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Attribute Based Characterization, Ranking and Optimum Selection of a Parabolic Trough Concentrator Using MADM-TOPSIS Approach

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A B S T R A C T

The selection of solar collector for a particular application is always been a matter of thought to the end users. Due to increasing complexity in design and features of different solar collectors the selection becomes tedious. The objective of this research is to generate and maintain a reliable and exhaustive database of parabolic trough concentrator (PTC) based on its different pertinent attributes. This database can be used to standardize the PTC selection procedure when the manufacturing company decides to use the PTC for a particular application. This saves time of the user as it provides a tool for selecting the most suited PTC according to the requirements. The PTC selection procedure helps in shortlisting the potentially suitable design using elimination search based on a few critical attributes. Subsequently, ranking of all the alternative designs is done by employing different attributes based specification methods. In this study, the ranking and selection are done using MADM-TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and explained with the help of an illustration. A SWOT (Strength, Weakness, Opportunity, and Threat) analysis is also done for the use of PTC technology.

1. Introduction

With the advent of non-conventional energy resources, solar energy utilization has increased for various applications such as water heating, space heating, and power generation [1]. Solar collectors are utilized to convert sun's radiations into useful heat which is used directly and indirectly for various domestic, commercial applications and power generation [2]. PTC is a flexible and widely used

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solar collector for efficiently using solar radiations for various applications mainly steam and power generation [3] throughout the world and its use in water and air heating applications is limited. Flat plate collectors are generally used for the hot water production because they are cheaper, but are less efficient than PTC. The selection of PTC for a particular application is a very difficult task as there are a large number of designs available in the global market from different manufacturers. So, different considerations such as performance, availability, reliability, maintenance, and economics concerned with the parabolic trough concentrator are considered during the selection. The identification of maximum number of attributes results into the maximum amount of information about the system making it more exhaustive in nature. This is very helpful in the comparison of all the designs available in the global market and further selection of the PTC. There are a number of reported studies regarding the design, use of alternate materials, and performance characteristics of the parabolic trough concentrator for the different applications and also the comparison of different collectors with the PTC. Bondal and Maji [4] exhaustively reviewed the development of absorber tube, reflector, heat transfer fluid, and tracking system for enhancing the efficiency of PTC system. Loni et al. [5] developed a thermal model and investigated a PTC using Maple and Sol Trace software with receivers of different dimensions. The results showed that the highest thermal efficiency of 77% was obtained during the investigation of all receivers. A cubical cavity receiver used at optimum aperture width resulted in better performance in comparison to the trapezoid cavity receiver [6]. Abd Elbar et al. [7] made changes in the design of absorber tube with semi-circular plate and fins for large sized PTCs. The results showed enhancement in optical and thermal efficiency of the system. Wu et al. [8] studied the influence of dust collection on the reflectivity of PTC. Various surface properties of the reflector were investigated using different technologies like SEM (scanning electron microscopy) and X-ray diffraction. The results indicated highest decrease in the reflectivity when the dust was accumulated at the bottom edge in comparison to the top edge and centre of the reflector. Wang et al. [9] performed thermal simulation and cost analysis on a PTC solar power plant. The results from thermal analysis indicated high dependence of condenser back pressure on power production and ambient temperature. The results from cost analysis indicated reduction in net income with lowered tariffs. PTC is used in several applications namely drying [10], power generation [11], and solar water desalination [12]. Habchi et al. [13] integrated different tubular thermoelectric generators to the PTC to tackle cracking problem in the heat transfer fluid. The results indicated increase in concentration ratio and decrease in heat losses. The two axis tracking system consisting of lightweight and low cost materials reduced the total cost of the PTC system [14]. Integration of power tower with PTC based solar power plant enhanced the highest capacity factor by nearly 18% [15]. Gong et al. [15] and Almanza et al. [16, 17] worked on the development and mean life of aluminium first-surface mirrors for solar energy applications. The research works mentioned above shows that the performance of a PTC depends on important design parameters of components namely absorber tube, reflector, support structure, heat transfer fluid and tracking system. Therefore, these parameters are important attributes of the PTC and are used to describe and evaluate its performance. The MADM-TOPSIS approach is applied for ranking and optimum selection in various fields. It is applied for selecting the optimum solar panel out of many alternative options for electricity generation in rural areas [18]. MADM-TOPSIS is used to identify the best possible site for the construction of PV power plant as this approach is applied to calculate the optimum distance between alternative sites and finding out the best one [19]. Present literature shows TOPSIS is applied in the optimum selection of bamboo based products for rural communities [20], selection of logistics mode between two countries [21], and in the selection of manipulator robots [22] from different alternatives available in the global market.

