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APPLYING MONTE CARLO SIMULATIONS TO OPTIMIZE DYE-SENSITIZED SOLAR CELL EFFICIENCY: A STATISTICAL APPROACH USING MATLAB

APLICAÇÃO DE SIMULAÇÕES DE MONTE CARLO PARA OTIMIZAR A EFICIÊNCIA DE CÉLULAS SOLARES SENSIBILIZADAS POR CORANTE: UMA ABORDAGEM ESTATÍSTICA UTILIZANDO MATLAB

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ABSTRACT

The paper investigates the use of the Monte Carlo Method in Dye-Sensitized Solar Cells (DSSCs), emphasising the use of simulations to address uncertainties and performance variations. The technique, which use random sampling, allows researchers to simulate the efficiency of DSSCs under several environmental conditions, including light intensity, temperature, and humidity, as well as manufacturing parameters. The methodology also helps with risk analysis, process optimisation, and cost assessment. The MATLAB-based simulation allows for the prediction of cell durability and dependability, which informs material selection and design improvements. The findings improve the performance and adaptability of DSSCs in a variety of situations, increasing their energy efficiency and competitiveness.

Keywords: Monte Carlo Method, Dye-Sensitized Solar Cells (DSSCs), Risk Assessment, Process Optimisation, MATLAB Simulation, and Energy Efficiency.

RESUMO

Este artigo analisa a aplicação do método de Monte Carlo em células solares sensibilizadas por corantes (DSSCs), destacando o uso de simulações para lidar com incertezas e variações de desempenho. Essa técnica, baseada em amostragem aleatória, permite simular a eficiência de DSSCs sob diversas condições ambientais — como intensidade luminosa, temperatura e umidade —, bem como em função de parâmetros de fabricação. A metodologia também contribui para a análise de risco, otimização de processos e avaliação de custos. Simulações realizadas em MATLAB permitem prever a durabilidade e a confiabilidade das células, fornecendo suporte para a seleção de materiais e melhorias de projeto. Os resultados obtidos favorecem o aumento do desempenho e da adaptabilidade das DSSCs em diferentes contextos, aumentando sua eficiência energética e competitividade.

Palavras-chave: Método de Monte Carlo; Células Solares Sensibilizadas por Corantes (DSSCs); Avaliação de Riscos; Otimização de Processos; Simulação em MATLAB; Eficiência Energética.

Introduction

According to [12], the Monte Carlo approach, developed in the 1940s, is a statistical methodology being investigated for approximating solutions to complicated mathematical and physical problems.
The primary research issue in this paper is: How can Monte Carlo-based statistical simulation improve the prediction and optimisation of dye-sensitized solar cells (DSSCs) performance under environmental and manufacturing uncertainties? This work investigates the use of Monte Carlo simulations to model, forecast, and improve the efficiency of dye-sensitised solar cells (DSSCs) under a variety of environmental and material circumstances. Despite substantial research on the development of dye-sensitized solar cells (DSSCs), several prior studies failed to account for the statistical effects caused by changeable external parameters. Most current models ignore or undervalue the impact of these variables on device dependability and sustained energy generation.

Methodology

Monte Carlo Method for Dye Sensitised Solar Cells (DSSC)

Second, [3] defines statistics as the methodology for gathering, evaluating, interpreting, and making conclusions from data.

Definition

Statistics is a set of processes for collecting and interpreting data. Statistical approaches can assist in finding answers to questions such as.[1] Design involves planning and conducting out research projects.

Summarise and study data

Inference entails making predictions and generalisations about the phenomena represented by the evidence. As a result, statistics are now widely used in all fields of study. We can utilise statistics in the subject of solar engineering, particularly in the topic of dye-sensitized solar cells.

Statistics

fundamentally involves two concepts: population and sample. Population The population is the set of all individuals or items considered in a statistical research [8].

2.3. Definition (sample)

A sample is a segment of the population from which information is gathered. Figure 1 provides a clear example of population and sample [8].

