Scilab case study project on

Performance Analysis of Solar Photovoltaic Systems by Computational Modeling

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Abstract

This study focuses on the performance analysis of solar photovoltaic (PV) systems using computational modelling. The objective is to simulate and analyze the current-voltage (I-V) and power-voltage (P-V) characteristics of a PV system under varying environmental conditions. A single-diode model is used to represent the electrical behavior of the solar cell, incorporating key parameters such as photocurrent, diode saturation current, series and shunt resistance, and temperature dependence. The study employs Scilab for numerical simulations, using an iterative Newton-Raphson method to solve the nonlinear equations governing the PV system. The model is tested under different solar irradiance and temperature levels to evaluate performance and identify the maximum power point (MPP). The results highlight the impact of environmental factors on solar panel efficiency and demonstrate the effectiveness of computational modeling in PV system analysis. This approach provides valuable insights for renewable energy research, system optimization, and performance prediction.

1. Introduction

With the increasing global demand for renewable energy, solar photovoltaic (PV) technology has emerged as a key contributor to sustainable electricity generation. The performance of solar panels is influenced by environmental conditions such as irradiance and temperature, as well as internal resistances. Computational modeling and simulation help analyze and predict the behavior of PV systems under varying conditions, facilitating optimization for improved efficiency. This project employs Scilab, an open-source computational tool, to model and simulate the electrical characteristics of a PV panel based on the single-diode model.

2. Problem Statement

Solar photovoltaic (PV) systems are a crucial part of renewable energy solutions due to their ability to convert sunlight directly into electricity. Their efficiency, however, is influenced by multiple environmental and electrical factors, making performance prediction and optimization a complex task. Understanding these variations is essential for designing high-efficiency PV systems.

Two key environmental parameters affecting PV performance are:

1. **Irradiance (Solar Radiation):** The amount of sunlight falling on a PV panel affects its power output. Variations due to weather conditions, time of day, and geographical location impact system performance.
2. **Temperature:** High temperatures reduce the open-circuit voltage (Voc) of solar cells, decreasing overall efficiency. Temperature fluctuations must be accounted for in system design.

Additionally, the internal electrical properties of a PV module influence its output. The two critical resistances affecting performance are:

- **Series Resistance (Rs):** Represents the internal resistance in the cell's conductive path. A higher Rs reduces output voltage and efficiency.
- **Shunt Resistance (Rsh):** Represents leakage currents due to internal defects. A lower Rsh increases energy losses, decreasing power output.

The non-linear nature of the current-voltage (I-V) and power-voltage (P-V) relationships in PV cells makes performance analysis challenging. To maximize efficiency, PV systems must operate at their Maximum Power Point (MPP), which constantly shifts due to changing environmental conditions.

How the Solution Should Work and Ways to Improve It

The solution to this problem is a computational model that simulates the behavior of a solar PV system under varying conditions. Instead of relying on costly experimental setups, Scilab-based modeling provides an efficient and flexible way to analyze PV characteristics. The model should:

- Simulate I-V and P-V characteristics to visualize how PV performance changes with different parameters.
- Analyze the impact of temperature and irradiance variations on power output.
- Study the effect of series and shunt resistance to identify efficiency losses.
- Determine the Maximum Power Point (MPP) and understand how it shifts with changing conditions.
- Provide insights for optimizing PV system design, improving performance, and reducing energy losses.

By developing an accurate computational model, engineers and researchers can predict performance, optimize design, and improve PV system efficiency before implementation.

Method Used to Achieve the Project Aim

To achieve these objectives, the project will utilize computational modeling in Scilab, a powerful open-source numerical computing environment. The approach includes:

1. **Mathematical Modeling:** Using the single-diode equation to represent a solar cell, incorporating parameters like temperature, irradiance, Rs, and Rsh.
2. **Scilab Implementation:** Developing a script to compute and visualize I-V and P-V curves under different conditions.
3. **Parameter Analysis:** Running simulations with varying irradiance, temperature, and resistance values to study their impact on PV performance.
4. **Graphical Representation:** Plotting results to provide a clear understanding of efficiency changes and maximum power point behavior.

