Reliability analysis and condition monitoring of polymer based dye sensitized solar cell: a DOE approach

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Abstract
Organic Photo Voltaic cells such as dye sensitized solar cells (DSSC) are bringing about a revolution in the sustainable field. Better economic feasibility and decent efficiencies make it more eminent amongst the available products in the market. Reliability of these cells becomes an area of concern as environmental and electrical energy parameters wobble dynamically. The research article focuses on new techniques for observing the lifetime of a DSSC experiencing the impact of warning parameters like light source temperature, frequency, humidity and thermal stresses on working factors of DSSC such as Fill Factor, voltage, current and Efficiency. Optimization of prediction of failure for lifetime of the cell is done by Design of Experiment (DOE) methodology based on Taguchi’s model using Minitab 18.1 software. The health condition of fabricated dye sensitized solar cells (DSSC) is monitored using Accelerated life testing as well as analytical method. Analysis shows that the mean lifetime of the fabricated dye sensitized solar cells (DSSC) using the experimental method and analytical method is 18 488.67 h and 22 167.05 h respectively. The error analysis shows that the analytical method has 3.63% error, which confirms its accuracy as 96.37%.

1. Introduction

To understand solar cell performance, it becomes essential to evaluate its degradation mechanisms with respect to an independent parameter of time. In order to access the stability of any device its lifetime reliability measurements must be compared to similar results of other devices based on different geometries, manufacturers or groups. However, due to the lack of defined standards, it becomes difficult to evaluate such Organic Photo Voltaic cells. One such attempt to define the protocols had been done by Reese et al, which has been followed by many researchers and manufacturers as a consensus for determining the lifetime of the DSSCs. (Reese et al 2011). Before launching the device in the real-world, variety of experiments are conducted on the components (Bhargava et al 2017). It has become a critical issue for the researchers and industry to study the stability issues of OPVs for the same, accelerated life testing (ALT) has become the need of the hour. However, as per the area of application of the OPVs at the commercial front, it becomes vital to predict the expected reliable lifetime for outdoor operations of the cell (Kettle et al 2017).

According to the statement for stability assessment consensus for perovskite photovoltaic cells, 2020, ISOS (International Summit on Organic Photovoltaic Stability) protocols were specially restructured based on unified stability assessments and existing standards for understanding the failure modes of the PV cells (Khenkin et al 2020). These protocols have defined a new overview to the testing scenarios of the PV cells and some standard factors have been evolved as the lifetime affecting parameters of the cell. An intermediate measurement at 100 h is kept as a part of the protocol (Asghar et al 2010).
2. Fabrication & Residual life calculation of a GPE based DSSC

The DSSC was prepared using organic dye applying Dr Blades method (flowchart 1). The properties of the cell were studied and the results compared for the various ratios of LE & PGE used.

The DSSC fabricated for studying its lifetime was composed of a glass substrate (TCO conductive glass substrate coated with TiO₂) used as electrodes; a Photosensitizer Dye (organic dyes) used for sensitization and an
electrolyte (gel-based polymer electrolyte). Fallah et al (2019) and See et al (2020). For the working of a DSSC, the molecules from the anthocyanin extracted from the dye get adsorbed at the surface of TiO$_2$ nanoparticles. The interface amongst TiO$_2$ and dye leads to the transfer of electrons from dye fragments to the conductive band of TiO$_2$ (Supriyanto et al 2018). These molecules then obtain photons from sunlight and generate electrons via the oxidation of dye. However, during the extraction of anthocyanin from dyes, suitable extractions and storage parameters are expected to be maintained (Amogne et al 2020). The electrolyte further liberates the redox couple and completes the path of electron flow and hence helps in the regeneration of the lost dye molecule. The final cell was fabricated using a combination of liquid electrolyte (triiodide) and polymer gel electrolyte (gelator) in the ratio 8:2 which gave an efficiency of 11.32% as shown in figure 1.

Residual life calculations of the cell beginning from the selection of parameters affecting the cell to further accelerating life testing, in order to measure the average lifetime of the fabricated dye sensitized solar cells (DSSC).

3. Test design methodology

Accurate performance results of the solar cell as a function of an independent parameter of time is the most substantial part of understanding degradation mechanisms. A test sequence design depicting the design methodology is shown in figure 2.

This research laid stress on building a residual lifetime analysis for a polymer gel electrolyte based DSSC, beginning from the analysis of its life affecting parameters to optimising the parameters and further exploring the remaining useful lifetime. The optimisation and evaluation of all the life affecting parameters are done with DOE (design of experiments). An L16 orthogonal matrix is built using Taguchi approach which involves four factors at four different levels (Tsai et al 2013). To validate this analytical residual life calculation proposed technique, Arrhenius accelerated life testing approach is applied. Error analysis is performed to identify the accuracy of the analytical method with respect to the experimental technique.