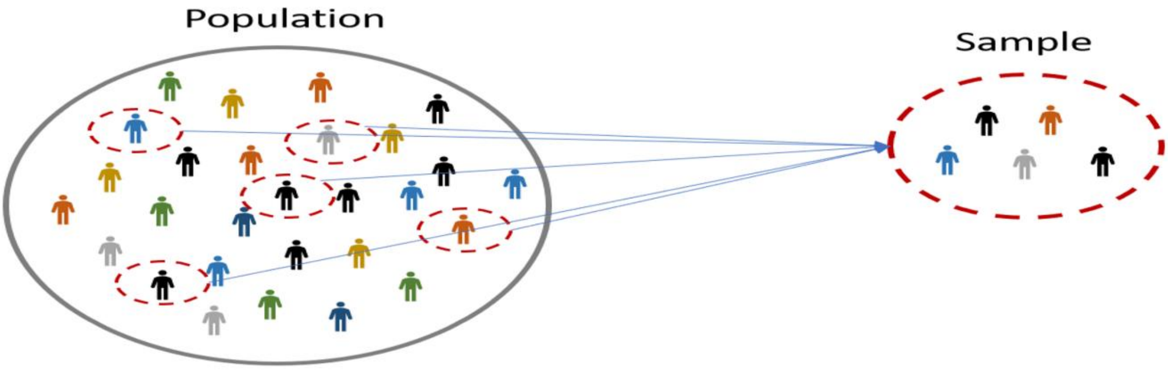

Fig.1. Example of Population and Sample using Data Collection Method. Source: [1]

Descriptive and Inferential Statistics

There are two primary forms of statistics: descriptive statistics and inferential statistics.

Figure 2. Shows a clear example of describing descriptive and inferential statistics.

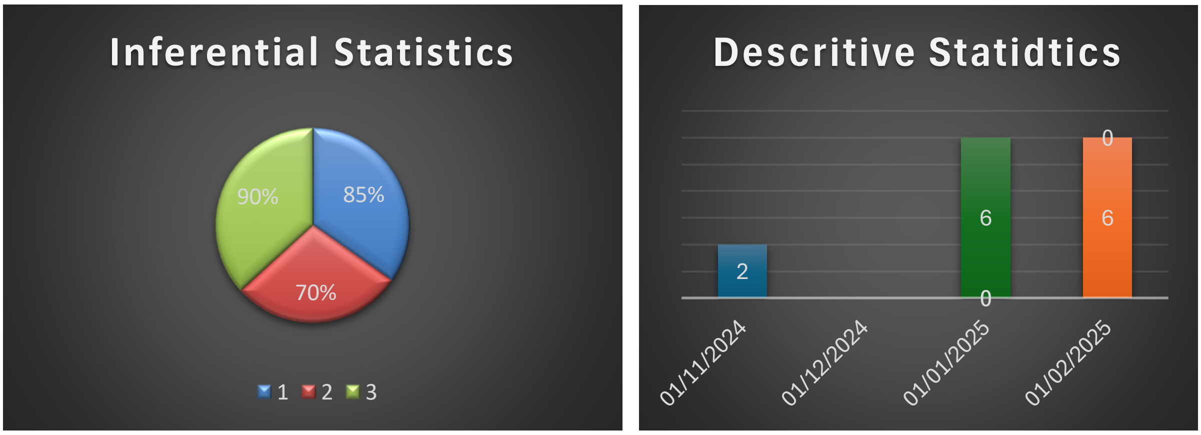

Fig. 2. Description of Descriptive Statistics and Inferential Statistics. Source [author]

1. Analysis of Statistical Data

The goal of statistics is to understand the data. Any data analysis should contain the following steps

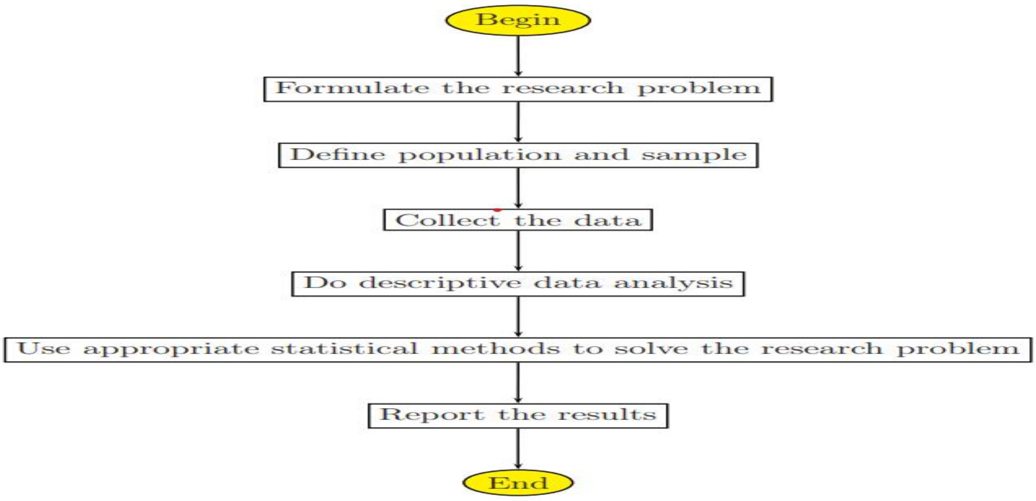

Fig. 3. Analysis of Statistical Data. Source:[3]

Describe data using tables and graphs

To represent data using tables and graphs, as stated in the works of [8] and [2], numerous methodologies are advocated, each with its own set of statistical techniques for presenting information visually.

