Solar Stirling Dish Power Generation Atlas of India

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ABSTRACT

In this article, an atlas of solar electricity potential of Stirling dish power generation system is presented. Important parameters needed for solar power generation modeling are direct solar insolation, ambient temperature, wind speed, concentrator aperture area, rim angle, mirror reflectance, working fluid, operating temperature, receiver insulating material and intercept factor. The input data values averaged over a 10-year period is obtained from India Meteorological Department, Pune. The useful energy delivered by a collector is evaluated with consideration for various heat losses. An average value of solar electricity potential of a 25.3 kW parabolic dish collector is found to be maximum of 15.3 kW for Jodhpur and minimum of 12.7 for Calcutta. Maps of annual variation of solar electricity potentials, comparison of electricity potentials of Indian cities for different months, average electricity potentials and annual electrical energy generation for various Indian cities have been developed. To produce 25 kW of electrical power on all the days of a year, three different dishes are recommended for the Indian cities of Jodhpur, Trivendrum and Calcutta. This atlas provides knowledge and aids in exploitation of solar electricity generation for Indian climatic conditions.

Keywords: Stirling dish; direct solar insolation; heat losses; solar electricity potential; power generation modeling

INTRODUCTION

Energy is the most basic need of the people in the world, and it is needed more than ever. A majority of world energy supplies are provided by fossil fuels, which are causing environmental problems. Long term projections indicate that world energy demand may increase drastically, with most of this increase taking place in developing countries. In the last few years, fossil fuel resources are rapidly depleting. As a result, new and renewable energy technologies are required to play a greater role in the future energy mix. These sources can create a significant impact in the generation of grid electricity because of the progress made in biomass power, wind power and small hydro power in the last few years. The ninth five-year plan (1999) reported that the demand for electricity in India is growing approximately 8% per year. The Ministry of Power blue print for power sector development (2001) stated that India would need 100,000 MW generation capacity by 2012. Accordingly, The Ministry of Power (2003) prepared an action plan for implementation during the tenth and eleventh five-year plans. Research and development exercises over the years have established solar energy as a potential source of renewable energy.

Implementation of solar power plants in regions of high insolation is the most promising option for an environmentally compatible electricity supply strategy. The parabolic dish concentrator received considerable attention in recent years. Schmidt et al. (1983) outlined some experiences gained in solar farm systems and possible future development trends of such farm systems using point focusing dish collectors. Jaff (1983, 1988) presented the results of development testing of various parabolic dish concentrators and addresses problems of optimizing the optical characteristics of dish collectors for solar thermal power systems. Factors affecting the design of paraboloidal dishes for providing high quality heat, potentially cost competitive with alternative solar thermal technologies, is discussed (Kaneff 1983). Friedman et al. (1993) presented a new two stage optical design for parabolic dish concentrators that can realistically attain close to 90% of the thermodynamic limit to concentration with practical compact designs. Kaushika (1993) reported viability aspects of paraboloidal dish solar collector systems. Kaushika and Reddy (2000) presented performance characteristics of a low cost steam generation system, which incorporates the recent designs and materials innovations of the parabolic dish technology. The diversity of construction approaches and technologies of dish concentrators are in use in recent years. The most prominent development is the transition from glass-metal to stretched membrane designs (Jaffe 1988, Mancini 1991).

Dish solar collectors achieve highest performance of all concentrator types in terms of annual collecting energy and peak solar concentration (Lopez and Stone 1992). Stirling engines are preferred for these systems because of their high efficiencies, high power density, and potential for long term and low maintenance operation. Parabolic dish solar power plants can be used for decentralized power generation in rural and remote areas with no connection to the power grid.

Knowledge of solar electrical power generation capabilities of various locations is a significant parameter for determining potential use in India. The atlas provides data and aides in exploitation of solar electricity generation for Indian climatic conditions. The atlas is a useful tool for engineers, meteorologists and researchers to provide the following services.

- Assessment of the solar electricity potentials of solar power generation in India.
- A broad overview with maps of the solar electricity resource potential across India.
- Selection of sites for construction of solar thermal power stations.

The objective of the present study is to investigate solar electricity potential of dish based power generation systems for various locations in India. A computer simulation program is developed to evaluate the useful energy delivered by the collector. Maps of annual variation of solar electricity potential, electricity potential for different months, average electricity potential and annual electrical energy generation of various Indian cities have been developed.