The extensive research is being carried out worldwide in enhancing PTC performance for different applications. Numerous PTC designs are commercially available in the global market making optimum selection of a particular design a complex task. In the present study, MADM-TOPSIS approach is applied on a PTC system for identification of relevant attributes, evaluation and optimum selection of PTC design out of various designs available. In this study, TOPSIS approach is explained with the help of an illustration. The application of TOPSIS approach in the optimum selection of a PTC design is not mentioned in the present literature and constitutes the novelty of this study. Moreover, the identification of all relevant attributes describing a PTC system forms an exhaustive database of parameters affecting its performance which makes this a novel study.

2. Characteristics and attributes of PTC

PTC system consists of various subsystems such as reflector, supporting structure, tracking system, receiver etc. which are interconnected to each other. The critical way of evaluating a PTC is the identification of attributes which affect the performance of the system. The selection of PTC system on the basis of limited attributes is highly incorrect as it results in an inaccurate selection. The process of identification of the attributes should be highly exhaustive in nature. The emphasis is on increasing the cost efficiency of the PTC system using alternate materials. The attributes are identified and classified under different categories to make them easily understandable. The classification is done on the basis of different parameters such as general, physical, performance etc. The identification of attributes and their categorization covers approximately all the factors affecting the PTC system. The above classification of the attributes can be restructured depending upon the author's mind set.

The PTC system is expressed in a detailed manner by the attributes which are quantitative in nature e.g. power output34 MW, length of the collector 150m etc. These attributes are expressed in the form of numerical values like 0, 1, 2, 3…….n.

