PERFORMANCE ANALYSIS OF PARABOLIC TROUGH SOLAR COLLECTOR (PTSC) SYSTEM

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Abstract

There are various attributes to determine the performance of a PTSC system and MADM is the simplest among all of them. This paper utilizes one of the attributes of MADM i.e. TOPSIS and explains the application of TOPSIS method using four different materials. Here it is shown that the best solution obtained by TOPSIS method is neither close to the positive ideal solution nor farthest from the negative ideal solution. The basic principle of TOPSIS is that the chosen alternative should have the shortest distance from the positive ideal solution and the longest distance from the negative ideal solution.

Keywords: PTSC, CSP, MADM, TOPSIS, photovoltaic, Mtoe, etc.

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Introduction

Energy plays a very vital and significant for the development of human civilization. Human civilization depends on the different forms of energy in day-to-day life for various needs. Energy production is a very essential component for the economic development of a nation. For a developing country like India, energy is very vital for its sustainability and growth in comparison to the developed countries.

According to a large scale energy forecast, it has been ensured that fossil fuel can meet the demand for the next decade [1]. But now the question arises, what will happen after that? Also, there are worrying consequences in context to the above scenario viz. excessive use of fossil fuel. The excessive use of such resources results in drastic climatic changes, strong CO_2 emissions, uncertainty to oil and gas supply, increase in fuel prices, etc. It is the time to think that what we are going to give our younger generation, a polluted society or a healthy environment.

The only solution to the above problems is the innovation of new technologies that would promise to provide pollution free environment. This can be achieved by innovating new advances in the field of energy generation based on renewable resources such as wind power, hydro power, solar power etc. These renewable sources can impose substantial effects on society in context to the pollution free environment. As far as electricity production is concerned, IPCC's report, released in April 2014, notices that renewable energy sources represent half of the additional capacity of 2012 [2].

Solar energy is the best possible remedy to overcome these environmental issues and can even generate more power than the generation of power by the conventional energy resources. In most of the developing nations, the level of solar radiation is considerably higher than developed nations. If we talk of India, a developing nation, the solar energy is sufficient enough to meet the country's electric demand. The average intensity of solar radiation received here is around 200MW per km sq and this amounts to 657.4 million MW for the whole geographical area of India i.e. 3.287 million km sq [3].

But there are certain restrictions regarding Indian sub-continent, 87.5% of the land is employed for agriculture, forest reserves, fallow land, etc., 6.7% for housing, industries, etc. and 5.8% of the land is either barren, snow covered or generally inhabitable. Only 12.5% of the land consisting of barren and fallow lands, which amount to 0.413 million km sq, is available for use of renewable resources. If only 10% of this land is used for solar power, 8million MW power per year (5.909 Mtoe) can be generated, which is far more than the country's energy demands [4].

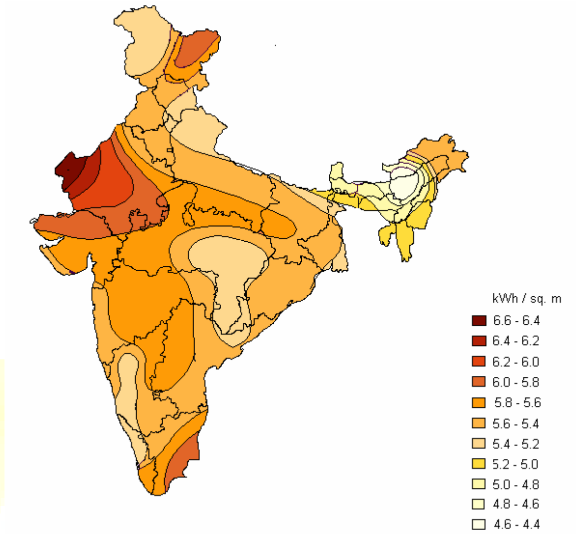
Solar Potential in India

India is having a tremendous solar potential because of its nearness to Equator. This country has nearly 300 sunny days which corresponds to solar radiation to a great extent. These days are sufficient enough to produce 5000 trillion kWh of energy. The following table predicts the amount of energy that can be generated annually using solar power [5].

