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Development of CSP plants in Wallacea region: solar intensity resource assessment and CSP plant design specification

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Abstract

Wallacea region is a significant location for doing research on biodiversity and geology. However, many places in the region still have problems of electricity availability. To balance between MDG and natural resources conservation, providing electricity based on green renewable energy is welcomed. The aim of this paper is to report preliminary assessment of solar thermal energy potential in the region and to provide design specification of concentrated solar power (CSP) plants. Firstly, resource assessment is described based on sun spot number, latitude and rain fall analysis. Secondly, CSP plants design specification is derived including power capacity, structure as well as solar tracking control system. From the work reported in this paper it is concluded that a CSP plant is feasible to be built at Nusa Tenggara Timur (NTT) which has specification as follows: power capacity of 100 kW, capacity factor of 19.2%, and annual solar power to electric efficiency of 10%. Such a plant can be realized using CSP panel area of 1,250 m^2 and it will produce annual electric energy of 168.36MWh. Furthermore, the prototype of CSP plant developed by the Indonesian Institute of Sciences (LIPI) may be deployed in the region after conducting improvement in power efficiency and the reliability of its solar tracking control system

Keywords: CSP, Wallacea region, solar intensity, resource assessment, design specification, solar tracking control system, LIPI.

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1. Introduction

This paper reports preliminary assessment of solar thermal energy potential in Indonesia in general and especially in Wallacea region, and provides design specification of concentrated solar power (CSP) plants to be built in the Wallacea region. Wallacea is a bio-geographical designation for a group of Indonesian islands separated by deep water straits from the Asian and Australian continental shelves shown within red area in figure 1 [1]. Wallacea region has special position since it is a significant location for doing research on biodiversity and geology. Biodiversity conservation in this region becomes an important issue [2]. However, many places in the Wallacea region still have problems of electricity availability [3][4][5]. The balance between development activities to achieve MDG (millenium development goal) and the natural resources conservation becomes challenging. In this context, providing electricity based on green renewable energy is welcomed.

One potential renewable energy source in the Wallacea region is solar thermal. In September 2005, Greenpeace International together with ESTIA and SolarPACES released a report concerning solar thermal power. A Concentrated Solar Power (CSP) plant produces electricity by concentrating solar radiation and converting it to high-temperature steam or gas to drive a turbine or motor engine [6]. Three most promising solar thermal technologies are: (1) parabolic trough, (2) solar tower, and (3) parabolic dish. Their advantages and disadvantages are described in the references [6][7][8]. Thermal transfer material can be heated to approximately 400°C in a parabolic trough CSP plant, 750°C in a parabolic dish CSP plant, and 1000°C in a solar tower CSP plant. The thermal transfer material includes steam, molten salts, liquid sodium and air.

The U.S. Department of Energy is managing a Solar Energy Technologies Program known as solar program. The solar program is driven by the Solar America Initiative (SAI) which is a Presidential initiative launched in 2007. The multi year program plan 2008-2012 fully incorporates concentrating solar power [9]. Meanwhile, the Research Center for Electrical Power and Mechatronics – Indonesian Institute of Sciences (LIPI) has been conducting research and development of concentrated solar power (CSP) systems since 2009. The objective of this R&D activity is to realize a prototype of 10kW electrical power plant using concentrated solar thermal power system [10][11].

The aim of this paper is to report preliminary result of solar thermal energy resources assessment in Indonesia in general and more specifically in the Wallacea region as well as to provide a design specification of a CSTP plant which is suitable to be built.

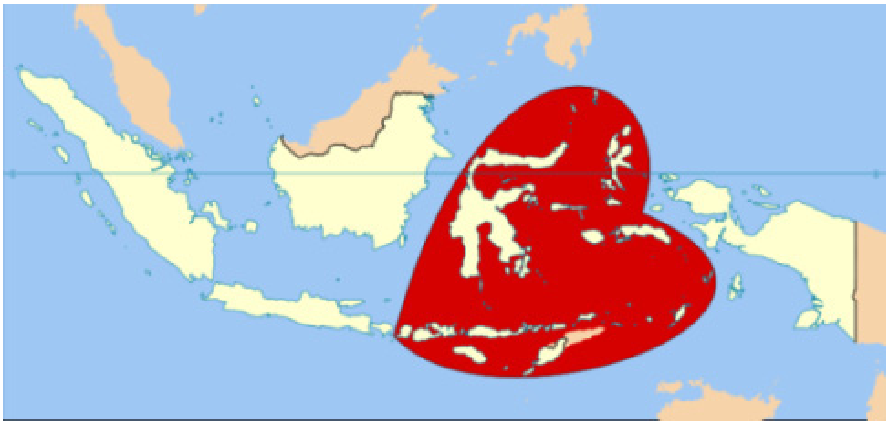

Figure 1. Wallacea region [1]

2. Resource Assessment

2.1. Affecting Factors

Solar thermal power intensity depends on the following factors.