METHODOLOGY

The atlas predicts the electrical power generated by the solar Stirling dish power generation system. Figure 1 shows a schematic diagram of a Stirling dish system with the major components. It consists of a concentrator and a power conversion unit located at the focal point of the dish. The concentrator reflects light into a receiver at the focus of dish. The power conversion unit consists of a receiver and a Stirling heat engine with an alternator. The concentrator tracks the sun by rotating around two axes and the sun's rays are brought to a point focus. A fluid flowing through a receiver at the focus is heated, and this heat is used to drive a Stirling engine. The parameters needed for solar power generation modeling in the atlas include direct solar insolation, ambient temperature, wind speed, concentrator aperture area, rim angle, mirror reflectance, working fluid, operating temperature, and receiver insulating material. The design characteristics of a 25.3 kW solar Stirling dish electricity system are shown in Table 1. The input data values of direct solar insolation, ambient temperature, and wind speed averages over the ten year period from 1981 to 1990 are taken from India Meteorological Department, Pune.

The receiver mounted at the focus of the dish collector is a critical component in the power generation system. It acts as a link between the concentrator and the energy utilization unit. Its essential feature is to absorb the maximum amount of concentrated solar energy and transfer it as heat with minimum losses to the working fluid. The total heat loss rate of the receiver consists of radiative, convective and conductive losses from receiver aperture, and radiative and convective losses of

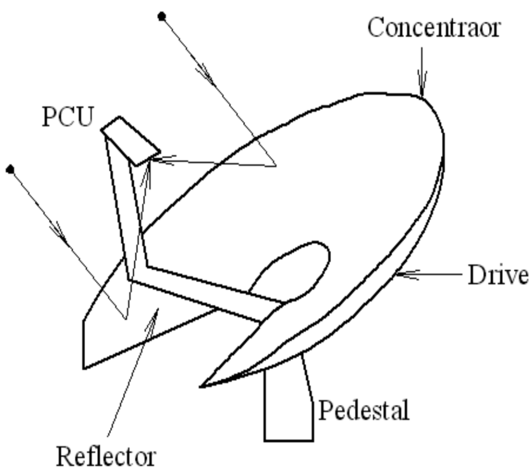

Figure 1. Stirling dish system with the major components

Table 1. Design characteristics of 25.3 kW solar Stirling dish electricity system

Concentrator aperture area	115 m^2
Focal length	7.45 m
Rim angle	47°
Reflectivity	0.9
Intercept factor	0.98
Stirling engine displacement	380 cc
Working fluid	Helium
Working fluid pressure	20 MPa
Output power	25.3 kW at 1000 W/m^2
Alternator	Induction, 1800 rpm
Alternator efficiency	93 %
Electrical power	480 V, 50 Hz, 3 phase
Peak net power efficiency	29.8 %

the external absorbing surface. The energy losses of the receiver for the present dish collector are investigated by using the procedure outlined in Kaushika and Reddy (2000).

The total heat loss rate for receiver Q_{TL} is expressed as

$$Q_{TL} = Q_{CND} + Q_{CNV} + Q_{RD} + Q_{SCNV} + Q_{SRD} \quad (1)$$

Conduction heat loss through the receiver wall is given by

$$Q_{CND} = \frac{1}{\left[\frac{1}{A_C h_1} + \frac{1}{K_A \sqrt{A_W} A_{Ins}} + \frac{1}{K_B \sqrt{A_{Ins}} A_C}\right]} \left(T_{W1} - T_{amb}\right) \quad (2)$$

Convection heat loss from inner receiver is given by

$$Q_{CNV} = h_0 A_1 \left(T_{W1} - T_{amb}\right) \quad (3)$$

Radiation heat loss from the inner receiver is given by

$$Q_{RD} = \sigma A_1 \varepsilon_{eff} \left(T_{W1}\right)^4 \quad (4)$$

where

$$\varepsilon_{eff} = \frac{1}{\left[1 + \left(\frac{1}{\varepsilon_{c1}} - 1\right)\frac{A_1}{A_W}\right]} \tag{5}$$