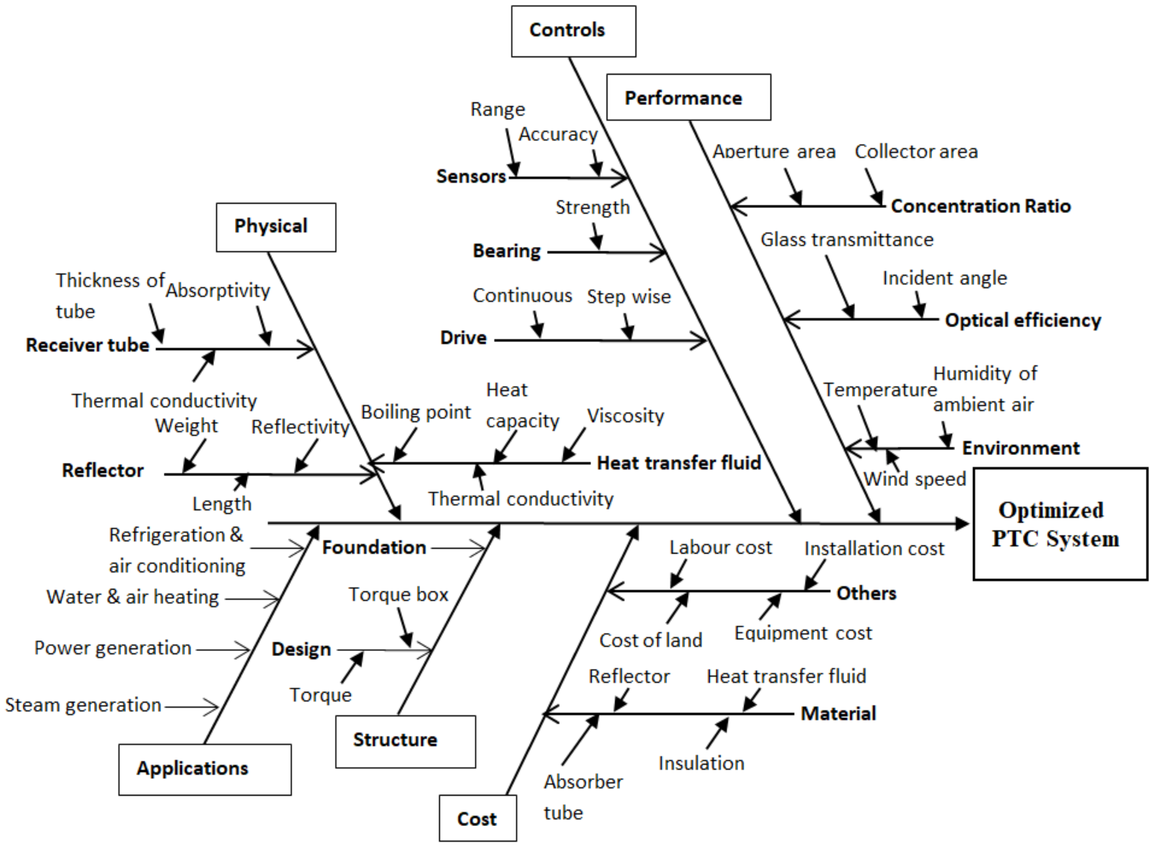

Figure 1. Cause and effect diagram of cost efficient PTC system

There are some attributes which only gives information about the subsystem or the component of the system e.g. type of drive, reflector material etc. are called as informative attributes. These attributes do not assign any numerical value and are only represented by alphabets A, B, C, D…... etc. Generally, the quantification of many of the attributes is not provided by the manufacturers. But if the manufacturer identifies and provides these attributes by itself then it will become very useful to the user, designer, maintenance personnel etc. as they can design and manufacture the PTC system by themselves. A cause and effect diagram is also made for the optimized PTC system.

Cause and Effect Diagram is very helpful in identifying and displaying all the possible causes of a particular problem. In the above figure the relationship between the given output and all the factors that are affecting the output are shown in figure 1. This technique helps in understanding relationships between different parameters.

The identification of the attributes is very useful for a well-established industry and for the one who is starting an industry. With the use of the entire informative database available a lot of information and knowledge is gathered which is highly beneficial for the one who is planning to start an industry in this area. It is also useful for an industry which is already established. In this case the sensitivity analysis can also be performed on a single or multiple no of attributes. This is considered very important because concentrating on one or two attributes rather than working on all of them the product can be made different and attractive than the other products present in the global market. So by making one very important attribute better than the others, the attribute will become a unique selling point (USP) of the product. The USP of the system is then highlighted during the advertisement of the product. Also in case of a sick unit a critical analysis is done on the above identified attributes. By this the loop holes present in the system are identified and removed hence making it a healthy and effective unit for use.

After the identification of the attributes the next step is to assign codes to the attributes which is either a numerical value or an alphabet. This is done under the coding scheme which is very important as it gives all the detailed information about the attributes. The attributes are qualitative and quantitative in nature. The qualitative attributes are non-deterministic and are of subjective or fuzzy type whereas the quantitative attributes are deterministic in nature. In this paper the quantitative attributes are given codes on an interval scale of 0-6, where 0 indicates that no information is available about the attribute and 6 indicates the best information and alternative present in the attribute. Now a PTC named Flagsol SKAL-ET 150 available in the global market is taken as an example and all the attributes are given codes on the basis of information available for Flagsol SKAL-ET 150 PTC. The codes assigned are represented in the table 1. The below table shows the information provided by the manufacturer to the user. The information presented here is for the better understanding of the PTC system.

3. The Selection Procedure

The selection of the best possible PTC design which is available in the global market for a given application is extremely important.

Table 1. Coding of attributes

Sr. no	**Attribute**	**Information**	**Code**
1	PTC type	Linear	LSolar
2	Application	Steam generation	2
3	Tracking system	Single axis	2
4	Reflector	Glass	6
5	Receiver	Evacuated tube	6
6	Solar radiation	Beam	B
7	Length of trough	148.5 m	6
8	Aperture width	5.77 m	6
9	Focal length	1.71 m	6
10	Length per collector module	12 m	6
11	Location of centre of gravity	3.5 m	6
12	Rim angle	80°	6
13	Concentration ratio	82	6
14	Collector efficiency	80%	6
15	Wind speed	31.5 m/s	5
16	Support structure material	Galvanized steel	G
17	Type of foundation	Pile	P
18	Scale of steam generation	Large	L
19	Type of Drive	Hydraulic	H
20	Tracking system	Two-axis	S

The main emphasis is to select a PTC design which is less in cost and effective for use in different applications and hence is cost efficient. So after consideration and evaluation of all the attributes of the different designs of the PTC available throughout the world market, the design which is best suited for a particular area and application is selected. The selection procedure consists of three stages namely elimination search, evaluation by TOPSIS procedure, final selection.