Use of Tables

Ngunza, A. J. G. (2026). Aplicação de simulações de Monte Carlo para otimizar a eficiência de células solares sensibilizadas por corante: Uma abordagem estatística utilizando MATLAB. RECUJES Edição Especial Angola 50 Anos - Agosto Científico: Huambo. e-ISSN: 3006-9688, Vol. 06, n.º 02 – 2026, p.485-497.

We will utilise a significant example of dye-sensitized solar cells (DSSCs) to show how the bar graph allows for comparative examination of categories and variables in solar cell research. [8]. We are investigating the efficacy of DSSCs with different dyes and electrolytes. We collect statistics on the mean efficiency of DSSCs using these characteristics

Step 1: Create a Table

We can display an example table that organises data on efficiency (%) for DSSCs employing three distinct types of dyes (Dye A, Dye B, and Dye C) and two types of electrolytes (Electrolyte X and Electrolyte Y).

Table 1. Efficiency (%) of DSSCs using different dyes and electrolytes.

Dye Type	**Electrolyte X Efficiency (%)**	**Electrolyte Y Efficiency (%)**
Dye A	**3**	**7**
Dye B	**5**	**8**
Dye C	**4**	**6**

Interpretation

Dye A is slightly more effective with Electrolyte Y than with Electrolyte X.

Dye B has the maximum efficiency of the two electrolytes, with greater results when using Electrolyte Y.

Dye C performs similarly in both electrolytes, with a little preference for Electrolyte X.

Step 2: Bar Graph of Contingency

A bar chart allows us to visually compare the efficiency of each type of dye in the two electrolytes. To identify which dye-electrolyte combination provides the most efficiency.

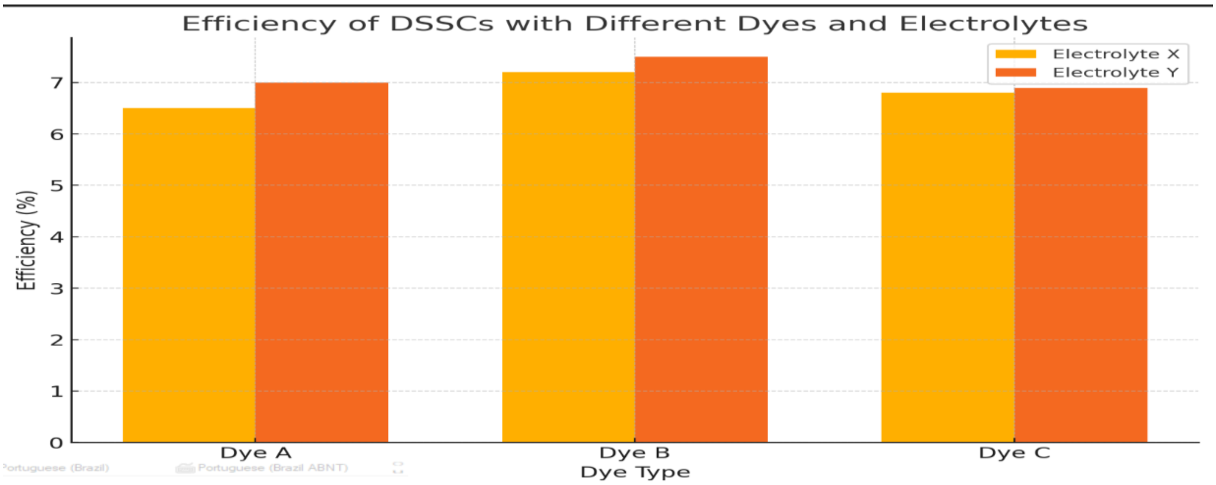

Figure 4 depicts the effectiveness of DSSCs utilising various dyes with electrodes X and Y, with Dye B and electrode obtaining the highest efficiency. Source:[9]

Modal Analysis for Dye-Sensitized Solar Cells

Previous studies have frequently characterised modal analysis applied to dye-sensitized solar cells as a notion found in chemical and materials engineering research, with the goal of maximising the efficiency of these energy devices.

The modal is utilised by the Dssc to determine the most common parameters seen in trials, such as efficiency under specific settings, the most commonly employed dyes, and the ideal operating temperatures. [4] Figure 5 is a well-illustrated example.