3.1. Analytical method for life prediction

To identify critical parameters for calculating residual life was the foremost task here (Liu et al 2012). The various factors that affect the lifetime and stability performance (as shown in figure 3) were explored. The paper focuses on new techniques for observing the lifetime of a DSSC experiencing the impact of waning parameters like light source temperature, frequency, humidity, OC voltage, SC current and thermal stresses on working factors of DSSC such as fill factor and efficiency and an analytical relationship between prognosticators and estimators was developed (Bhargava et al 2018c).

The ALT parameters have a significant impact on the lifetime of the DSSC. Therefore, the main purpose was to analyse the input performance parameters effect and observe their response on cells output. The expected lifetime was calculated by equation (1), keeping in mind the datasheet claimed lifetime and acceleration factors.
\[ \text{Lifetime (Expected)} = \text{Lifetime (D)} \times \text{Acceleration factors} \quad (1) \]

Equation (1) gives a relation between lifetime(expected), lifetime (on the datasheet) and accelerated factors for important input parameters.

### 3.1.1. Temperature’s effect on lifetime of the DSSC

As the thermal stresses increase, the derating and deterioration of cells also accelerate, as proposed by Bhargava et al. studies show that with every 10 degrees temperature rise, the life of the cell degrades by 2. For elevated temperatures, acceleration factor for temperature, \( A_F T \) was derived as in equation (2) (Tamizhmani and Kuitche, 2013).

\[ A_F T = e^{\left( \frac{E_a}{k(T_m - T_a)} \right)} \quad (2) \]

Where \( E_a \) is the activation energy (0.7eV for electronics), \( k \) is Boltzmann’s Constant, \( T_m \) is the maximum temperature in Kelvin, and \( T_a \) is the applied temperature.

Resolving the above as equation (3) (Bhargava et al 2018c),

\[ A_F T = 2^{\frac{T_m - T_a}{T_a}} \quad (3) \]

### 3.1.2. Voltage’s effect on lifetime of DSSC.

As explored by Mohsen et al. (Shojaeifar and Mohajerani 2019) the deterioration of DSSC life is effected not only by temperature acceleration factor but also by the rated voltage. By considering open-circuit voltage as influencing factor, the expected residual lifetime is calculated as equations (4) and (5) where \( AF_V \) is voltage acceleration factor; \( V_a \) & \( V_m \) are applied and maximum voltage, \( L \) is the length of electron diffusion, \( d \) is the length of coating on electrodes, \( D \) is diffusion coefficient, \( n \) is constant is equal to 1 (Aboulouard et al 2017, Cho et al 2019, Supriyanto et al 2019).

\[ V = \frac{KT_m \ln \left( \frac{L_{sc}}{qD \tanh \left( \frac{d}{L} \right)} + 1 \right)}{q} \quad (4) \]

Resolving the equation (Bhargava et al 2018c),

\[ AF_V = \left( \frac{V_a}{V_m} \right)^{-n} \quad (5) \]

where \( n \) is constant and is equal to 1, \( V_a \) & \( V_m \) are applied and maximum voltages respectively.

### 3.1.3. SC current density’s effect on lifetime of DSSC

Diffusion model describing the injection of photoelectrons in the mesoporous layer of irradiated DSSC, explaining the value of the short circuit current density applied was given by Koide et al. as in equation (6). The model was considered under steady-state conditions of temperature & humidity (Koide et al 2006). In such type of a diffusion model, two assumptions made were: electrons get transported through diffusion and diffusion length was considered constant; (Gong and Sumathy, 2012, Aboulouard et al 2017, Supriyanto et al 2019).

\[ J_a = J_m - \frac{qDn \tanh \left( \frac{d}{L} \right) \exp \left( \frac{qV}{KT_m} \right) - 1}{L} \quad (6) \]

Resolving the equation (6) we get (Bhargava et al 2018c),

\[ AF_J = K_i \left[ L \left( 1 - \left( \frac{\Delta T}{T_a} \right) \right) \left( \frac{\Delta T}{T_a} \right)^{L_k} \right] \quad (7) \]

where \( AF_J \) is the current density acceleration factor; \( K_i \) is the factor of multiplication (current density), its value is equal to 2; \( \Delta T \) is the increase in ambient temperature.