After the identification of 97 attributes, the attributes which are not important in the selection of parabolic trough solar collector are eliminated and the attributes which have direct effect on the selection procedure are separated out. These attributes are called as pertinent attributes. According to their applicability some values are assigned to these attributes by obtaining information from the user and the group of experts. These values are called as the threshold values. Hence the main focus is on the pertinent attributes by scanning the database of a parabolic trough solar collector system and leaving out the rest.

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 '**A**'. Each row of the matrix is allocated to the different parabolic trough solar collector system and each column to one attribute. Therefore, an element a_{ij} where, a_{ij}= value of j^{th} attribute for i^{th} parabolic trough solar collector system. The order of the decision matrix is m x n, where m = number of shortlisted parabolic trough solar collector system, n = number of pertinent attributes.

Step 2: In this step the relative importance matrix **'R'** 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, w_j are the weight vectors. The relative importance of one attribute over other is decided by the user itself or the group of experts.

Step 3: Now by using Eigen vector method the maximum Eigen value λ is to be obtained by the use of the equation shown below:

$$(A - \lambda I)W = 0 \quad (1)$$

where, $W = [w_1, w_2, w_3, \ldots\ldots\ldots, w_n]^T$

Step 4: 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 n_{ij} of the normalized matrix **N** can be calculated as

$$n_{ij} = d_{ij}/\sqrt{\sum d_{ij}^2}, \text{ where, } 1 \le i \le m \quad (2)$$

and d_{ij} is an element of the decision matrix

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

$V = [V_{ij}]$, where $V_{ij} = w_j \times n_{ij}$

and $i = 1, 2, 3, \ldots.., m$ (3)

After the elimination search the finite number of attributes which are sufficient to evaluate the system are shortlisted. On the basis of these attributes a number of designs are developed and after that the ranking of the parabolic trough solar collector system is done mathematically by 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 PTC system and farthest from the negative benchmark PTC system. Now the separation from the positive and negative benchmark PTC is calculated by the following formulae:

$$S_i^* = \sum_{j=1}^{n}[(v_{ij} - v_1^*)^2]^{1/2} \quad (4)$$

$$S_i^- = \sum_{j=1}^{n}[(v_{ij} - v_1^-)^2]^{1/2} \quad (5)$$

Where, i = 1, 2, 3…, m, S_i^* = positive benchmark PTC, S_i^- = negative benchmark PTC

The suitability index, 'C*' is a measure of the suitability of the air conditioning 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:

$$C^* = S_i^-/S_i^+ + S_i^- \quad (6)$$

Where, C^* = relative closeness to the positive benchmark PTC system. Now the ranking is done with the decreasing value of C^*

4. Results and discussion

The above mentioned theory of the MADM-TOPSIS approach will be easily understood with the help of an illustrative example. Suppose we need to select a parabolic trough concentrator for the Indian conditions. It is to be noted that here only parabolic trough concentrator which is a part of PTC system is taken into account and is illustrated just to explain the methodology. The minimum requirement is as follows:

Table 2. Minimum requirements

Parameter	Description
Concentration ratio	More than 70
Power Output	Less than equal to 25 MW
Optical efficiency	At least 75%
Type of drive used	Hydraulic
Tracking system	Two-axis
Reflector material	Thick mirror

After analysing the global market the 4 best possible PTC designs are selected and in this paper they 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 PTC designs are shown in the table mentioned below:

Table 3. Attributes for the candidate PTC available in global market

Sr. no	PTC name	Concentration ratio	Focal length	Optical efficiency	Length
1	Flagsol SKAL-ET 150	82	1.71	80	148.5
2	Sener	80	1.7	76	150
3	IST Solucar PT-2	63	1.73	75	149
4	Acciona solar power SGX2	81	1.72	77	130

Now the procedure for selection of PTC is as follows:

