Research Article

Material Selection for Dye Sensitized Solar Cells Using Multiple Attribute Decision Making Approach

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1. Introduction

Rapid depletion of conventional resources is a major source of concern for the world today. If not taken seriously, soon there shall be an inevitable energy crisis situation. To prevent such circumstances, researchers today are forced to explore alternate energy sources. Among available renewable energy sources, solar energy is the most promising and readily available alternative. Solar cells play a significant role in harnessing solar energy but, due to numerous reasons, we have still not been able to effectively use the power of sun. Conventional silicon (Si) solar cells generally require complex vacuum processing and fairly high temperature conditions which makes them an expensive energy source [1–3]. Moreover, their application is hampered by the lack of mechanical flexibility. Dye sensitized solar cells (DSCs) are attractive due to their simple and low cost fabrication technique. DSCs are different from almost all other types of solar cells in their functioning.

DSCs are composed of a sensitizing dye adsorbed on a wide band nanostructured semiconductor film, a redox electrolyte, and a counter electrode consisting of a catalyst. Future applications of DSCs depend upon the development and selection of suitable materials for their components so as to give the best performance.

Among various components of DSC, the nanocrystalline porous film electrode is most important as overall energy conversion of the cell is hugely affected by its morphological and electronic properties. There are many materials that are being used in the DSC while many more are being investigated. However, each of these materials has certain merits and limitations.

Choosing the material of desired properties from large number of available materials is a tedious task. A clear understanding of the functional needs of every component and analysis of various important factors are required for developing a comprehensive engineering design. Considering all the attributes at the same time in material selection is a difficult job; hence, a systematic approach to material selection process is required to screen and select the optimum material for device application.


Multiple criteria decision making (MCDM) methods are frequently used to find solution of uncertainty problems. These methods are classified into multiobjective decision...
2. Dye Sensitized Solar Cell Design

A DSC is basically a photoelectrochemical device in which a dye sensitized nanostructured semiconducting film deposited on a transparent conductive glass (TCO) substrate forms a working electrode or photoelectrode. Another platinum coated glass substrate serves as counter electrode. The intermediate space between these two electrodes is filled with a liquid or solid electrolyte (Figure 1).

The working electrode receives incident light which is absorbed by the dye molecules adsorbed on the metal oxide semiconductor film. The dye molecule gets excited transferring electron from highest occupied molecular orbital (HOMO) to lowest unoccupied molecular orbital (LUMO). The photogenerated electrons then move from dye molecules to the semiconductor and then to the TCO. The electrons are then collected by the counter electrode. In a complete cycle, the oxidized dye molecules are reduced by receiving the electrons from the electrolyte; at the same time, electrolyte gets regenerated by the electrons injected from the counter electrode.

There are certain parameters which define the performance of a solar cell. Incident photon to current conversion efficiency (IPCE) is the most important factor which depends on light harvesting efficiency (LHE) of sensitizing dye molecules, charge injection efficiency at dye-semiconductor interface, and charge transport efficiency in nanostructured film. LHE is ratio of the incoming photons to that of absorbed photons. It depends on the amount of dye absorbed. Charge injection efficiency is determined by many factors mainly acceptor density in semiconductor and potential difference between conduction band of semiconductor and LUMO of dye molecule, whereas charge transport efficiency depends on the electron diffusion length. To extract the photogenerated electrons, the electrons should reach the TCO faster than the recombination process. Thus, charge recombination at the device interface strongly influences the IPCE [26].

According to a unidirectional electron transporting principle of DSC, there exist four important interfaces in this device. Those are the interfaces of FTO/semiconductor, semiconductor/dye, dye/electrolyte, and the electrolyte/counter electrode [27]. The properties of the semiconductor play a decisive role in the charge carrier kinetics at the interface and hence in the device performance [28].

3. Materials and Properties for Photovoltaic Application

A nanostructured thin film of wide band gap semiconducting material is used as an electron collecting material. There are abundant semiconducting materials available, but still not all of them are suitable for photovoltaic applications. There are certain constraints which need to be addressed in order to choose best suited material to achieve commercial interests. Ideal semiconducting material for DSC application must possess the following properties:

(i) wide band gap,
(ii) high electron injection rate,
(iii) low cost,
(iv) high carrier concentration,
(v) low static dielectric constant,
(vi) high electron mobility.