- Solar activity (sunspot number).
- Location in the globe (latitude).
- Atmosphere condition (humidity/rain, clouds, and pollution).

In the following solar thermal resources are assessed based on the above three factors.

2.2. Effect of sun spot number and latitude in the globe

NOAA's National Geophysical Data Center (NGDC) provides data which shows correlation between sunspot number and solar irradiance since January 1979 [12]. Based on the data, we know that annual average solar irradiance I_{Sa} (W/m^2) mean value is 1,366 W/m^2 with the total variation is only about 1 W/m^2 during one cycle. Its cycle period is 10.4 years.

According to latitude, location in the globe can be classified into 3 categories as below [13].

- The most favorable belt. Location between latitudes 15°N and 35°N. These semi-arid regions are characterized by having the greatest amount of solar radiation, more than 90% of which comes as direct radiation because of the limited cloud coverage and rainfall (less than 250 mm/year which corresponds to 0,68 mm/day). Moreover, there is usually over 3,000 hours of sunshine per year (8,2 hours/day).
- Moderately favorable belt. It lies between the equator and latitude 15°N. Because the humidity is high, and cloud cover is frequent, the proportion of scattered radiation is quite high. There is a total of about 2,500 hours of sunshine per year (6.9 hours/day). The solar intensity is almost uniform throughout the year as the seasonal variations are only slight.
- Less favorable belt. It lies between latitudes 35°N and 45°N. Although the average solar intensity is roughly about the same as for the other two belts, there are marked seasonal variations in both radiation intensity and daylight hours. During the winter months solar radiation is relatively lower than in the rest of the year.
- Least favorable belt. It lies beyond latitude 45°N where about half of the total radiation is diffuse radiation, with a higher proportion in winter than in summer primarily because of the rather frequent and extensive cloud coverage.

2.3. Solar intensity in Indonesia

Presently available data concerning sun intensity in Indonesia is still very rare. Comparison of average solar power intensity during January in Indonesia region between 1979 and 1993 can be observed in the references [14][15]. It can be noted that there is solar power intensity decrease in Indonesia. In 1979, south part of Sulawesi island and most of Irian Jaya island had the maximum solar intensity of 240 W/m^2 while in 1993 the maximum solar power intensity became 230 W/m^2 which lies in south west part of Kalimantan island and eastern part of Nusa Tenggara Timur. This data indicates that air pollution of the form aerosol and other particles have contributed to declining of solar power intensity.

Hundreds of radiometer instruments that had been implemented at Antartics and Artics recorded solar power intensity decrease of 10% in the period from 1950 to 1990 meaning 2-3% decrease a decade. In Asia, United State of America and Europe where industry has developed faster the intensity decrease is larger, like in Hongkong it is recorded 37%.

Table 1. Reflectivity values of various surfaces [16]

Surface	Details	Albedo
Water	Small zenith angle	0.03-0.1
	Large zenith angle	0.1-1.0
Clouds	Thick	0.6-0.9
	Thin	0.3-0.5

2.4. Clouds effect and rain fall analysis in Indonesia

The reflectivity of the Earth or any material is referred to as its albedo, which is defined as the ratio of light reflected to the light received from a source, expressed as a number between zero (total absorption) and one (total reflectance). Table 1 shows reflectivity values of various surfaces. Thick cloud has albedo number of 0.6-0.9 while thin cloud has albedo number of 0.3-0.5 [16].

According to latitude, in term of solar thermal intensity Indonesia can be classified into moderately favorable location which has potential of sunshine 6,9 hours/day. However, clouds and rains significantly inhibit solar thermal intensity especially in rainy season. Since there is limited data concerning solar intensity in Indonesia, in order to assess resource potential of concentrated solar thermal power in this paper rain fall analysis is conducted.

Edvin Aldrian reported data on monthly average rain fall number in Indonesia during 1961-1993[17]. From the figure in the report, the following conclusion can be drawn.