Convection heat loss from the outer surface of the receiver is given by

$$Q_{SCNV} = h_2 A_2 \left(T_{W2} - T_{amb}\right) \tag{6}$$

Radiation heat loss from the outer surface of the receiver is given by

$$Q_{SRD} = \sigma\, A_2 \varepsilon_{c2} \left(T_{W2}\right)^4 \tag{7}$$

where h_0 and h_2 are convective heat transfer coefficients, which are evaluated from dimensionless relationships of free and forced convection (Mc Adams 1954; Jacob 1962)

$$h_0 = h_{on} + h_{of} \tag{8}$$

$$h_2 = h_{2n} + h_{2f} \tag{9}$$

$$h_{on} = 1.45 \left(T_{W1} - T_{amb}\right)^{0.333} \tag{10}$$

$$h_{2n} = 1.45 \left(T_{W2} - T_{amb}\right)^{0.333} \tag{11}$$

$$h_{of} = h_{2f} = 4.22 \left(V\right)^{0.805} \tag{12}$$

The useful energy delivered by collector is given by

$$Q_U = I_B A_P \rho \left[\phi_0 \alpha_{eff} + (1 - \phi_0)\, \alpha\right] - Q_L \tag{13}$$

The electrical power generated by the system is given by

$$P = \eta_{st} \eta_a Q_u \tag{14}$$

The atlas contains four sets of maps; the first set of maps indicates the annual variation of solar electricity potential for various cities over the Indian subcontinent. The cities considered in the present study across South India are Trivandrum, Mangalore, Chennai and Visakhapatnam, and across North India are Mumbai, Pune, Nagpur, Bhavnagar, Ahmedabad, Jodhpur, New Delhi and Calcutta. The second set of maps indicates the comparison of solar electricity potential of various cities for the representative months of January, April, July and October. The third set of maps indicates the average solar electricity potential of various cities across India. The fourth set of maps indicates the annual electrical energy generation of various cities across India.

RESULTS AND DISCUSSION

The Stirling dish power generation system is analyzed using the mathematical model. The average solar electricity potential and annual electrical energy generation of various cities are investigated and reported in Table 2. Annual variation of solar electricity potential of 25.3 kW parabolic dish for various cities in India is shown in Figure 2 to Figure 4. The electricity potential are high during summer season and fairly uniform across the most of the stations over the country, stations producing power over 20 kW. A reversal in the gradient occurs during June to July, with the onset of the south west monsoon over the peninsula. During August, the electricity potential is low over the country, on the order of 5 kW. With the withdrawal of the monsoon season in

Table 2. Average Solar Electricity Potentials (ASEP) and Annual Electrical Energy Generation (AEEG) of various Indian Cities

City	*ASEP (kW)*	*AEEG (kWh)*
Trivandrum (T)	12.8	30,067
Mangalore (M)	12.9	39,290
Chennai (C)	13.6	37,902
Visakhapatnam (V)	13.7	41,612
Mumbai (MU)	13.3	40,994
Pune (P)	14.3	43,333
Nagpur (N)	13.3	41,265
Bhavnagar (B)	14.0	48,800
Ahmadabad (A)	14.1	48,367
Jodhpur (J)	15.3	51,036
New Delhi (ND)	13.3	37,615
Calcutta (CA)	10.7	27,554

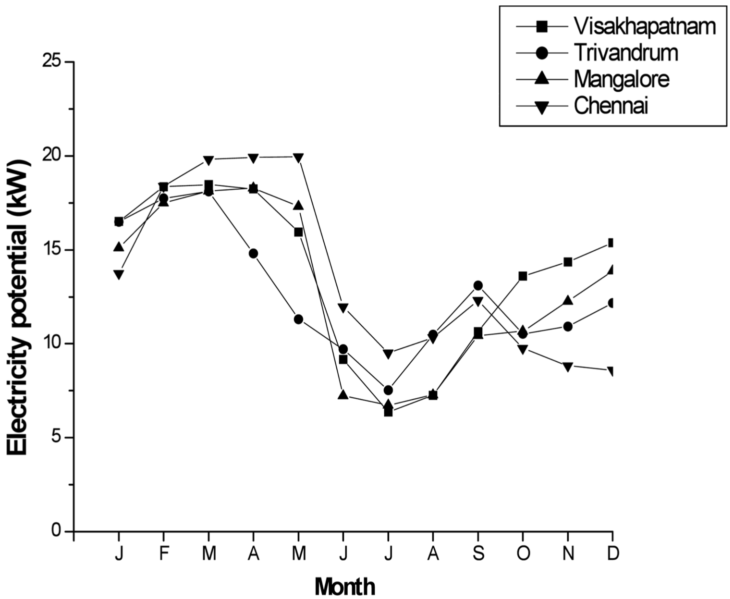

Figure 2. Comparison of electricity potential over the year among Visakhapatnam, Trivandrum, Mangalore, and Chennai