There are many candidate materials that are available for the application in DSCs but only few possess the desired
properties as mentioned above. Materials which are generally used in the photoelectrode of DSC are titanium oxide (TiO₂), zinc oxide (ZnO), tin oxide (SnO₂), and indium (III) oxide (In₂O₃) [29–32]. These all are wide band gap semiconductors having low cost and are easily available. ZnO and SnO₂ particularly have fairly high mobilities which lead to fast electron conduction process. The importance of metal oxide film is evident by the fact that the selection of materials for other components of the cell is based upon their compatibilities with it. The dye is selected based on its relative band edge positions in sync with that of semiconductor used. So, while choosing the candidate materials for thin film, it is important to analyze their capability of working in tandem with the commercially available set of dyes. The electron injection rate in the film largely depends upon this compatibility. Also, the carrier concentration in the candidates should be high for better efficiencies.

Thus, there is a need to carefully select the material for the fabrication of thin film as it plays a significant role in increasing the active surface area as well as enhancing photon absorption.

So, based on all the factors already mentioned before, the following materials were considered suitable candidates for the preparation of mesoporous layer on FTO:

1. zinc oxide (ZnO),
2. titanium oxide (TiO₂),
3. tin oxide (SnO₂),
4. indium (III) oxide (In₂O₃).

The major parameters that were considered for their analysis are electron injection time, cost, bulk mobility, band gap, and effective mass static dielectric constant.

4. Selection of Material

TOPSIS method has received lot of attention in the field of material selection. Shanian and Savadogo [33] used TOPSIS for selecting the material for bipolar plates for polymer electrolyte fuel cell. Rao and Davim [34] introduced a decision making model based on both TOPSIS and analytic hierarchy process (AHP). Chauhan and Vaish [35] also employed TOPSIS and VIKOR to evaluate and assess the properties of magnetic materials. Chatterjee et al. [18] used VIKOR and ELECTRE methods to find the relative ranking of candidate materials by simultaneously considering their respective properties.

Although ELECTRE methods generate good output, they still have certain drawbacks. As the number of alternatives increases, the computational procedure becomes more complex and elaborate. Also, ELECTRE methods only provide rank of each material but do not give any numerical value.

The advantage of AHP over other methods is its flexibility and intuitiveness. It supports group decision making by determining the geometric mean of the individual pairwise comparisons. But it has the disadvantage that the problem has to be decomposed into a number of subsystems for pairwise comparisons which is not always feasible.

The VIKOR and TOPSIS method use different aggregation functions and normalization process. VIKOR method uses linear normalization whereas TOPSIS method uses vector normalization. Finding the optimal point in the VIKOR is based on the measure of closeness to positive ideal solution. Therefore, it is more suitable in the circumstances in which the risk of the decisions is less important to the decision maker and maximum profit is the priority.

TOPSIS is a good choice for material selection as it is a relatively more systematic process. It is useful for both qualitative and quantitative data. It gives the output with a numerical value that provides the better understanding of differences and similarities among the alternatives.

TOPSIS method is employed to find the best alternative in the present work. It was first proposed by Hwang and Yoon in 1981 [36].

The methodology comprises calculating the Euclidean distance of the given alternative from the positive and the negative ideal solution, respectively. The concept is that the best possible alternative will be the one which is closest to the positive ideal solution and the farthest from the negative ideal solution.

The TOPSIS method consists of the following steps.

Step 1 (construction of the normalized decision matrix). The Euclidean length of a vector, the element \( r_{ij} \) of the normalized decision matrix \( R \), is evaluated using the following transformation:

\[
    r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m}(X_{ij})^2}}, \quad j = 1, 2, \ldots, n; \quad i = 1, 2, \ldots, m, \quad (1)
\]

where \( r_{ij} \) is the normalized preference measure of the \( i \)th alternative. “\( m \)” is the number of alternatives and “\( n \)” is the number of criteria.

Step 2 (construction of the weighted normalized decision matrix). Multiply the columns of the normalized decision matrix \( V \) to obtain weighted normalized decision matrix:

\[
    V = RW = \begin{pmatrix}
    w_1 \cdot r_{11} & w_2 \cdot r_{12} & \cdots & w_n \cdot r_{1n} \\
    w_1 \cdot r_{21} & w_2 \cdot r_{22} & \cdots & w_n \cdot r_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    w_1 \cdot r_{m1} & w_2 \cdot r_{m2} & \cdots & w_n \cdot r_{mn}
    \end{pmatrix}, \quad (2)
\]

Step 3 (determination of the ideal and negative ideal solutions). The ideal solution and negative ideal solution value sets are determined, respectively, as follows:

\[
    \{V^*_i, V^*_2, \ldots, V^*_n\} = \left\{ \left( \text{Max}_{i} V_{ij} \mid J \in K \right), \left( \text{Min}_{i} V_{ij} \mid J \in K' \right) \mid i = 1, 2, \ldots, m \right\},
\]

\[
    \{V^-_1, V^-_2, \ldots, V^-_n\} = \left\{ \left( \text{Min}_{i} V_{ij} \mid J \in K \right), \left( \text{Max}_{i} V_{ij} \mid J \in K' \right) \mid i = 1, 2, \ldots, m \right\}, \quad (3)
\]
Table 1: Various properties of different possible semiconducting materials.