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

$$D = \begin{bmatrix} 82 & 1.71 & 80 & 148.5 \\ 80 & 1.70 & 76 & 150 \\ 63 & 1.73 & 75 & 149 \\ 81 & 1.72 & 77 & 130 \end{bmatrix} \quad (7)$$

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

$$R = \begin{bmatrix} 1 & 2 & 0.5 & 2 \\ 0.5 & 1 & 0.33 & 1 \\ 2 & 3 & 1 & 2 \\ 0.5 & 1 & 0.33 & 1 \end{bmatrix} \quad (8)$$

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

$$A - \lambda_{max}I = \begin{bmatrix} 1-\lambda & 2 & 0.5 & 2 \\ 0.5 & 1-\lambda & 0.33 & 1 \\ 2 & 3 & 1-\lambda & 2 \\ 0.5 & 1 & 0.33 & 1-\lambda \end{bmatrix} \quad (9)$$

Also, ($A-\lambda_{max}I$) = 0, on solving the above matrix we have λ = 3.9264, 0.0368, 0.0368, 0. Therefore, λ_{max} = 3.9264, now $A - \lambda_{max}I$ =

$$\begin{bmatrix} -2.9264 & 2 & 0.5 & 2 \\ 0.5 & -2.9264 & 0.33 & 1 \\ 2 & 3 & -2.9264 & 2 \\ 0.5 & 1 & 0.33 & -2.9264 \end{bmatrix} \quad (10)$$

The weights for each attribute using the eigen vector associated with the maximum eigen value are calculated. This can be represented by the equation,

$$(A - \lambda I)W = 0$$

$$\begin{bmatrix} -2.9264 & 2 & 0.5 & 2 \\ 0.5 & -2.9264 & 0.33 & 1 \\ 2 & 3 & -2.9264 & 2 \\ 0.5 & 1 & 0.33 & -2.9264 \end{bmatrix} \begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = 0 \quad (11)$$

On solving this above matrix we have,

$w_1 = 0.4936$, $w_2 = 0.2628$, $w_3 = 0.7863$, $w_4 = 0.2628$

Step 4: In this step the normalized specification matrix is calculated which helps to provide the dimensionless elements of the matrix. It is denoted by **'N'.**

$$n_{ij} = d_{ij}/\sqrt{\sum d_{ij}^2}, \text{ where, } 1 \leq i \leq m \quad (12)$$

$$N = \begin{bmatrix} 0.4372 & 0.0091 & 0.4265 & 0.7917 \\ 0.4296 & 0.0091 & 0.4081 & 0.8055 \\ 0.3533 & 0.0097 & 0.4206 & 0.8356 \\ 0.4725 & 0.0100 & 0.4491 & 0.7583 \end{bmatrix} \quad (13)$$

Step 5: In this step the weighted normalized specification matrix is calculated. It is denoted by **'V'.**

$$V = \begin{bmatrix} 0.2158 & 0.0024 & 0.3354 & 0.2081 \\ 0.2120 & 0.0024 & 0.3209 & 0.2117 \\ 0.1744 & 0.0025 & 0.3307 & 0.2196 \\ 0.2332 & 0.0026 & 0.3532 & 0.1993 \end{bmatrix} \quad (14)$$

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 PTC.

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

V^* = (0.2332, 0.0026, 0.3532, 0.2196) and

V^- = (0.1744, 0.0024, 0.3209, 0.1993)

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^* = 0.0274, S_2^* = 0.0394, S_3^* = 0.0629, S_4^*= 0.0203

$S_1^- = 0.0447$, $S_2^- = 0.0396$, $S_3^- = 0.0226$, $S_4^- = 0.0671$

$C_1^* = 0.6201$, $C_2^* = 0.5017$, $C_3^* = 0.2639$, $C_4^* = 0.7675$

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

Table 4. Evaluation and ranking of four PTC alternatives

PTC product name	**TOPSIS suitability index**	**Rank**
Flagsol SKAL-ET 150	0.4022	1
Sener	0.6232	2
IST Solucar PT-2	0.6862	4
Acciona Solar Power SGX 2	0.4560	3

4.1 SWOT Analysis

The SWOT analysis is done for the use of parabolic trough concentrator technology in India. With the increased focus on power generation through solar energy creates an opportunity for PTC technology for power generation and other applications. The strength of the PTC technology, its weakness, the various opportunities for PTC technology in India, and the threats from the surroundings are presented below in figure 2.