### 3.1.4. Environmental parameter: humidity’s effect on lifetime of DSSC

Humidity plays a significant role when determining the reliability conditions for the lifetime of the cell. The cell gets damaged due to moisture content in the air and can lead to electrolytic corrosion in case of DSSCs electrolytic presence. Consequently, the efficiency and hence the fill factor of the DSSC decreases and affects its reliability. As suggested by (Caswell, 2015) and (Park et al 2013) the acceleration factor for humidity can be calculated using equation (8)

\[ AF_H = e^{0.00044(R_H e^{\Delta T} - R_H m^{\Delta T})} \quad (8) \]
Where, AFH is the humidity acceleration factor; \( \eta \) is humidity activation exponent having a value equal to 2, RHa is applied humidity and RHm is the maximum value of humidity.

After taking consideration for the reliability prediction for lifetime of the cell having the ALT equations of temperature, SC current density, voltage and humidity, the final equation was formed as equation (9) (Stadler and Maurer 2019)

\[
\text{Lifetime (Expected)} = \text{Lifetime (D)} \times \text{AFT} \times \text{AFV} \times \text{AFJ} \times \text{AFH}
\]

(9)

where Lifetime (D) is lifetime claimed by the manufacturer in the datasheet (Infinity OPV); AFT is the temperature acceleration factor, AFV is the voltage acceleration factor, AFJ is current density acceleration factor, AFH is the humidity acceleration factor (Tamizhmani and Kuitche 2013, Caswell 2015)

Therefore,

\[
\text{Lifetime (Expected)} = \text{Lifetime (D)} \times \frac{2^{\frac{\eta}{2}}}{\eta} \times \left( \frac{V_a}{V_m} \right)^\eta \times \text{Ki} \times \left[ A \left( \left( \frac{1 - (\frac{R_h}{R_m})}{\text{e}^{0.00044 \times (\text{RHa} - \text{RHm})}} \right) \right) \right]
\]

(10)

Hence, equation (10) represents the expected lifetime of the cell using acceleration factors of all the performance affecting parameters of the life of the cell.

3.2. Experimental method for life prediction

Accelerated Life Thermal cycling ISOS T-2 test was performed to calculate the lifetime of the DSSC experimentally. In this, a fabricated DSSC was chosen for the experiment and placed on the hot tray as shown in the figure 4. A total of 20 DSSC were fabricated according to Infinity OPV manufacturer specifications. The initial parameters were analysed upon and the manufacturer datasheet was also verified with the selected and calculated parameters (Stadler and Maurer 2019). Electrolyte filling was done for the DSSCs and thereafter the DSSCs were kept on the hot plate periodically such that the cycle of ranging the temperature from ambient value to 95 °C (as the high level of setting for independent variables) as shown in figure 4.

A precision of 95% is considered for the given experimental setup (Caswell 2015). Experiment was conducted as per the Taguchi model. When the efficiency decreased to 20% and the open circuit voltage fell to zero value, the DSSC stopped conducting as a cell. The lifetime was calculated using the Arrhenius law (Haillant et al 2011, Stadler and Maurer 2019).

The experiment was conducted at accelerated values of temperature, voltage, current density & humidity and the observations were recorded over a period of 45 days (1000 h) cyclically as per the ISOS T-2 thermal cycle protocol. For validation of residual life, the overall failure was calculated using the relation (Kiilunen 2014)

\[
\text{FIT(\lambda)} = \frac{\text{number of failures}}{\text{number of components} \times \text{testing hours} \times \text{acceleration factor}}
\]

(11)

Where, Acceleration Factor,

\[
\text{AE} = \text{e}^{\text{Ea}/(K \times (T_i - T_m))}
\]

Where, \( E_a \) is the activation energy (eV); \( K = \text{Boltzmann constant} \), \( T_i \) is test temperature, \( T_m \) is maximum temperature. The life calculated analytically was compared with the life calculated experimentally.
4. Results and discussions

After analysis of various performance parameters of the cell, results on the lifetime prediction of the cell were compared and helped in the validation of the experimental approach. The residual life was calculated using ALT approach and was validated using experimental methods. The statistical and ANN techniques were used for the prediction of results.

4.1. Analytical method for residual life calculations

Equation (9) is used to find the lifetime of the cell after the design matrix values and acceleration factors are calculated.

4.1.1. Optimisation of mathematical modelling using DOE

For optimising the mathematical model, the design of the experiments approach using Taguchi Model was followed. Using this approach, a relationship between reliability process variables and the response of the systems life was found out. The Taguchi approach being a systematic approach for the design, conduct and analytics of experiments plays a significant role in quality statistics planning. The steps followed in the design, conduct and analytics of experiments are as shown in figure 5.

