be 70 % based on a preliminary CFD study. Therefore, the amount of solar concentration for 20 MWe electricity is estimated to be



297 MWt. Thus, the target value of heliostat field is set to 192 MWt and the heat capacity of thermal storage tank is set to 964 MWh.

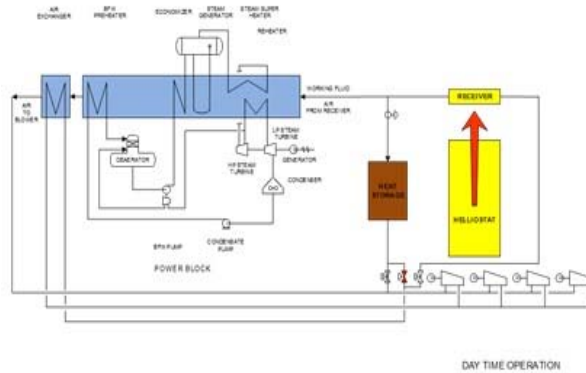


Figure-3. Flow diagram of 20 MWe CL-plant.

Table-2. Target value of 20 MWe CL-plant.

| | | |
|---------------------|---------|-------------------------------------|
| Solar concentration | 297 MWt | |
| Thermal energy | 192 MWt | Heat loss: 8% Receiver loss: 30% |
| Electric generation | 20 MWe | Thermal efficiency 24 % |

Heliostat field

Mirrors of CL system are controlled with dual axis for sun tracking as shown in Figure-4. One axis is oriented east and west, which adjusts the rotation angle of the mirror. The other axis is orthogonal to the rotation axis and adjusts the elevation angle of the mirror. The rotation angle varies with the diurnal motion of the sun. The elevation angle varies with the seasonal changes, therefore it would not change in the daytime. All the mirrors on the same position of the mirror line can be controlled with the same motion. Therefore, expansion of the heliostat field is easier than tower system.

Mirror of the heliostat is composed of several small facets to focus the reflected beam to one point. Each facet needs to be inclined to make a curvature, therefore the facet arrangement is optimized as shown in Figure-5. Then the simulation study was carried out to optimize the geometrical arrangement of heliostat field as shown in Figure-6. The total size of the mirror is designed to 1.8 m × 1.5 m. Then, the effect of shadowing and blocking caused by neighbor mirror, receiver and receiver support was examined. These analysis were performed using the new optical simulation software based on ray tracing and Monte Carlo method. Figure-7 shows the basic unit of the heliostat field which consists of 4 mirror lines with 60 heliostats. 15 heliostats are arranged on the one mirror line which lies on the east-west axis. The heliostats are arranged with equal interval of 2.2 m and the distance of the each mirror line is 3.2 m. The receiver line is crossed

at right angles with the mirror lines and positioned between 3rd and 4th heliostat. The receiver is established 15 m above the ground. The heliostats which are distant from the receiver need to have longer interval or height, because the reflected sunlight is blocked by the neighbor mirror. Therefore, the northern 4 heliostats are installed on the inclined ground.

Table-2 shows the parameters of the heliostat field. The total efficiency of heliostat includes mirror reflection, receiver conversion efficiency, cosine effect, shadowing effect and blocking effect. The total thermal energy per 1 unit of heliostat field P_{HF} is given by following equation.

$$P_{HF} = \text{DNI} \times \eta \times N_{\text{mirror}} \times A \times (1 - L) \quad (1)$$

Assuming that direct normal irradiation, DNI = 1.00 kW/m², total efficiency $\eta = 0.371$, number of the mirror per unit $N_{\text{mirror}} = 60$, size of the mirror $A = 2.7 \text{ m}^2$ and thermal translation loss $L = 0.167$, 50 kWt of thermal energy is obtained by one unit of heliostat field. 192 MWt of thermal energy is required for 20 MWe power as shown in Table-2. As a result, 3,840 unit of heliostat field is required. The size of total heliostat field is 1,760 m × 1,628 m.