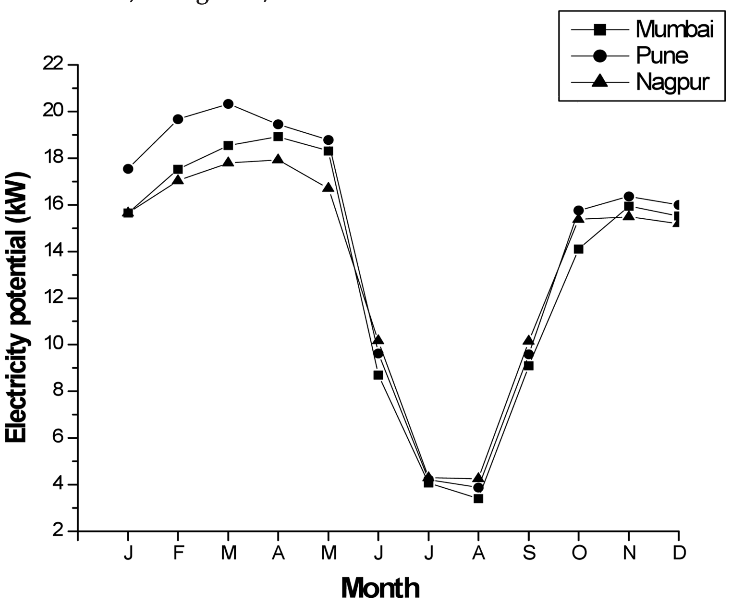

Figure 3. Comparison of electricity potential over the year among Mumbai, Pune, and Nagpur

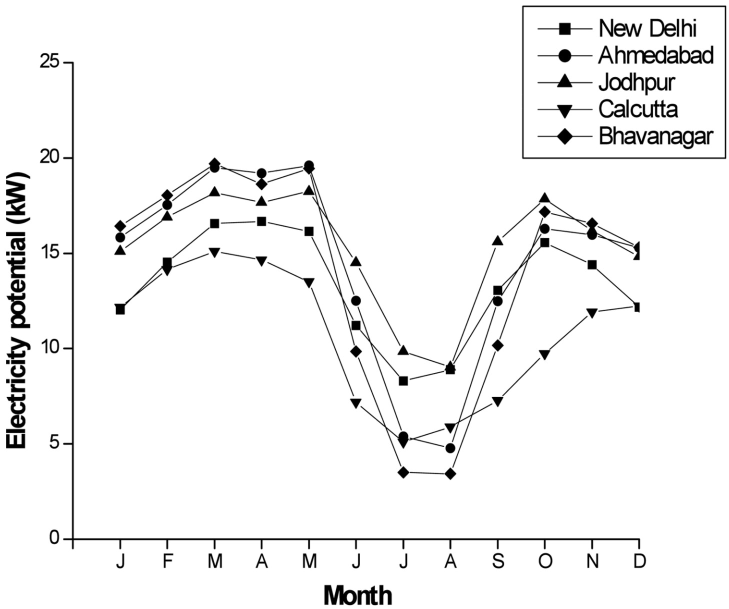

Figure 4. Comparison of electricity potential over the year among New Delhi, Ahmedabad, Jodhpur, Calcutta, and Bhavnagar

October and the setting in of winter conditions, the winter pattern is re-established over the country by November. A gradient in direct solar insolation intensities on clear days exists during the winter months, from December to February, with low electricity potential in the north and high in south, as a result of the increasing inclination of solar rays and decreasing length of the day with increasing latitude. The electricity potential of northern stations during these months is less than that of southern stations by nearly 4.5 kW.