Total land area (km sq)	3, 287, 590
Number of sunny days	300
Unit potential from 1m sq	4 kWh/ day
Conversion efficiency	15%
1 km sq (Mn units/ yr)	120
0.5% land of land use (km sq)	16,438
Potential units (in billions)	1972

Calculation of Solar Potential in India [5]

The Indian economy is growing rapidly and providing the electricity generation capacity to support this growth is the main focus at present to solve. Till 2017, it is assumed that the capacity growth will increase to 300GW from 167GW in 2010. Solar power is poised to play a big role in this regard. The main enabler for PV and CSP projects is the Jawaharlal Nehru National Solar Mission (JNNSM), launched in 2010 by the then Prime Minister, Dr. Manmohan Singh [6].



Solar Radiation on India [7]

Available Solar Technologies

There are two types of technologies to harness solar energy which are based on the following criteria:

1. Direct conversion of solar energy to electricity

   This can be achieved by employing solar photovoltaic like solar cells. It is the only technology which converts solar radiation into electricity and store them in batteries for further use.

2. Indirect conversion of solar energy into electricity

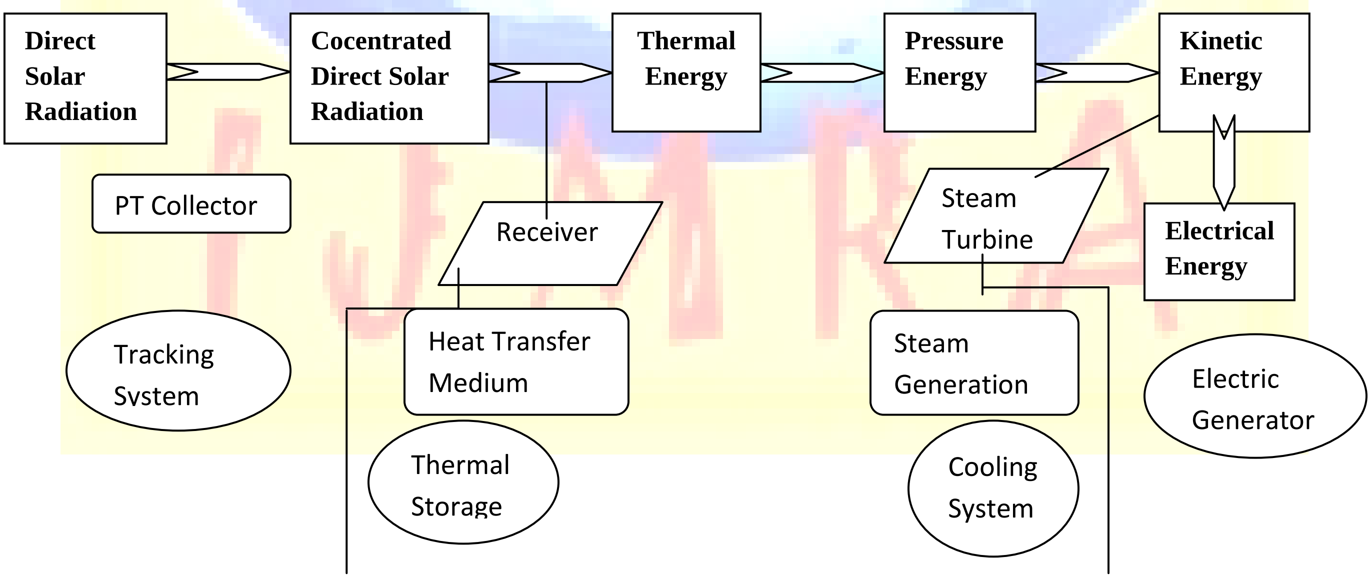
   This can be achieved by installing concentrated solar power (CSP) systems which harness solar energy and convert it into electricity or can be utilized for thermal applications such as cooling or heating, etc. These systems work similarly like steam power plant, the only exception is the fuel. Steam power plant uses coal or gases as primary source to vaporize water whereas; CSP system utilizes solar radiation as the primary source of fuel for the same function. Various CSP systems employed are parabolic trough solar collector system (PTSC), parabolic dish collector system, Fresnel collector system, solar power tower, etc.