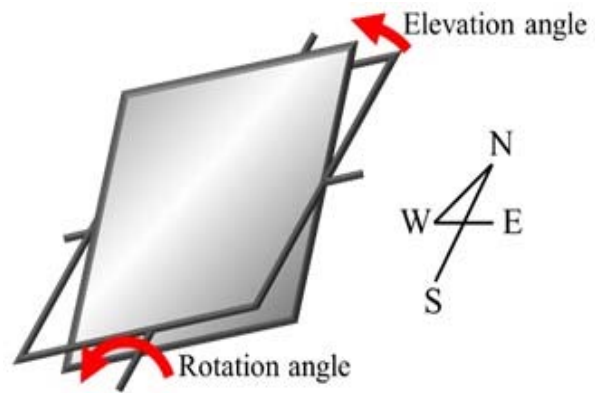


Figure-4. CL-Heliostat.

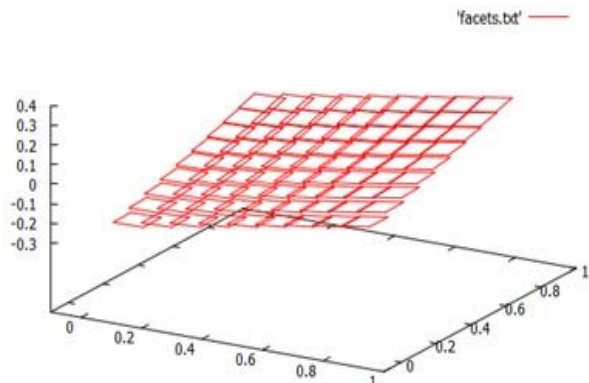


Figure-5. Design of mirror facet.

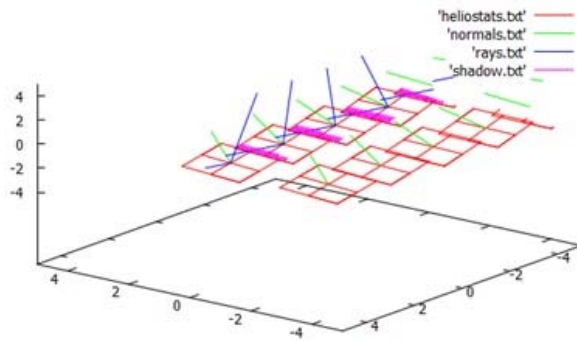


Figure-6. Simulation of shadowing.

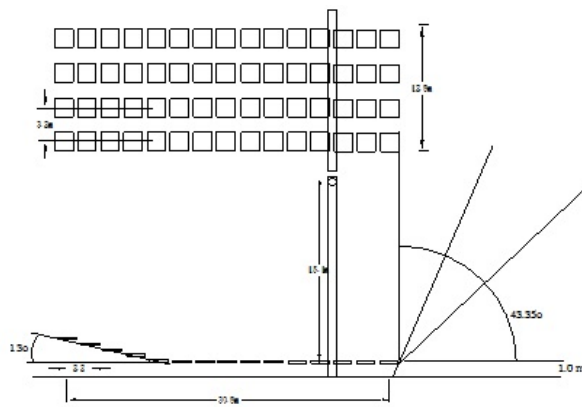


Figure-7. One unit for 50 kWt heliostat field.

Heat storage tank

Pebble heat storage system is applied for CL-CSP plant since high temperature of around 600 °C can be obtained. As shown in Table-3, 964 MWt of heat capacity is required to cover the generation at night. The size of the heat storage tank is calculated to meet the capacity of 964 MWt. The specific heat of pebble c_{pebble} is assumed to be 600 J/kgK. The temperature of input air is 600 °C and after releasing the heat from the tank, the temperature decreases to 200 °C. Therefore, the temperature difference $\Delta T = 400$ °C. A thermal energy of 964 MWh is converted to $Q = 3,473$ GJ and the required mass of pebbles is given by

$$m_{eff_pebble} = \frac{Q}{c_{pebble} \cdot \Delta T} \quad (2)$$

Therefore $m_{eff_pebble} = 14,470$ ton is obtained. Thermocline moving range $R = 0.6$ and the total mass of pebbles is calculated to be 24,120 ton.