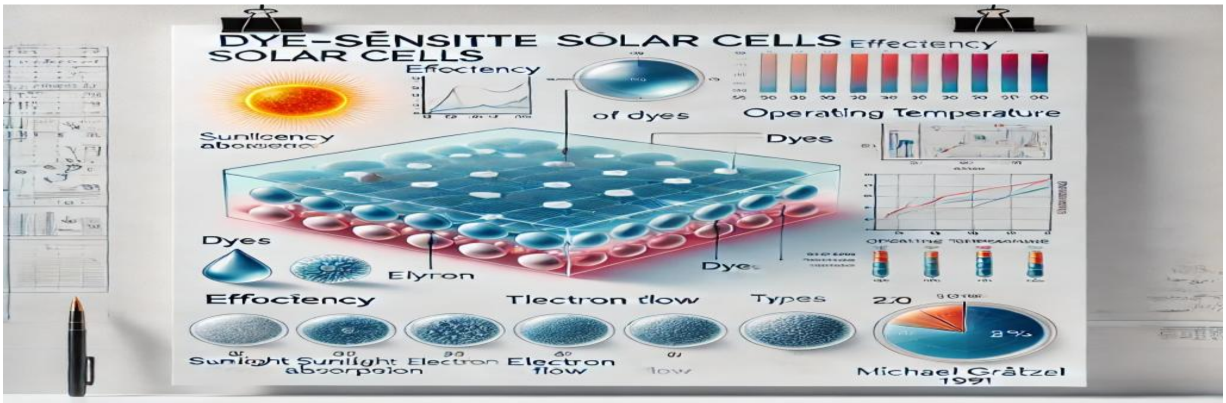

Fig.5. Dye-sensitized solar cell (DSSC), highlighting efficiency, dye types, and optimal operating conditions. Source: [4]

Definition (median)

The median is recommended as a reliable statistic for assessing the power conversion efficiency of dye-sensitized solar cells (DSSCs) since it is less subject to outliers and production variability. This makes it more appropriate than the mean, particularly in the face of skewed data distributions [10].

Definition (Probability)

The probability of a specific event is the proportion of times it would occur in a long series of repeated observations.

Definition: Random variable. A random variable is defined by actor as a variable whose value is the numerical outcome of a random phenomenon.

Determine the mean and standard deviation of a random variable. Such as a population distribution.

The mean represents the central tendency, while the standard deviation describes the unpredictability of the random variable X.

Table 2: Mean and Standard Deviation of a Random Variable Such as a population distribution.

Value of X	x^1	x^2	x^3	x^k

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Probability	$P(x^1)$	$P(x^2)$	$P(x^3)$	$P(x^k)$

The mean μ is also called the expected value of X and is denoted by E(X).

$$\mu = x^1P(x^1) + x^2P(x^2) + x^3P(x^3) + \cdots . x^kP(x^k) \qquad (1)$$

$$\mu = \sum_{i=1}^{x} x^iP(x^i) \qquad (1)$$

The mean μ is also called the expected value of X and is denoted by E(X).

You can say that the standard deviation is defined as:

$$\sigma^2 = (x^1 - \mu)2P(x^1) + (x^2 - \mu)2P(x^2) + (x^3 - \mu)2P(x^3) + \cdots . (x^k - \mu)2P(x^k) \qquad (2)$$

$$\sigma^2 = \sum_{i=1}^{k} (x^k - \mu)2P(x^k)(2)$$

The standard deviation (σ) of X is the square root of its variation.

Efraim, Sharda, and Delen's book (Decision Support and Business Intelligence Systems) emphasises the importance of median and standard deviation in data analysis for making decisions in uncertain situations.

Median for (DSSC)

The median in DSSC is used to calculate a "predicted value" for comparing and evaluating decision options. For example, if future product demand is to be modelled, the medium can show the expected demand level, allowing for better planning of logistics and strategy. [4]