In India, first type of solar technology i.e. solar photovoltaic is highly in demand. It is used in street lightening systems and also in solar home lightening systems. India currently has around

1.2 million solar home lightening systems and 3.2 million solar lanterns distributed [8]. Also India has been ranked the no. 1 market in Asia for solar off-grid products [9]. But, a major drawback of photovoltaic (PV) systems is the mass energy storage. It requires large number of batteries to store that energy even to power a house and occupies a lot of space. This can be overcome by installing CSP systems as they require less space in comparison to PV systems and also generate more power.

Here, we will focus on PTSC (parabolic trough solar collector) system. Typically, in a CSP plant, the heat energy is transferred to mechanical energy with the help of a steam turbine and then to electricity by a dynamo or generator coupled to the turbine. Concentrated solar thermal power plant had shown an initial growth period in the 1980's [6]. Since2005, CSP project activities gained considerable momentum. This sector is believed to grow at a very high rate.

For a country like India, embarking on growing its involvement with CSP, a successful prototype plant has been constructed by IIT Bombay at Solar Energy Centre (presently known as NISE-National Institute of Solar Energy), Gwalpahari (near Gurgaon), Haryana. This technology has enormous educational values with a benefit of spreading awareness about this technology.



Flow Chart Depicting the PTSC Working

The established plant has the following specifications:

Installed capacity	1 MW
Solar field aperture area	8000 m^2
Number of collector assemblies	12
Number of loops	3
Number of SCA length	4
SCA length	120
Number of modules per loop	10
Number of heat collector element	360
Heat transfer fluid (HTF)	Therminol VP-1
Heat transfer medium	Water (distilled)
Operating temperature	350^o C
Operating pressure	40 bar
Developer	IIT Bombay

Energy flow diagram in parabolic trough solar collector (PTSC) system [10]

Performance Evaluation of CSP plant

Solar energy is utilized to fulfill our daily needs like water heating, space heating and power generation. A PTSC system is used for all the above applications. This system is mainly used for the steam and power production throughout the world but its use in the water and air heating applications is very limited. Flat plate collectors are generally used for the hot water production because they are comparatively cheaper than the PTSC system and also are easily available in the market. But they are less efficient than PTSC system which justifies their use for the water heating applications. The major problem with this technology is its unawareness amongst the people as they do not know what the best options are and which PTSC is to select from the global market. So there arises a need of PTSC system to be reached to the common man.

For the performance of CSP plants, a method from multi approach decision making (MADM) has been implemented here and that is TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) procedure. TOPSIS is a multiple criteria method to identify solutions from a set finite set of alternatives. The basic principle is that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. [11]

Evaluation by TOPSIS procedure [12]

A mini-database is formed which comprises of all the satisfying solutions. Now, one has to find out the best solution out of all. These solutions are ranked in order of merit in the selection procedure.

Step 1: All of the information available from the database about these satisfying solutions is represented in the matrix form. This matrix is called as decision matrix 'D'. Each row of the matrix is allocated to the different parabolic trough solar collector system and each column to one attribute.

Step 2: This step includes the construction of Normalized Specification Matrix, 'N' from the decision matrix. This matrix 'N' is represented on a common scale of 0 to 1. An element nij of the normalized matrix N can be calculated as

$$n_{ij} = \frac{d_{ij}}{\sqrt[2]{\sum_{i=1}^{m} d_{ij}^2}} \qquad (1)$$

Where, d_{ij}= an element of the decision matrix.

Step 3: In this step the relative importance matrix 'A' is formed for the relative importance of the attributes over other. Element a_{ij} of the relative importance matrix represents the relative importance of the i^{th} attribute over the j^{th} attribute i.e. (w_i/w_j) where w_i, wj are the weight vectors.