Figure 5 to Figure 7 illustrates a comparison of solar electricity potential of various cities for the representative months of January, April, July and October. Solar electricity potential is highest in April and lowest in July for all stations. Abbreviations used for various cities are expanded in Table 2. Figure 8 illustrates a comparison of average solar electricity potential for various cities across India. The highest value is reported for Jodhpur and the lowest for Calcutta. Figure 9 illustrates a comparison of annual electrical energy generation of various cities across India. Annual electrical energy generation was found to be highest for Jodhpur, 51,036 kWh, and lowest for Calcutta, 27,554 kWh.

To produce electrical power of 25 kW on all the days of a year, the following recommendations are made for Indian cities. A parabolic dish with an aperture area of 207 m2 with reflectivity of 0.9 at Jodhpur, a parabolic dish with an aperture area of 230 m2 with reflectivity of 0.93 at Trivendrum and a parabolic dish with an aperture area of 262 m2 with reflectivity of 0.93 at Calcutta will produce electrical power of 25 kW throughout the year. With advancement of technology, a number of promising new reflective materials for solar thermal energy conversion are available. Silvered thick sumped glass with a proprietary multilayer paint system has reflectance of 0.93, Spanish glass mirrors with copper free and lead free paint has reflectance of 0.933, Pilkington glass mirrors with copper free and lead free paint has reflectance of 0.928 and highly polished pure aluminum can have a reflectance as high as 0.97.

CONCLUSION

The developed solar power generation atlas provides an outlook for electricity potential for various locations in India. The atlas provides a broad overview, with maps with reference to their potential for power

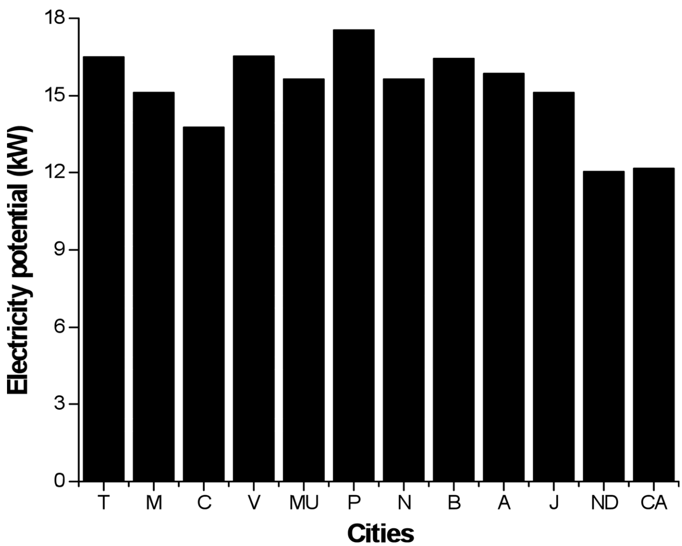

Figure 5. Comparison of electricity potential of various Indian cities for the month of January

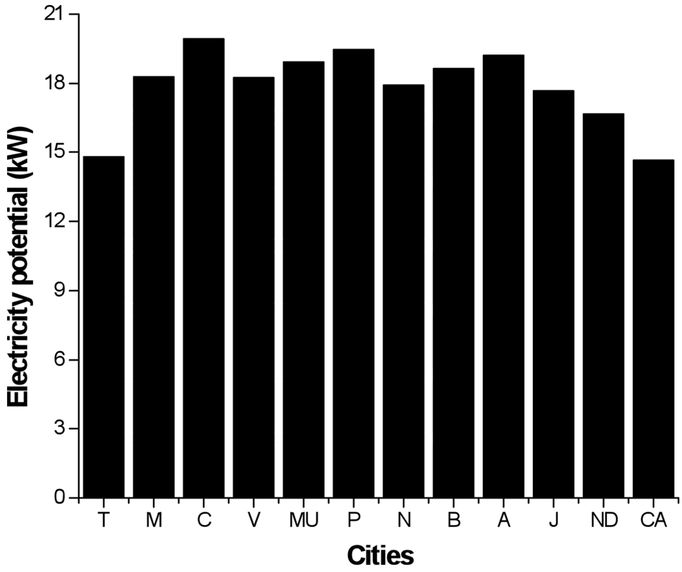

Figure 6. Comparison of electricity potential of various Indian cities for the month of April