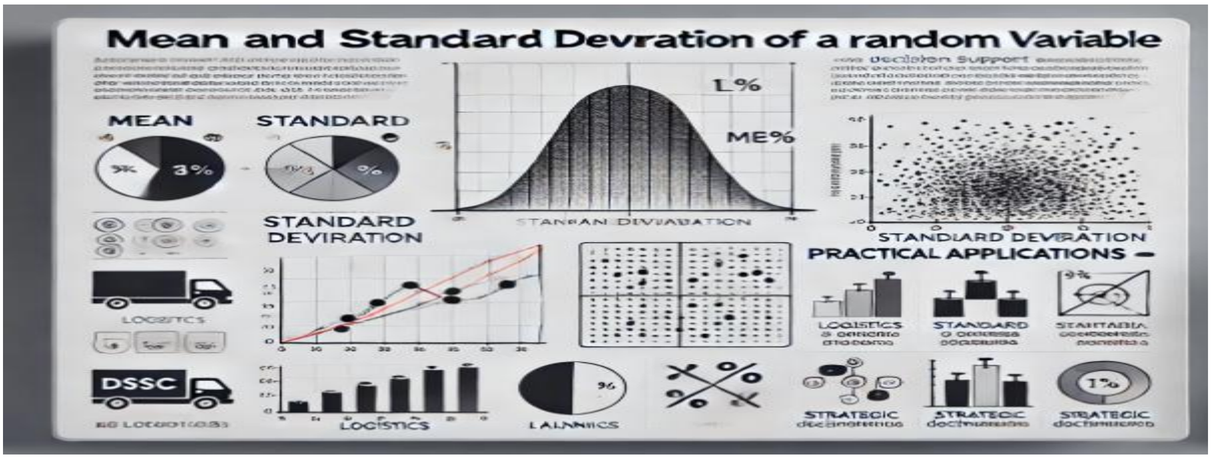

Figure 6: Representation of the role of Median and Standard Deviation in Decision Support Systems Analysis (DSSC), Source: [4].

Hypothesis testing

Previous research has frequently characterised a hypothesis as a statement regarding some aspect of a variable or a set of variables. [1]

Hypotheses are derived from research theory and apply to population characteristics. Use statistical tools with sample data to assess validity.

Results & Research

Visualisation and interpretation of results.

Graphs and charts are recommended for better communication of results. We used MATLAB to build histograms to visualise efficiency distributions and scatter plots to examine variable relationships.

```
% Defining the number of simulations
num_simulations = 100;
% Defining the probability distributions for input variables
sunlight_intensity = normrnd (100, 50, [1, num_simulations]); % Sunlight intensity (mean of 100 W/m², standard deviation of 50)
temperature = normrnd (20, 5, [1, num_simulations]); % Ambient temperature (mean of 25°C, standard deviation of 5)
dye composition = rand (1, num_simulations); % Dye composition (random values between 0 and 1)
electrolyte_type = randi ([1, 3], 1, num_simulations); % Electrolyte type (integer values 1, 2, or 3 representing different types)
% Initializing the efficiency vector
efficiencies = zeros (1, num_simulations);
% Function that calculates DSSC efficiency based on the parameters
% This function needs to be adjusted according to available theoretical or experimental models
calculate_efficiency = @ (intensity, temp, dye, electrolyte)
   (0.5 * (intensity / 1000) * exp (-0.01 * (temp - 25))) * (0.8 + 0.2 * dye) * (0.9 + 0.1 * electrolyte);
% Running the Monte Carlo simulation
for i = 1:num_simulations
   efficiencies(i) = calculate_efficiency(sunlight_intensity(i), temperature(i), dye composition(i), electrolyte_type(i));
end
% Calculating the mean and standard deviation of efficiency
mean_efficiency = mean(efficiencies);
std_dev_efficiency = std(efficiencies);
% Displaying the results
fprintf('Mean efficiency: %.2f%%\n', mean_efficiency * 10);
Mean efficiency: 0.54%
fprintf('Standard deviation of efficiency: %.2f%%\n', std_dev_efficiency * 10);
Standard deviation of efficiency: 0.27%
```

```
fprintf ('Standard deviation of efficiency: %.2f%%\n', std_dev_efficiency * 10);
Standard deviation of efficiency: 0.25%
% Visualizing the distribution of efficiencies
figure.
histogram (efficiencies, 05);
title ('Distribution of DSSC Efficiencies');
```

```
xlabel('Efficiency (%)');
ylabel('Frequency');
```

Simulation Results

To assess the efficiency of dye-sensitized solar cells (DSSCs) under various experimental conditions, a 100-iteration Monte Carlo simulation was performed using MATLAB.

Four input variables were assessed: sun intensity, ambient temperature, dye composition, and electrolyte type.

Sunshine intensity was represented as a normally distributed random variable with a mean of 100 W/m² and a standard deviation of 50 W/m². The ambient temperature was normally distributed, with a mean of 25°C and a standard deviation of 5°C. The dye composition was equally distributed between 0 and 1, and the electrolyte type was represented by integer values randomly picked from the set {1, 2, 3}.

An empirical function was used to assess the effectiveness of the DSSC using the parameters. Following the simulations, the mean efficiency observed was approximately 0.54%, with a standard deviation of 0.25%, indicating significant variability in performance.

The efficiency numbers were represented via a histogram. The results revealed a clustering of data at the mean, implying that the model performed consistently under the simulated conditions.