The DOE approach follows the enlisted steps (Bhargava et al 2017, Bhargava et al 2018a, Bhargava et al 2018b, Bhargava et al 2018c, Bhargava and Handa, 2018).

| Process Variables | Units | Notation | 1 (Very Low) | 2 (Low) | 3 (Moderate) | 4 (High) |
|-------------------|-------|----------|--------------|---------|--------------|----------|
| Humidity          | Rh    | r        | 69           | 75      | 88           | 92       |
| Voltage           | V     | V_m     | 0.503        | 0.402   | 0.354        | 0.251    |
| S.C. Current Density | Am^{-2} | J_sc   | 0.59         | 0.605   | 0.646        | 0.794    |

Table 2. L16 Orthogonal Array.

| Run | Temperature | Humidity | Voltage | Current density |
|-----|-------------|----------|---------|-----------------|
| 1   | 69          | 62       | 0.503   | 0.794           |
| 2   | 69          | 64       | 0.402   | 0.646           |
| 3   | 69          | 66       | 0.251   | 0.605           |
| 4   | 69          | 67       | 0.209   | 0.59            |
| 5   | 75          | 62       | 0.402   | 0.605           |
| 6   | 75          | 64       | 0.503   | 0.59            |
| 7   | 75          | 66       | 0.209   | 0.794           |
| 8   | 75          | 67       | 0.251   | 0.646           |
| 9   | 88          | 62       | 0.251   | 0.59            |
| 10  | 88          | 64       | 0.209   | 0.605           |
| 11  | 88          | 66       | 0.503   | 0.646           |
| 12  | 88          | 67       | 0.402   | 0.794           |
| 13  | 92          | 62       | 0.209   | 0.646           |
| 14  | 92          | 64       | 0.251   | 0.794           |
| 15  | 92          | 66       | 0.402   | 0.59            |
| 16  | 92          | 67       | 0.503   | 0.605           |
4.1.1.1. Independent variables selection
Before the experiment is performed, the knowledge of the product specifications and process under investigation is important for the purpose of identifying the factors that may likely influence the outcome. Here temperature, humidity, voltage (open circuit), and short circuit current density are taken as independent variables.

4.1.1.2. Number of level settings for independent variables
After the decision of independent variables is made, the number of levels settings for each independent variable is made. Here four different levels are selected as very low, low, moderate, high as shown in table 1.

4.1.1.3. Orthogonal array selection
After deciding the minimum number of levels for the experiments, the orthogonal array is selected based on the number of independent variables and the number of factor levels for each independent variable. L16 orthogonal array was created for four factors using Taguchi Model, as shown in table 2.

4.1.1.4. Independent variables assigning to each column
It’s important to consider the order in which independent variables are assigned to the vertical column. The actual level values of each design variable must be decided before the conduct of the experiment.

4.1.1.5. Conduct of the experiments
Experiments were conducted as per the selection of the orthogonal array according to their combination levels. The calculations were done as per the equation for the design matrix. Using equation (10),

\[
\text{Lifetime (Expected)} = \text{Lifetime (D)} \times 2^{2m-2n} \times \left( \frac{V_a}{V_m} \right)^n \times K_1 \left[ \left( 1 - \left( \frac{n_m}{m} \right) \left( \frac{\Delta T}{10^2} \right) \right) \right] \times e^{10.0044[RHa^{0.7} \cdot Rh^0.7]}
\]

the acceleration factors were calculated. Residual life was calculated as per Taguchi methodology in Minitab 18.1 software as shown in table 3.

The residual lifetime of fabricated Dye Sensitised Solar Cell (DSSC) is calculated using experimental technique i.e., accelerated life testing with L16 matrix. The calculated lifetime of DSSC is enlisted in table 4.

Table 3. Calculated residual life using the analytical method.

| Run | Temperature (°C) | Humidity (% R_h) | Voltage (Volts) | Current Density (A m^{-2}) | Lifetime (Analytical) (hours) |
|-----|------------------|------------------|----------------|--------------------------|-------------------------------|
| 1   | 69               | 62               | 0.503          | 0.794                    | 1153.83                       |
| 2   | 69               | 64               | 0.402          | 0.646                    | 1034.965                      |
| 3   | 69               | 66               | 0.251          | 0.605                    | 4117.68                       |
| 4   | 69               | 67               | 0.209          | 0.59                     | 5494.907                      |
| 5   | 75               | 62               | 0.402          | 0.605                    | 1672.64                       |
| 6   | 75               | 64               | 0.503          | 0.59                     | 1264.79                       |
| 7   | 75               | 66               | 0.209          | 0.794                    | 1834.33                       |
| 8   | 75               | 67               | 0.251          | 0.646                    | 1332.68                       |
| 9   | 88               | 62               | 0.251          | 0.59                     | 1142.67                       |
| 10  | 88               | 64               | 0.209          | 0.605                    | 1179.9                        |
| 11  | 88               | 66               | 0.503          | 0.646                    | 2332.2                        |
| 12  | 88               | 67               | 0.402          | 0.794                    | 4111.96                       |
| 13  | 92               | 62               | 0.209          | 0.646                    | 303.5                         |
| 14  | 92               | 64               | 0.251          | 0.794                    | 279.77                        |
| 15  | 92               | 66               | 0.402          | 0.59                     | 358.91                        |
| 16  | 92               | 67               | 0.503          | 0.605                    | 291.31                        |