- December – February may be categorized as rainy season with high rain fall, while June – August is categorized as dry season with low rain fall;
- Other months are categorized as transition season;
- The starting and ending months of both rainy season and dry season are affected by some meteorological factors such as El Nino and La Nina.
- Further analysis of the figure in the report gives the following understanding.
- The least rain fall regions which have rain fall less than 4 mm/day in 8 months: NTT.
- The less rain fall regions which have rain fall less than 4 mm/day in 7 months: NTB.
- The moderate rain fall regions which have rain fall less than 4 mm/day in 5 months: Jatim and Sulut.
- The semi moderate rain fall regions which have rain fall less than 4 mm/day in 4 months: Jateng and DIY.

Climate is changing so that climate forecasting is crucial. To forecast rain fall in the future, a climate model is necessary. Haris Syahbuddin and Tri Nandar Wihendar have used climate model named ARPEGE Climate Version 3.0 to model rain fall zone from 1950-1979 and to estimate rain fall zone from 2010-2039 in Indonesia [18]. ARPEGE Climate Version 3.0 was developed by Centre National de la Recherches Meteoroligie (CNRM) in cooperation with Laboratoir Oceanografique Dynamique (LODIC) and CERFACS in France. This model is based on interaction process of atmosphere, ocean and poles. It also takes into account the effect of CO_2 concentration in the stratosphere.

Further analysis of the research result conducted by Haris Syahbuddin and Tri Nandar Wihendar [18] leads to the following conclusion on 2010-2039 forecasting:

- During April-September (dry season) south part of Timor island and Sumba island have rain fall of 4 – 5 mm/day, middle part of Timor island, Flores island, and North Sulawesi 5-6 mm/day, and other islands in the Wallacea region have rain fall more than 6 mm/day.
- During October – March (rainy season): Sumba island, south part of Timor island, south part of Flores island and part of North Sulawesi have rain fall of 5 – 6 mm/day, while north part of Timor island has rain fall of 6-7 mm/day.
- Some parts of Java and Sumatra islands will have rain fall similar or even less than NTT.

Based on the above analysis result, this paper proposes locations which are suitable to install SCP plant as follows.

- In Wallacea region: south part of Timor island, Sumba island, middle part of Timor Island, Flores island and North Sulawesi.
- In Java: Yogyakarta, Central and West Java.
- In Sumatra island: Sumatra Utara and Sumatra Selatan.

Since Timor and Sumba do not have other energy resources such as coal and geothermal while they are not connected to PLN back-bone JAMALI electrical power networks, this paper proposes these two locations as the most suitable places to install SCP plants.

3. CSP Plant Design Specification

3.1. Power capacity and effective panel area

Thermo dynamics power of steam in a system P_{tm} is expressed as below.

$$P_{tm} = C_p \dot{m}(T_{mk} - T_{ml}) \qquad (1)$$

C_p [J/(Kg.K)] indicates latent thermal coefficient, $\dot{m}$ is the debit of the medium fluid [Kg/s], T_{mk} [K] and T_{ml} [K] are temperatures at high side and low side. The relationship of thermo dynamics power of steam P_{tm} and solar thermal intensity P_{si} is given as equation (2).

$$P_{tm} = \eta_t A_{ef} P_{si} \qquad (2)$$

η_t indicates power coefficient of the thermal system, A_{ef} [m^2] is effective area of the solar thermal panel, and P_{si} [W/m^2] is solar power intensity.

The medium fluid (steam) rotates a turbine and a generator to produce electric power. The thermal power is converted to electrical power P_e by a thermal to electric efficiency value η_{me} as follows.

$$P_e = \eta_{me} P_{tm} \qquad (3)$$

Therefore, effective panel area A_{ef} is given by:

$$A_{ef} = \frac{1}{\eta_{me}\eta_t P_{si}} P_e \qquad (4)$$

An example of solar radiation measurement data can be found in the reference [8]. It was measured on July 1st 1997 at Solar Electric Generation System (SEGS) VI plant in Kramer Junction, California. By observation, it can be obtained that during sunny time (between 09:00 to 17:00) solar field efficiency η_t is around 60% and solar to electric efficiency is around 20% (corresponds to $\eta_{me} = 33.3\%$). Since solar intensity is around 1000 W/m^2, electrical power of 1 kW can be realized by installing a 5 m^2 CSP panel.

From point of view of investment, instead of using peak efficiency, it is more acceptable to use net annual efficiency η_{se} to derive effective area of panel A_{ef} as follows.

$$A_{ef} = \frac{N_h C_f P_{ed}}{\eta_{se} E_{asi}} \tag{5}$$

P_{ed} denotes electric maximum capacity (W), C_f expresses annual capacity factor, η_{se} is net solar to electric annual efficiency, E_{asi} is annual solar intensity (W.h/m^2), and N_h represents number of hours (h). In this paper we define $N_h = 8760$ (h) per year.