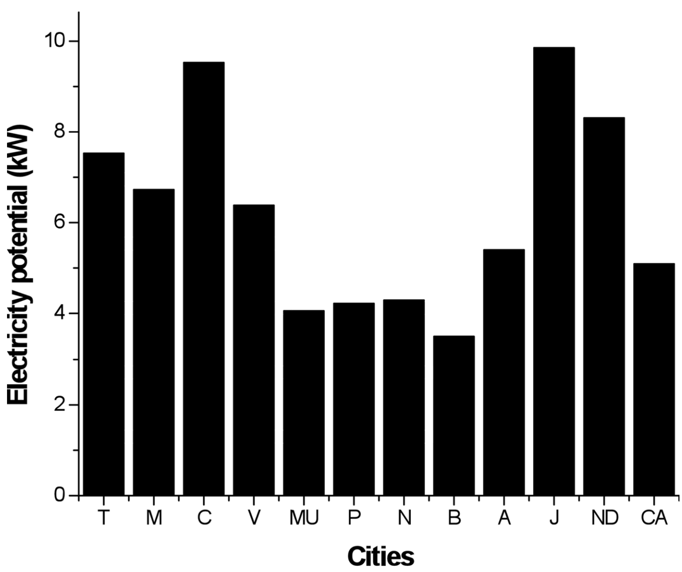

Figure 7. Comparison of electricity potential of various Indian cities for the month of July

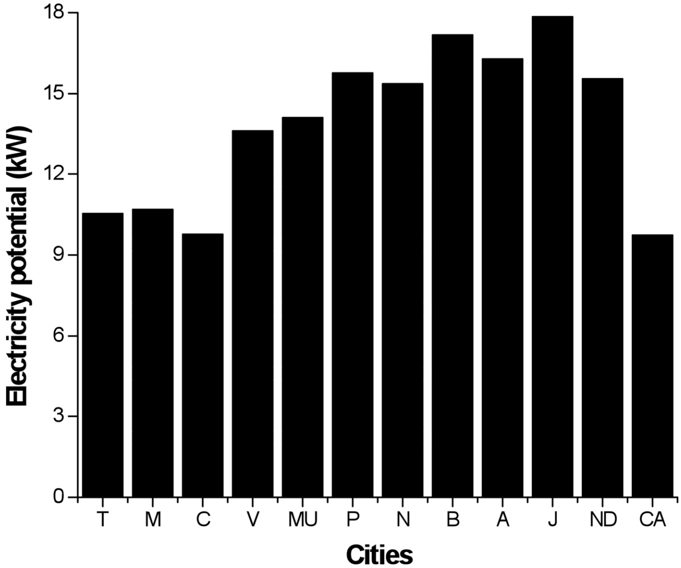

Figure 8. Comparison of electricity potential of various Indian cities for the month of October