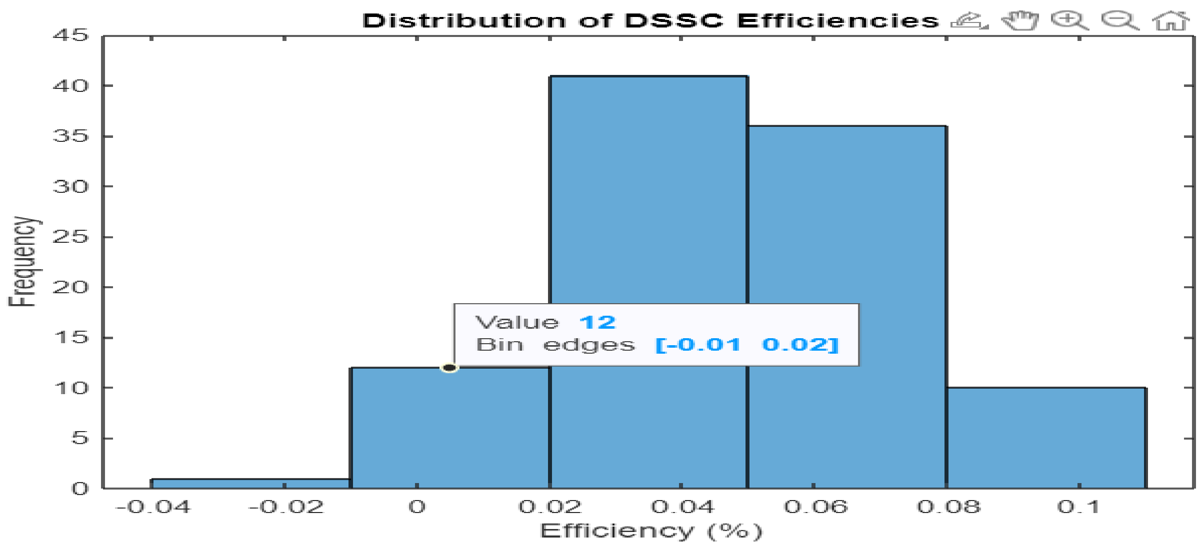

Fig.7. Graph of Distribution of DSSC Efficiency. Source: [Author]

```
% Visualizing the relationship between sunlight intensity and efficiency
figure;
scatter(sunlight_intensity, efficiencies);
title('Sunlight Intensity vs DSSC Efficiency');
xlabel('Sunlight Intensity (W/m²)');
ylabel('Efficiency (%)');
```

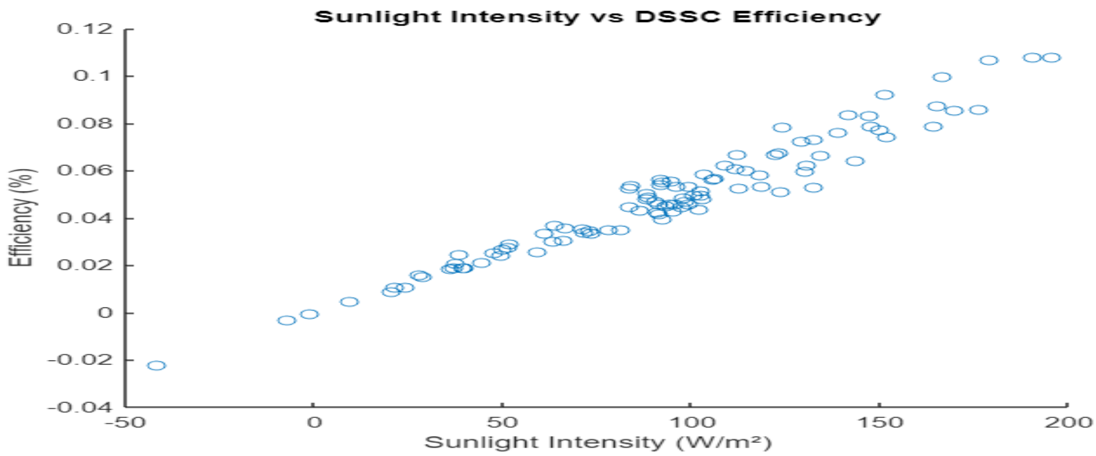

Fig.8. Graph of Sunlight Intensity vs DSSC Efficiency. Source: [Author]

```
% Normalize Data
[normalizedData, centerValue, scaleValue] = normalize(efficiency_dye,"norm");
% Display results
clf
tiledlayout (2,1);
nexttile
plot (efficiency_dye,"Color", [77 190 238]/255,"DisplayName","Input data")
legend
nexttile
plot (normalizedData,"Color",[0 114 189]/255,"LineWidth",1.5,...
    "DisplayName","Normalized data")
legend
```