$$m_{pebble} = \frac{m_{eff_pebble}}{R} \quad (3)$$

The density of pebbles ρ_{pebble} is assumed to be 2.7 ton/m³. Assuming that the void fraction $\varepsilon = 0.52$, due to the pebble is the sphere, the volume of the heat storage tank V_{tank} is calculated to be 17,180 m³.

$$V_{tank} = \frac{m_{pebble}}{\rho_{pebble} \cdot \varepsilon} \quad (4)$$

The parameters of the heat storage tank are shown in Table-3. In order to evaluate the volume (size) of the heat storage tank, ceiling diameter of 24 m, bottom diameter of 18 m, and height of 13 m was designed. The hot air flows into the tank from the top and the cooled air flows out from the bottom of the tank. Since the volume of the hot air is larger, the tank is cone shaped. The volume of the tank is about 4,500 m³ and 4 tanks are applied to achieve the heat storage.

Table-3. Parameters of the heat storage tank.

| | |
|-----------------------------|-----------------------|
| Heat storage capacity | 964 MW |
| Specific heat of the pebble | 600 J/kgK |
| Temperature of input air | 600 °C |
| Temperature of output air | 200 °C |
| The amount of pebbles | 24,120 ton |
| The size of the tank | 17,180 m ³ |

Cost estimation

For the cost estimation, the receiver height of the air receiver was re-examined, because the height of the receiver gives a high sensitivity against the cost. In the above result on the receiver height, we have selected 15 m to reduce the blocking and shadowing effect below 1.0%. When the receiver height was lowered to 10 m, the blocking and shadowing effect increased to 5.0%. However, the plant cost can be reduced by nearly half. Therefore, for the cost estimation of the 20 MWe CL-plant, the receiver height was adopted to 10 m for Figure-7 of the basic unit of the heliostat field (4 mirror lines with 60 heliostats). The breakdown of the construction cost are power block of 1,167M yen (generator 500M yen, steam generator 667M yen), thermal storage block of 700M yen, solar concentration block of 5,143M yen, piping of 4,500M yen, others of 700M yen, and total of 12,210M yen. Levelized electricity cost (LEC) was evaluated to be US\$0.1151/kWh (initial investment US\$7,520/kWe, useful life 25 years, fixed percentage of depreciation 10%, insurance 0.5%, maintenance US\$70/kWh/year, capacity factor 0.9). This is about 2/3 of the LEC, which is about US\$0.19/kWh, (initial investment US\$10,000/kWe, capacity factor 0.8) for the existing 24h CSP plant equivalent initial investment.

CONCLUSIONS

A 20 MWe cross linear solar power plant was designed in order to evaluate the feasibility for CL-CSP plant. For cost competitive CSP plant, pebbles and air were applied as thermal storage media and working fluid respectively. Energy balance of the daily operation of the CL-plant was estimated. The mirror design of the heliostat was optimized by the optical simulation software and the



layout of the heliostat field was also simulated. Basic parameter of the heat storage tank was also calculated for stable electric generation at night. Finally, the installation cost was estimated in order to be compared with the conventional CSP-plant. The result shows the cost competitiveness of the CL-plant.

NOMENCLATURE

| | |
|-------------------------|---|
| A | Size of mirror [m^2] |
| c_{pebble} | Specific heat of pebble [J/kgK] |
| CL | Cross Linear |
| CSP | Concentrated Solar Power |
| DNI | Direct Normal Irradiation [W/m^2] |
| M | Million |
| $m_{\text{eff pebble}}$ | The effective mass of pebbles [kg] |
| m_{pebble} | The mass of pebbles [kg] |
| N_{mirror} | Number of mirror per unit [-] |
| L | Thermal translation loss [-] |
| LEC | Levelized Electricity Cost [$\text{US\$}/\text{kWh}$] |
| P_{HF} | Thermal energy per 1 unit of heliostat field [W] |
| Q | Heat capacity [J] |
| R | Thermocline moving range [-] |
| V_{tank} | Volume of heat storage tank [m^3] |
| ΔT | Temperature difference of heat storage tank [K] |
| ε | Void fraction [-] |
| η | Total efficiency of heliostat [-] |
| ρ_{pebble} | Density of pebble [ton/m^3] |

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