Mean Lifetime (hours) 22 167.05
Comparison between analytical and experimental methods for residual life

When the optimisation of the residual life is obtained using the DOE approach, a comparison is done between the experimental and the proposed analytical methods for finding the life of the cell. The error analysis is conducted using the relative approach of the formula given in equation (14) below

\[
\text{Error(\%)} = \frac{(\text{Experimental Response} - \text{Analytical Response})}{\text{Experimental Response}} \times 100
\]  

An error percentage of 3.63% was calculated upon comparing the analytically calculated life with the experimental one.

Table 4. Experimental lifetime calculations.

| Run | Temperature (°C) | Humidity (% Rh) | Voltage (Volts) | Current density (A m\(^{-2}\)) | Lifetime ( Experimental) (hours) |
|-----|------------------|-----------------|-----------------|-------------------------------|---------------------------------|
| 1   | 69               | 62              | 0.503           | 0.794                         | 1153.83                         |
| 2   | 69               | 64              | 0.402           | 0.646                         | 1130.1                          |
| 3   | 69               | 66              | 0.251           | 0.605                         | 2800                            |
| 4   | 69               | 67              | 0.209           | 0.59                          | 3160.1                          |
| 5   | 75               | 62              | 0.402           | 0.605                         | 1688.1                          |
| 6   | 75               | 64              | 0.503           | 0.59                          | 1250.42                         |
| 7   | 75               | 66              | 0.209           | 0.794                         | 1800                            |
| 8   | 75               | 67              | 0.251           | 0.646                         | 1390                            |
| 9   | 88               | 62              | 0.251           | 0.59                          | 1140.6                          |
| 10  | 88               | 64              | 0.209           | 0.605                         | 1065.9                          |
| 11  | 88               | 66              | 0.503           | 0.646                         | 297                             |
| 12  | 88               | 67              | 0.402           | 0.794                         | 409.3                           |
| 13  | 92               | 62              | 0.209           | 0.646                         | 310                             |
| 14  | 92               | 64              | 0.251           | 0.794                         | 266.7                           |
| 15  | 92               | 66              | 0.402           | 0.59                          | 355.6                           |
| 16  | 92               | 67              | 0.503           | 0.605                         | 271.02                          |
| Mean Lifetime (hours) | 18 488.67 |

5. Comparison between analytical and experimental methods for residual life

When the optimisation of the residual life is obtained using the DOE approach, a comparison is done between the experimental and the proposed analytical methods for finding the life of the cell. The error analysis is conducted using the relative approach of the formula given in equation (14) below

\[
\text{Error(\%)} = \frac{(\text{Experimental Response} - \text{Analytical Response})}{\text{Experimental Response}} \times 100
\]  

An error percentage of 3.63% was calculated upon comparing the analytically calculated life with the experimental one.
The error in each run of the orthogonal array is shown in figure 6. An average accuracy of 96.36% was obtained from the attained results as shown in table 5.

The residual lifetime calculated by analytical as well as experimental technique is shown graphically, as in figure 7, for all the 16 runs.

The evaluation suggested that the proposed methodology had an average error of 3.63%, in comparison with the experimental approach. This validated the proposed technique with an average accuracy of 96.37%.

6. Conclusion

This research work is focused on the residual lifetime prediction for a polymer-based dye sensitised solar cell. The Remaining Useful Lifetime (RUL) of the dye sensitised solar cell is calculated using the analytical method as well as an experimental method. The experiments are designed using L16 orthogonal array, based on Taguchi’s approach. Minitab 18.1 is used to generate the optimised orthogonal array. An error analysis is conducted to
explore the accuracy of the analytical method for calculating the residual lifetime of polymer-based dye sensitised solar cell. It has been observed that the analytical method is 96.37% accurate while calculating the lifetime of dye sensitised solar cell.

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