Step 4: Now by using Eigen vector method the maximum Eigen value λ is to be obtained by the use of the equation shown below:

$$(A-\lambda I)\mathbf{W} = \mathbf{0} \qquad (2)$$

Where W = {w1, w2, w3…………....wn} ^{T}, where $\sum_{i=1}^{n} wi = 1$

Step 5: In this step the weighted normalized specification matrix 'V' is obtained by the following expression:

$$V = [V_{ij}],$$

$$\text{Where } V_{ij} = w_j * n_{ij},$$

Where i=1, 2, 3…………, m (3)

A. TOPSIS method:

The above matrix V is used to obtain the positive and negative benchmark parabolic trough solar collector system which is supposed to have best and worst possible attribute magnitudes. Now the optimum design should be the one which is the closest to the positive benchmark PTSC system and farthest from the negative benchmark PTSC system. Now the separation from the positive and negative benchmark PTSC is calculated by the following formulae:

$$S_i^* = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_1^*\right)^2\right\}^{\frac{1}{2}} \qquad (i = 1, 2, 3\ldots, m) \qquad (4.\ a)$$

$$S_i^- = \left\{\sum_{j=1}^{n}\left(V_{ij} - V_1^-\right)^2\right\}^{\frac{1}{2}} \qquad (i = 1, 2, 3\ldots, m) \qquad (4.\ b)$$

Where,

S_i^* =Positive benchmark PTSC

S_i^* = Negative benchmark PTSC

B. Determination of suitability index

The suitability index, 'C*' is a measure of the suitability of the PTSC system for the chosen application on the basis of attributes considered. It is defined as the relative closeness to the HBS, and is expressed as

$$C^* = S_i^- \left(S_i^* + S_i^*\right), \quad i = 1, 2\ldots m \qquad (5)$$

Where, C^* = relative closeness to the positive benchmark PTSC.

Now the ranking is done with the decreasing value of C^*.

Sr. No.	Name of PTSC
1	Flagsol SKAL-ET 150
2	Acciona Solar Power SGX 2
3	IST Solucar PT-2
4	Sener

Alternative PTSC designs from the global market

Let us take an example:

Suppose we want to select a parabolic trough solar collector for the Indian conditions. It is to be noted that here only parabolic trough collector which is a part of PTSC system is taken into account and is illustrated just to explain the methodology. The minimum requirement is as follows:

Concentration ratio	more than 70
Power Output	<=25 MWat least 75%
Optical efficiency	at least 75%
Type of drive used	Hydraulic
Tracking system	two axis
Reflector material	thick mirror

After analyzing the global market the 4 best possible PTSC designs are selected and are compared and ranked with the use of the MADM-TOPSIS methodology. According to their use for different application areas the best suited design is selected. The values of the quantitative attributes of different PTSC designs are shown in the table mentioned below:

Attributes for the PTSC

Sr. No.	PTSC	Concentration Ratio	Focal Length	Optical efficiency	Length
1	Flagsol SKAL-ET 150	82	1.71	80	148.5

2	Acciona Solar Power SGX 2	81	1.72	77	130
3	IST Solucar PT-2	63	1.73	75	149
4	Sener	80	1.7	76	150

Now the procedure for the selection of the PTSC is as follows:

Step-1: Formation of the decision matrix 'D', in which the rows of the matrix are candidate PTSC and the columns are their attribute values.

$$D = \begin{bmatrix} 82 & 1.71 & 80 & 148.5 \\ 80 & 1.7 & 76 & 150 \\ 63 & 1.73 & 75 & 149 \\ 81 & 1.72 & 77 & 130 \end{bmatrix} \quad (6)$$

Step 2: Construction of relative importance matrix from decision matrix. A group of experts and the user will determine the importance of one attribute over the other. The relative importance matrix which is formed from the decision matrix is shown here.

$$A = \begin{vmatrix} 1 & 2 & 0.5 & 2 \\ 0.5 & 1 & 0.33 & 1 \\ 2 & 3 & 1 & 2 \\ 0.5 & 1 & 0.33 & 1 \end{vmatrix} \quad (7)$$

Step 3: Now the maximum Eigen value of the relative importance matrix R is to be found out. Therefore $(A - \lambda_{max}I)$ is equal to

$$\begin{vmatrix} 1-\lambda & 2 & 0.5 & 2 \\ 0.5 & 1-\lambda & 0.33 & 1 \\ 2 & 3 & 1-\lambda & 2 \\ 0.5 & 1 & 0.33 & 1-\lambda \end{vmatrix}$$