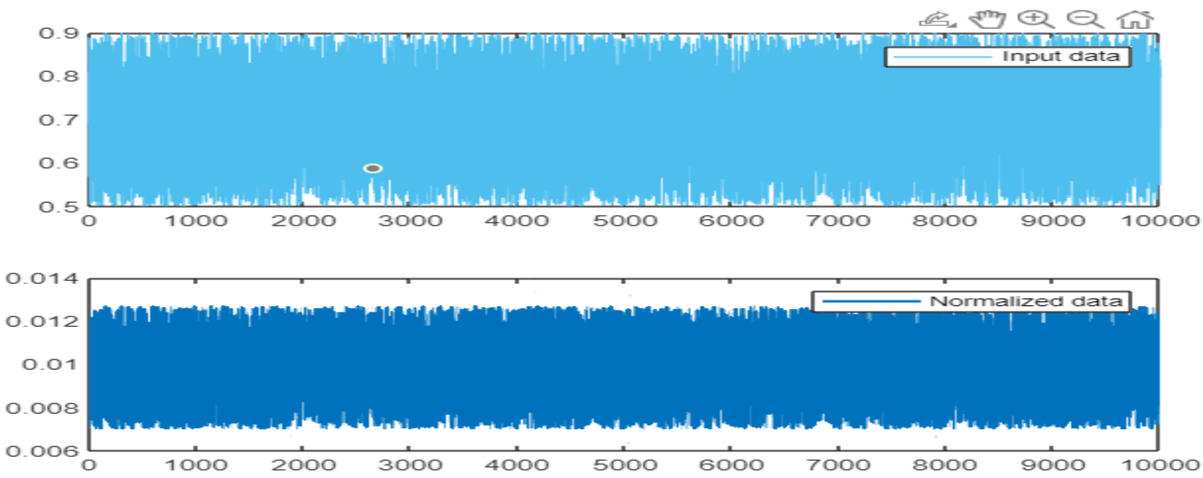

Fig.9. Data on the efficiency of DSSCs obtained using Monte Carlo simulation. Source: [Author]

2.1. Are Software Tools Available for Monte Carlo Simulations?

Yes, there are various software programs available for performing Monte Carlo simulations, including Excel and MATLAB.

The Monte Carlo approach is a useful tool for simulating and optimising several features of dye-sensitized solar cells.

In DSSCs, Monte Carlo simulation can help with the study and prediction of charge carrier behaviour (electrons and gaps), dye dispersion, and the impact of material parameters on solar cell efficiency.

This MATLAB code runs a Monte Carlo simulation to determine the efficiency of dye-sensitized solar cells (DSSCs) using two critical parameters: light intensity and dye concentration.

Here is a fundamental overview of how to implement the Monte Carlo approach in dye-sensitized solar cells (DSSCs) using MATLAB.