The net solar to electric annual efficiency η_{se} can be expressed as follows [8].

$$\eta_{se} = SF_e \times (TSTL_e \times SC_e) \times PL \times PWA \tag{6}$$

SF_e, $TSTL_e$, and SC_e denote solar field efficiency, thermal to power plant efficiency due to thermal storage thermal loses, and steam cycle efficiency, respectively. PL is efficiency due to electrical parasitic load and PWA is efficiency due to plant wide availability. The 1989 era 30MW SEGS parabolic trough plant (SEGS VI) has the following efficiency values:$SF_e = 37.3\%$,$TSTL_e = NA$ (assumeb to be 100%), $SC_e = 35.1\%$, $PL = 82.4\%$, and $PWA = 98\%$, so that its total annual solar to electric efficiency is $\eta_{se} = 10.6\%$ [8].

While research should be conducted in near future to measure (estimate) value of annual solar intensity in Wallacea region, this paper proposes hypothetic specifications shown in table 2 for CSP plants to be built at the Wallacea region (SEGS Wallacea-1).

Assuming that dry season lasts for 8 months per year at NTT, and that during dry season the sunshine period is 6.9 hours/day with solar intensity is 800 W/m^2, a 100kW SEGS can be realized by effective solar panel area of 1,250 m^2. It will produce electric energy of 168.36MWh a year.

Table 2. The proposed hypothetic specification

Project	Base line [8]		Proposed SEGS Wallacea- 1
	SEGS VI 1989	Trough 100-2004 S&L	
P_{ed}	30MWe	100MWe	100kWe
C_f	22.2%	53.5%	19.2%
η_{se}	10.6%	14.0%	10%
SF_e	37.3%	-	45%
$TSTL_e$	NA (100%)	-	80%
SC_e	35.1%	-	35.1%
PL	82.4%	-	82.4%
PWA	98%	-	98%

3.2. Structure and material selection

A SEGS is constructed by 7 main elements those are: (1) solar concentrator, (2) solar power receiver, (3) piping of high thermal fluid (heat transport media), (4) thermal storage, (5) turbine, (6) electric generator, and (7) control system. Solar concentrator, solar power receiver, the piping of heat transport media, mounting structure, and solar tracking mechanism constitute a solar field system. All these elements affect the efficiency of the solar field system. The thermal storage should be make to minimize thermal loses. The energy conversion machine is composed by steam turbine and electric generator.

Figure 2 shows a photo of the prototype of CSP system developed at the Research Center for Electrical Power and Mechatronics (RCEPM) – Indonesian Institute of Sciences. This CSP system has dimension as follows: parabolic trough mirror length 6 m, aperture width 2 m, focus distance 75 cm, absorber pipe diameter 2,5 cm and glass pipe housing diameter 7 cm [10]. A trial experiment was conducted on August 18^{th} 2011 from 9:20 to 11:30 at the RCEPM-LIPI building top roof located at latitude of 6˚52’52” S. The measured solar intensity during this two hours ten minutes experiment varies from 851 W/m^2 to 1015 W/m^2 with average value of 957 W/m^2. Solar power received by the panels is 11.5 kW. From the experiment data, thermal power of the thermal transfer material was calculated to be 1.02 kW. Thus, efficiency from solar power to thermal power is around 8.9%. The SEGS Wallacea-1 will be built based on the structure of this prototype.

Concentrator efficiency depends on mirror reflectivity, mirror cleanliness and contour precision. Reflectivity may be increased from 93,5% of silvered 4mm thick glass to 95% for front surface reflectors with a hard coat for protection. Cleanliness may be improved from 95% to 96% and be maintained at high cleanliness due to glass anti-soiling coating that is already being used on building window glass. Mirror washing technique also has significant role on mirror reflectivity performance.

Coating and reliability of the receiver used in a solar field affects the receiver thermal efficiency. Anti soiling coating may improve receiver soiling factor from 98% to 99%. Solel UVAC selective coating may give solar absorptance of 96%, emittance of 9,1%, and envelope glass transmissivity of 96,5% at 400°C. Reliability of the receiver depends on number of tubes, lost of vacuum, broken glass, and coating defect.

Fig 2. A prototype of CSP system at the RCEPM-LIPI [10].