<table>
<thead>
<tr>
<th>Properties</th>
<th>ZnO</th>
<th>TiO₂</th>
<th>SnO₂</th>
<th>In₂O₃</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Band gap (eV)</td>
<td>3.37</td>
<td>3.2</td>
<td>3.8</td>
<td>3.75</td>
<td>[40, 41]</td>
</tr>
<tr>
<td>(2) Cost (Rs/5 g)</td>
<td>3000</td>
<td>800</td>
<td>5000</td>
<td>7000</td>
<td></td>
</tr>
<tr>
<td>(3) Electron injection time (×10⁻¹² s)</td>
<td>150</td>
<td>0.1</td>
<td>10</td>
<td>10</td>
<td>[39, 40]</td>
</tr>
<tr>
<td>(4) Mobility (cm²·V⁻¹·s⁻¹)</td>
<td>200</td>
<td>1</td>
<td>250</td>
<td>160</td>
<td>[41–44]</td>
</tr>
<tr>
<td>(5) Effective mass (mᵢ*)</td>
<td>0.3</td>
<td>7.0</td>
<td>0.3</td>
<td>0.3</td>
<td>[45, 47]</td>
</tr>
<tr>
<td>(6) Dielectric constant (K)</td>
<td>8.0</td>
<td>173</td>
<td>250</td>
<td>8.9</td>
<td>[48]</td>
</tr>
</tbody>
</table>

where

\[ K = \{ j = 1, 2, 3, \ldots, n \text{ and } j \text{ is associated with benefit criteria} \}, \]

\[ K' = \{ j = 1, 2, 3, \ldots, n \text{ and } j \text{ is associated with cost criteria} \}. \]

Step 4 (measurement of separation distances from ideal and negative ideal solutions). Euclidean distances for each alternative are, respectively, calculated as

\[ S_i' = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_{ij}^*)^2}; \quad i = 1, 2, \ldots, m, \]  

\[ S_i = \sqrt{\sum_{j=1}^{n} (V_{ij} - V_{ij}^*)^2}; \quad i = 1, 2, \ldots, m. \]  

Step 5 (calculation of the relative closeness to the ideal solution). The relative closeness to the ideal solution can be defined as

\[ C_i = \frac{S_i'}{S_j' + S_i'}; \quad i = 1, 2, \ldots, m; \quad 0 \leq C_i \leq 1. \]  

The higher the closeness means the better the rank.

Step 6 (ranking of the preference order). The preference order is ranked on the basis of the order of \( C_i \). Hence, the best alternative is the one which is nearer to the ideal solution and farther from the negative ideal solution.

5. Results and Discussion

The properties of nanostructured film have significant influence on the whole performance of DSC.

Values of various properties of available materials have been enlisted in Table 1.

The metal oxide semiconductors are being extensively used for solar energy conversion. Nowotny [37] analysed functional properties of various metal oxides semiconductors including TiO₂ which are required for the fabrication of high performance photosensitive devices. Scaife [38] showed that the photovoltaic performance of a solar cell depended remarkably on the semiconductor material used. They studied the effect of mesoporous oxide semiconductor thin films properties on solar cells.

The transport of the injected electrons through nanostructured network is the most important process affecting the device performance. Near infrared absorption studies conducted on nanocrystalline thin films made of different materials but dyed with same Ru-complex dye reveal different injection times [39]. It has been observed that the transport kinetics is a function of electron density in the film, which is generally explained by trapping and detrapping rate in the states in the band gap.

Aroutiounian et al. [40] investigated the properties of different metal oxide semiconductors such as band gap and mobility for photoelectrochemical conversion of solar energy. If the electron mobility in their bulk single crystal phases is high, then it is possible to achieve higher overall electron mobility in the respective nanostructured films which may then reduce charge recombination loss at the electrolyte interface which is composed of oxidized redox species, hence enhancing device performance [41–44]. A wide band gap semiconductor with good carrier mobility is the second essential requirements for the photoelectrode.

The goal of any emerging solar cell technology is to achieve commercialization and compete with other technologies in photovoltaic market. The cost of silicon photovoltaic module has reduced from US$4W⁻¹ in 2008 to only US$1.25W⁻¹ in 2011 with module efficiencies from 15 to 20%. On the other hand, CdTe based thin film modules have achieved efficiencies of 14% at costs of US$0.50W⁻¹. In the future solar cell market, DSCs need to increase power conversion efficiency with low cost fabrication procedures and good stability. Low module cost of DSCs can project them as attractive alternate energy source. Therefore, cost is third important factor influencing its commercial prospects.