Also, $(A-\lambda_{max}I) = 0$,

On solving the above matrix we have, $\lambda_{max} = 3.93$

Therefore, Now

$$(A-\lambda_{max}I) = \begin{vmatrix} -2.93 & 2 & 0.5 & 2 \\ 0.5 & -2.93 & 0.33 & 1 \\ 2 & 3 & -2.93 & 2 \\ 0.5 & 1 & 0.33 & -2.93 \end{vmatrix} \quad (8)$$

Step 4: In this step the weights for each attribute using the Eigen vector associated with the maximum Eigen value are calculated. This can be represented by the equation,

$$(A-\lambda_{max}I)\ w = 0 \quad (9)$$

$$\begin{vmatrix} -2.93 & 2 & 0.5 & 2 \\ 0.5 & -2.93 & 0.33 & 1 \\ 2 & 3 & -2.93 & 2 \\ 0.5 & 1 & 0.33 & -2.93 \end{vmatrix} \begin{vmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{vmatrix} = 0$$

Also we know that,

$$w_1 + w_2 + w_3 + w_4 = 1 \quad (10)$$

On solving this above matrix we have,

$$w_1 = 0.2732;\ w_2 = 0.1457;\ w_3 = 0.4352;\ w_4 = 0.1457$$

Step 5: In this step the normalized specification matrix is calculated which helps to provide the dimensionless elements of the matrix. It is denoted by 'N'.

$$n_{ij} = \frac{d_{ij}}{\sqrt[2]{\sum_{i=1}^{m} d_{ij}^2}} \quad (11)$$

Therefore, normalized specification matrix N is equal to

$$N = \begin{vmatrix} 0.533 & 0.498 & 0.519 & 0.513 \\ 0.520 & 0.495 & 0.493 & 0.518 \\ 0.409 & 0.504 & 0.486 & 0.515 \\ 0.526 & 0.501 & 0.499 & 0.449 \end{vmatrix}$$

Step 6: In this step the weighted normalized specification matrix is calculated. It is denoted by 'V'.

$$V = \begin{vmatrix} 0.1456 & 0.0726 & 0.2260 & 0.0748 \\ 0.1421 & 0.0722 & 0.2147 & 0.0755 \\ 0.1119 & 0.0735 & 0.2119 & 0.075 \\ 0.1439 & 07310. & 0.2175 & 0.0654 \end{vmatrix}$$

The weighted normalized matrix involves both the attribute values and their relative importance to each other. So this matrix provides a very good basis for the comparison of the attributes with each other and with the benchmark PTSC.

C. TOPSIS method for ranking:

The weighted normalized attributes for the positive and negative benchmark PTSC's are obtained which are as follows:

$V^* = (0.1456, 0.0735, 0.2260, 0.0755)$ (12a)

$V^- = (0.1119, 0.0722, 0.2119, 0.0654)$ (12b)

Now from the formulas above mentioned in the explanatory part of the TOPSIS method and relative closeness to the ideal solution can be calculated and the values for the same are as follows:

$$S_1^* = 0.0011; S_1^- = 0.0377; C_1^* = 0.9707$$

$$S_2^* = 0.0119; S_2^- = 0.0319; C_2^* = 0.7284$$

$$S_3^* = 0.0365; S_3^- = 0.0096; C_3^* = 0.2087$$

$$S_4^* = 0.0132; S_4^- = 0.0324; C_4^* = 0.7096$$

As the C* value of the first PTSC is the highest therefore it is the best design available from the global market. Also the C* value of third PTSC is the lowest, so it is the worst design available amongst all the four designs.

Conclusion

As shown in the Following table the Flagsol SKAL-ET 150 is the highest ranked PTSC amongst all the four alternative designs on the basis of TOPSIS procedure and is hence the best option for the users.

Sr. no	Name of collector	Area under the curve	Rank
1	Flagsol SKAL-ET 150	0.9707	1st
2	Sener	0.7284	2nd
3	IST Solucar PT-2	0.2087	4th
4	Acciona Solar Power SGX 2	0.7096	3rd

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