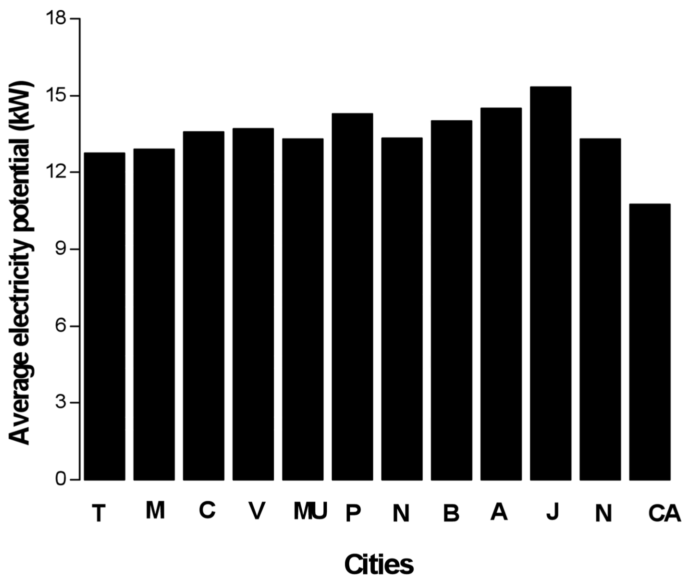

Figure 9. Comparison of average electricity potential of various Indian cities

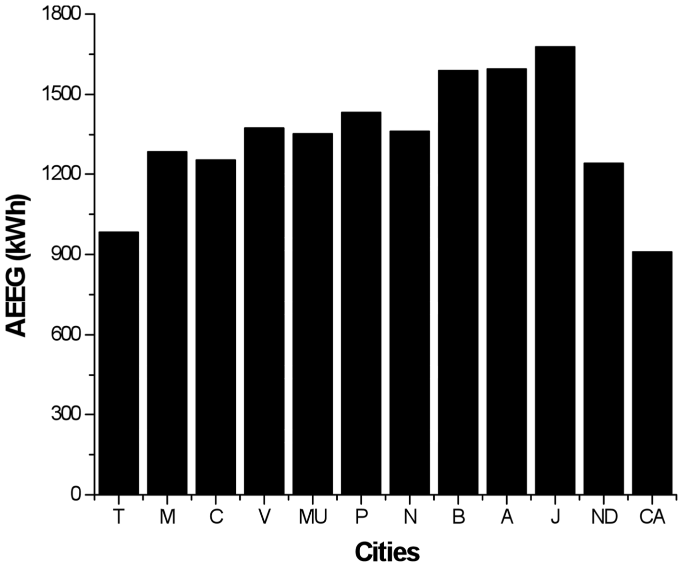

Figure 10. Comparison of annual electrical energy generation of various Indian cities

generation. It is a useful tool in selection of the sites for the construction of solar thermal power stations. The electrical power developed by an Stirling dish system at various locations was investigated. Average values of electricity potential for the South Indian cities of Visakhapatnam, Trivandrum, Chennai and Mangalore were 13.7 kW, 12.8 kW, 13.6 kW, 12.9 kW, respectively and the North Indian cities of Jodhpur, Bhavnagar, Ahmedabad, Mumbai, Pune, Nagpur, New Delhi and Calcutta were 15.3 kW, 14 kW, 14.1 kW, 13.3 kW, 14.3 kW, 13.3 kW, 13.2 kW, and 10.7 kW, respectively. Annual electrical energy generation was found to be highest for Jodhpur, 51,036 kWh, and lowest for Calcutta, 27,554 kWh. The generated electrical energy data presented was a useful source of information for the estimation of energy harvest potential of solar Stirling dish system. This information can be utilized to compare power generation capabilities among cities across India and derive significant statistics for the solar power generation using a Stirling dish system.

To produce an electrical power of 25 kW on all days of a year, a parabolic dish with an aperture area of 207 m^2 with reflectivity of 0.9 at Jodhpur, a parabolic dish with an aperture area of 230 m^2 with reflectivity of 0.93 at Trivendrum and a parabolic dish with an aperture area of 262 m^2 with reflectivity of 0.93 at Calcutta are recommended. The present study is an attempt to promote solar power generation in India with the purpose of reducing the use of conventional power plants and the environmental problems associated with them.

Nomenclature

A_1 Focal image/aperture area of the receiver, m^2
A_2, A_c Area of the outer surface of the copper sheet of the receiver, m^2
AEEG Annual electrical energy generation
A_W Heat transfer area of the inner receiver, m^2
A_{Ins} Area of the outer surface of the insulation of the receiver, m^2
A_P Aperture area of the concentrator, m^2
I_B Beam component of the solar radiation, W/m^2
I_G Global solar radiation, W/m^2
k_A Thermal conductivity of the insulating material, W/m . K
k_B Thermal conductivity of the outer copper sheet, W/m . K
Q_{CND} Conduction heat loss through the receiver wall, W
Q_{CNV} Convection heat loss from the inner receiver, W
Q_{RD} Radiation heat loss from the inner receiver, W
Q_{SCNV} Convection heat loss from the outer surface of the receiver, W
Q_{SRD} Radiation heat loss from the outer surface of the receiver, W
T_{w1} Inner surface temperature of the receiver, K
T_{w2} Outer surface temperature of the receiver, K
T_{amb} Ambient temperature, K
V Outside wind velocity, m/s
ρ Reflectivity of the dish
α_{eff} Effective absorptance of the receiver,
α Absorptivity of the receiver
ε_{C1} Emissivity of the inner surface of the receiver
ε_{C2} Emissivity of the outer surface of the receiver
ε_{eff} Effective emittance of the receiver
η_{st} Stirling engine efficiency
η_a Alternator efficiency

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