In addition to this, the effective mass of conduction band electrons is another important parameter which defines the electronic structure of conduction band of metal oxide semiconductor film. The available density of states is directly related to the effective mass. Higher density of states facilitates faster electron injection [45–47]. Electronic density of states has more influence on the device performance and bulk dielectric constant plays only a secondary role [48].

Considering all the above factors and conditions, weight priorities for respective parameter are evaluated.
Using (1), we have the following. The normalized matrix \( R \) is
\[
R = \begin{pmatrix}
0.4761 & 0.3280 & 0.9955 & 0.5587 & 0.0427 & 0.0460 \\
0.4520 & 0.0874 & 0.0006 & 0.0027 & 0.9969 & 0.9959 \\
0.5368 & 0.5467 & 0.0663 & 0.6984 & 0.0427 & 0.0575 \\
0.5298 & 0.7654 & 0.0663 & 0.4470 & 0.0498 & 0.0512
\end{pmatrix}.
\]
(7)

The weighted matrix \( W \) is
\[
W = [5 4 6 3 2 1].
\]
(8)

The weighted normalized matrix \( V \) is
\[
V = \begin{pmatrix}
2.3805 & 1.3120 & 5.9730 & 1.6761 & 0.0854 & 0.0460 \\
2.2600 & 0.3496 & 0.0036 & 0.0081 & 1.9938 & 0.9959 \\
2.6840 & 2.1868 & 0.3978 & 2.0952 & 0.0854 & 0.0575 \\
2.6490 & 3.0616 & 0.3978 & 1.3410 & 0.0996 & 0.0512
\end{pmatrix}.
\]
(9)

The following values of separation variables were calculated from the above matrix:
\[
\begin{align*}
S_1' &= 6.3616 & S_1 &= 2.5999 \\
S_2' &= 2.3317 & S_2 &= 3.3687 \\
S_3' &= 2.6781 & S_3 &= 1.9872 \\
S_4' &= 3.4158 & S_4 &= 1.6910.
\end{align*}
\]
(10)

The relative closeness to the ideal solution hence can be found using (6). The ranks are assigned based on their “C” values and are given by in Table 2. The larger the value of closeness, the better the rank.

So from the ranks obtained, we can conclude that, out of the selected materials, titanium dioxide (TiO\(_2\)) was found to be the best suitable material for the photoelectrode of DSC followed by tin dioxide, indium (III) oxide, and zinc oxide.

The evaluation of solar cell performance depends on certain key parameters: energy conversion efficiency and fill factor. It has been reported that TiO\(_2\) based DSCs have achieved 11.5% power conversion efficiency [49–52], which is much higher than that of its other competitors, SnO\(_2\) and ZnO [53–56].

Still conventional nanoparticulate SnO\(_2\) -DSCs have comparatively small conversion efficiencies of around 1-2% due to low value of open circuit voltage (Voc) and fast recombination process [57, 58].

But, the band gap of SnO\(_2\) is much larger (\(E_g = 3.8 \text{ eV}\)) to be able to utilize the far ultraviolet portion of the light spectrum. SnO\(_2\) shall be the best material to be used with dyes that absorb long wavelength sunlight. Still a lot of research is in progress to develop such dyes [59–62].

Also, it has higher electronic mobility and long term stability as compared to both single crystal TiO\(_2\) and ZnO [63–66].

To increase conversion efficiency, various types of coating materials on to SnO\(_2\) surface, such as Al\(_2\)O\(_3\), MgO, TiO\(_2\), NiO, Y\(_2\)O\(_3\), and ZnO, have been investigated for the interfacial potential barrier [64–66]. For instance, a carefully controlled MgO/SnO\(_2\) core-shell particle electrode achieved a high efficiency of 72% by retarding the recombination process [65]. These factors together make it a potential candidate for application in DSC. It has proved to be the second best material after TiO\(_2\).

Currently, for ZnO-based DSCs, efficiencies of up to about 4–6% are being reported [63–66]. It is worth noting that photoelectrode properties for TiO\(_2\) based DSCs are now approaching optimum theoretical values, while those for SnO\(_2\), In\(_2\)O\(_3\), or ZnO still offer room for improvement of several orders of magnitude.

It can be observed that the proposed result is in compliance with the experimental findings, hence justifying the validity of proposed study.

### 6. Conclusions

Strategic evaluation of the properties of available semiconductor materials for DSCs was conducted by employing the MADM approach using Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). It was observed that titanium dioxide (TiO\(_2\)) was the best suited material followed by tin dioxide, indium (III) oxide, and zinc oxide. These results are also in agreement with experimental findings which supports the use of TiO\(_2\) in DSC in order to get high performance device.

### Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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### References