Table 3. Steam turbine efficiencies

Turbine inlet temperature	ABB (SEGS IX)	S&L Estimate (GE STGPER basic)
390°C	37,7%	37,5%
450°C	-	39,5%
500°C	-	40,6%

The steam cycle foundation is the Rankine cycle. As the inlet steam conditions (pressure and temperature) increase, the Rankine cycle efficiency increases. Table 3 shows reference of steam turbine efficiencies used in this paper. The type of heat transfer fluid (HTF) determines the operational temperature range of the solar field. The synthetic oil (Therminol VP-1) has its operating temperature of approximately 390°C. A nitrat salt HTF, such as HitecXL, has operating range of 500°C and allows substantially smaller piping to be used in the solar field which results in lower solar field piping heat losses overall.

Thermal storage system is proposed to use two tanks indirect, VP-1 HTF, solar salt storage system. To realize capacity factor of 50% it is estimated to operate for 10 to 12 hours per day. According to experience of the authors in renewable power generations development, one important thing should be noticed concerning material of the CSP system which will be built in the Wallacea region. Corrosion due to salty ocean environment must be taken into account in selecting all components.

3.3. Solar panel tracking control system

In order to maximize solar power conversion, the solar panel must be controlled so that it always faces perpendicularly to the sun. A prototype of solar tracking control system was developed to be implemented to the prototype of CSP plant at the RCEPM-LIPI [11]. Since it would be implemented in latitude less than 15˚, it was designed to have only one degree of freedom.

Figure 3 shows the solar panel equipped with the designed solar tracking control system. The solar tracker is composed of a slewing bearing, gear box, electrical motor, power amplifier, sensors, electronic controller, Remote Terminal Unit (RTU), and Human Machine Interface (HMI) computer. The RTU is used to transmit data from/to the control room, while the HMI is used for calibration at the plant site. One CSP panel of the prototype is about 679 kg in weight and it is rotated by an actuator in its center of gravity. Considering the angular velocity of the sun is about 0.0042 ˚/sec, a small DC motor was used to save energy consumption. The motor specification is as follows: 1.16 Nm, 6,09 rpm and 0.74 W. Motor spindle is coupled to the panel spindle using a gear box with gear ratio of 1:7300.

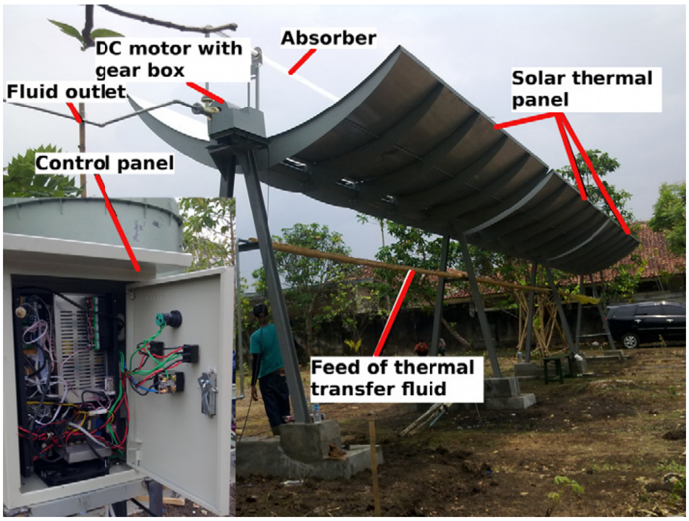

Fig 3. Solar tracking control system [11].

The solar tracking control system was then applied to a prototype of CSP plant at Yogyakarta which has 3 CPS panels installed in serial. From functional assessment testing conducted late 2011, it was obtained that the control system could track the panel to the sun direction but it could not bear against torque induced by strong storm winds. Improvement will be conducted to make it stronger.

4. Conclusions and recommendations

Presently data concerning solar intensity in Indonesia is still scarce. Solar intensity is heavily affected by clouds and rain as indicated by albedo number that clouds reflect 60% to 90% of solar radiation to atmosphere. According to rain fall (clouds) forecasting analysis results the most promising locations to install CSP plants in Indonesia are Nusa Tenggara Timur (NTT) and Nusa Tenggara Barat (NTB).

A CSP plant can be built at NTT which has specification as follows: electric power capacity of 100 kW, capacity factor of 19.2%, and annual solar power to electric efficiency of 10% . It can be realized by effective panel area of 1,250 m^2 and will produce electric energy of 168.36 MWh a year. Different CSP plants with different electrical power capacity may be built by making variation in solar panel area.

The prototype of CSP plant developed at the Indonesian Institute of Sciences (LIPI) whose recent thermal efficiency is 8,9% is recommended to be improved so that it can be deployed to construct CSP plants at the Wallacea region.

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