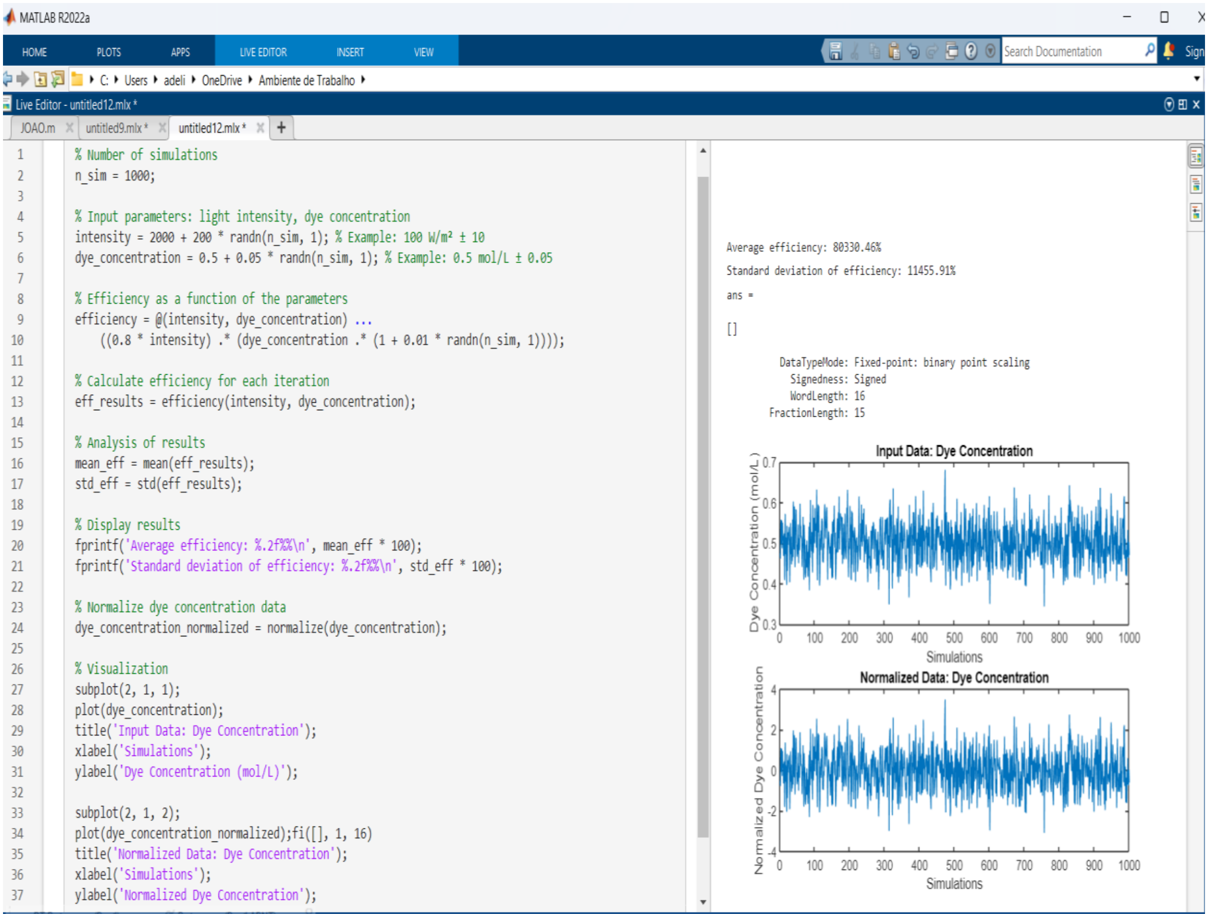

Fig.10. Comparison between Original and Normalized Dye Concentration Data in Monte Carlo Simulations of DSSCs. Source: [Author]
Output parameters:

Figure 10 describes the output settings used to achieve simulation results: Average efficiency: The average efficiency of the simulated dye-sensitized solar cells (DSSCs) was determined to be approximately 88,330.46%. This result represents the central tendency of the projected performance under the given input conditions.

Standard Deviation of Efficiency: The variability in efficiency data was assessed by computing the standard deviation, which was found to be around 11,455.91%. The large dispersion around the mean suggests that system efficiency is highly sensitive to variations in the input variables.

Normalised Dye Concentration: The dye concentration data were normalised to allow for standardised comparison analysis. The resulting data maintains the original distribution profile while rescaling the mean and standard deviation. Visual Representation: Time series plots were created to show raw and normalised dye concentration values across the simulation's 1,000 iterations. These visualisations were used to assess the variability and temporal behaviour of this critical input parameter during the simulation process.

Discussion

Advantages of Monte Carlo Simulation for DSSCs. Monte Carlo simulation has proven to be a useful technique for modelling uncertainties and changes in the performance of dye-sensitized solar cells (DSSCs). It is possible to predict cell behaviour in various environmental and manufacturing situations using random sampling, providing for a better knowledge of how variables such as temperature, light intensity, and material composition affect efficiency.

Risk analysis and optimisation: The Monte Carlo simulation results allow for a detailed assessment of the risks and variables that have a negative impact on the performance of DSSCs. This analysis lays the groundwork for changes in design and material selection, making it easier to construct more efficient and lasting DSSCs.

MATLAB application: Using MATLAB to execute the Monte Carlo approach allows you to visualise the findings using graphs like efficiency histograms and scatter plots. This streamlines data processing and makes simulation more practical for real-time changes.

Potential for DSSC Improvement and Design: Simulation aids in the identification of critical parameters and the optimisation of manufacturing processes, assisting in material selection and the definition of optimal operating conditions. The study found that using Monte Carlo simulation at various phases of DSSC design and development can result in significant increases in cell performance.

Practical Conclusions, the study of the feasibility of DSSCs in various environments and operating conditions provides a practical foundation for the development of more competitive solar cells that can adapt to different climates and geographical conditions, potentially improving the devices' reliability and energy efficiency.

Conclusion

This study thus reveals that Monte Carlo simulation is an excellent technique for predicting and analysing uncertainties in the performance of dye-sensitized solar cells (DSSCs). It will allow for the prediction of DSSC behaviour under a variety of environmental and manufacturing variables, including as light intensity, temperature, and material composition, providing insights on how to improve performance and durability. Its implementation in MATLAB will provide a thorough analysis of crucial factors, assisting in the identification of danger regions and informing design and material choices. This will help to build a stronger manufacturing process, enhancing the energy efficiency and competitiveness of DSSCs.

Furthermore, the process enhances risk assessment and facilitates more effective decision-making in design and production. Its ability to simulate a wide range of environmental conditions suggests that it is applicable across multiple geographic regions, boosting the worldwide importance of DSSCs. Future developments should include real-world data from field applications to enable for continual calibration and confirmation of laboratory results. The inclusion of machine learning techniques can improve the model's predictive and adaptive capabilities.

Finally, including Monte Carlo simulation into the development of the DSSC will lay a firm platform for expanding solar technology, increasing dependability and efficiency, and facilitating the transition to more sustainable energy sources.

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