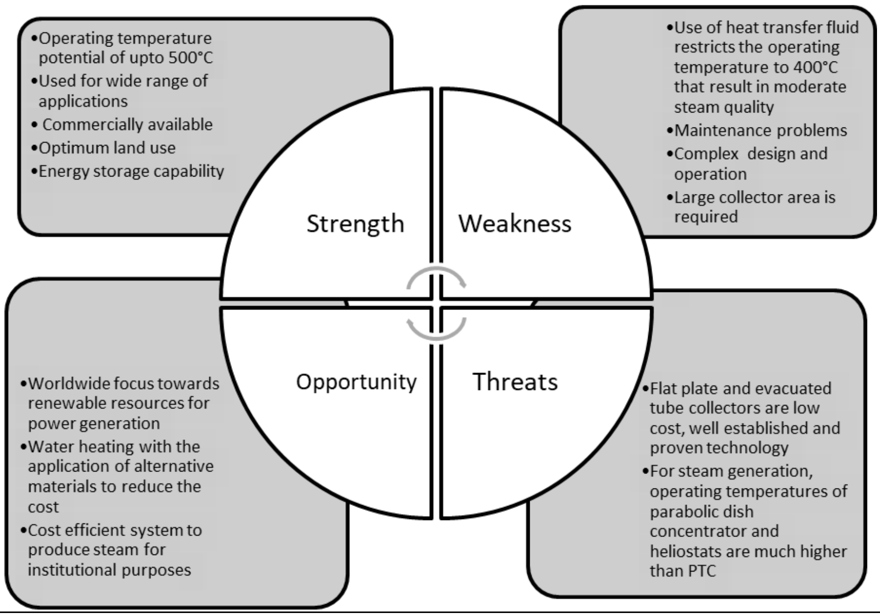

Figure 2. SWOT analysis

In the above SWOT analysis it is observed that there is lot of scope of PTC technology in India. As the operating temperature of the PTC system is very which can be used for the steam/power generation. But for the water heating applications the PTC system is rarely used due to its high cost. But with the use of alternate materials the overall cost of the system will be reduced so as to make it affordable for the water heating. Also due to a rapid increase in the power demands there is a huge scope of the installation of the PTC power plant in India. Moreover it can produce steam for the daily life applications e.g hotels, hospitals, residential complexes etc very efficiently. If the tracking and focussing errors are reduced and with the use of suitable materials the PTC technology can overpower flat plate collectors for water heating applications.

5. Conclusion

This study use a mathematical approach (MADM-TOPSIS) for the comparison, ranking and optimum selection of the PTC. It involves the identification of different attributes affecting a PTC system which are then used for the selection of the above system for a particular application. The attributes are then given codes in the coding scheme. The cause and effect diagram is also made for the optimized PTC system. The usefulness of the identification and the cause and effect diagram are discussed. Then by the use of

TOPSIS procedure the best and the worst design possible are selected so as to make it easier for the buyer to choose the design which is closest to the best possible design. The identification of the attributes is done in an exhaustive way which includes all the components of the PTC system. It is done by applying the coding scheme to all the attributes so that even the smallest of the information and parameters affecting the PTC system are presented. This is very useful as it allows even the common man to assemble the PTC system by himself. The SWOT analysis is also done to analyse the different factors which are considered in the use of PTC technology in the whole world. The overall work done and presented here in this paper is very useful for the user, designer, manufacturer and the maintenance personnel in the industry.

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Nomenclature	
A	Decision matrix
a_{ij}	Value of j^{th} attribute for i^{th} parabolic trough solar collector system
C^*	Relative closeness to the positive benchmark PTC system
d_{ij}	Element of decision matrix
I	Identity matrix
N	Normalized Specification Matrix
n_{ij}	Element of the normalized matrix **N**
R	Relative importance matrix
S_i^*	Positive benchmark PTC
S_i^-	Negative benchmark PTC
V	Normalized specification matrix
V_{ij}	Elements of normalized specification matrix
V^*	Weighted normalized attributes for positive benchmark PTC
V^-	Weighted normalized attributes for negative benchmark PTC
w_i, w_j	Weight vectors
λ	Eigen value
λ_{max}	Maximum eigen value

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