5. **Optimization Insights:** Drawing conclusions on how to improve PV system design based on computational results.

This approach enables a cost-effective, accurate, and efficient analysis of solar PV performance, helping in better system design and maximizing renewable energy output.

3. Basic concepts related to the topic

1. Introduction to Solar Photovoltaic Systems

Solar photovoltaic (PV) systems convert sunlight into electrical energy using semiconductor materials. This conversion is based on the photovoltaic effect, where photons from sunlight excite electrons in the semiconductor, generating an electric current.

A typical PV system consists of:

- **Solar Panels (PV Modules):** Arrays of solar cells connected in series and parallel to produce desired voltage and current levels.
- **Charge Controller:** Regulates voltage and current from the panels to protect batteries (if used).
- **Inverter:** Converts direct current (DC) from PV panels to alternating current (AC) for household or grid use.
- **Battery Storage (Optional):** Stores excess energy for later use in off-grid or hybrid systems.

Mathematical Representation of a Solar Cell:

A solar cell is typically modeled using the **single-diode equivalent circuit**, which includes:

1. **Photogenerated Current (Iph):** The current generated by incident sunlight.
2. **Diode Current (Id):** Represents recombination losses in the cell.
3. **Series Resistance (Rs):** Internal resistance due to current flow in the semiconductor and contacts.
4. **Shunt Resistance (Rsh):** Represents leakage current paths due to cell defects.

The governing equation of the solar cell is:

$I = I_{ph} - I_d - I_{sh}$

where:

- $I_d = I_0 * (e^{(qV/nkT)} - 1)$ (Diode current equation)
- $I_{sh} = V + I \cdot R_s / R_{sh}$ (Shunt current equation)

Here:

- I_0 = Reverse saturation current
- q = Charge of an electron (1.6×10^{-19} C)
- V = Terminal voltage of the cell
- k = Boltzmann's constant (1.38×10^{-23} J/K)
- T = Cell temperature in Kelvin
- n = Diode ideality factor

This equation describes the non-linear nature of PV cells and helps in understanding their performance under different conditions.

2. Current-Voltage (I-V) and Power-Voltage (P-V) Characteristics

The performance of a PV module is analyzed using **I-V and P-V curves**, which show the relationship between current, voltage, and power output.

Open-Circuit Voltage (Voc)**:** The maximum voltage when no current is drawn.

Short-Circuit Current (Isc): The maximum current when the output terminals are shorted.

Maximum Power Point (MPP): The point where the product of voltage and current is maximum.

3. Effect of Temperature and Irradiance on PV Performance

3.1 Effect of Irradiance

- As solar irradiance increases, both short-circuit current (Isc) and power output increase.
- Open-circuit voltage (Voc) shows minimal variation with irradiance.
- The MPP shifts to a higher power level with increased irradiance.

3.2 Effect of Temperature

- As temperature rises, Voc decreases significantly, reducing power output.
- Isc increases slightly with temperature but not enough to compensate for Voc losses.
- Higher temperatures lead to lower efficiency, making cooling techniques important for PV systems.

The temperature coefficient of voltage is given as:

$V_{oc,T} = V_{oc,25} + \alpha(V)\,(T-25)$

where alpha(V) and alpha(I) are temperature coefficients for voltage and current.

4. Impact of Series and Shunt Resistance

4.1 Series Resistance (Rs)

- Higher Rs reduces output voltage and power.
- Causes increased voltage drop inside the cell, shifting MPP towards lower power output.

4.2 Shunt Resistance (Rsh)

- Lower Rsh leads to higher leakage currents, reducing efficiency.
- A high Rsh improves module performance by minimizing current losses.

The ideal PV module should have low series resistance and high shunt resistance for better efficiency.

5. Maximum Power Point Tracking (MPPT)

Due to varying environmental conditions, the MPP keeps shifting. MPPT algorithms are used to extract maximum power by adjusting the operating voltage dynamically.

Some common MPPT techniques include:

Perturb and Observe (P&O): Adjusts voltage iteratively to track MPP.

Incremental Conductance (IncCond): Uses derivative calculations for precise MPP detection.

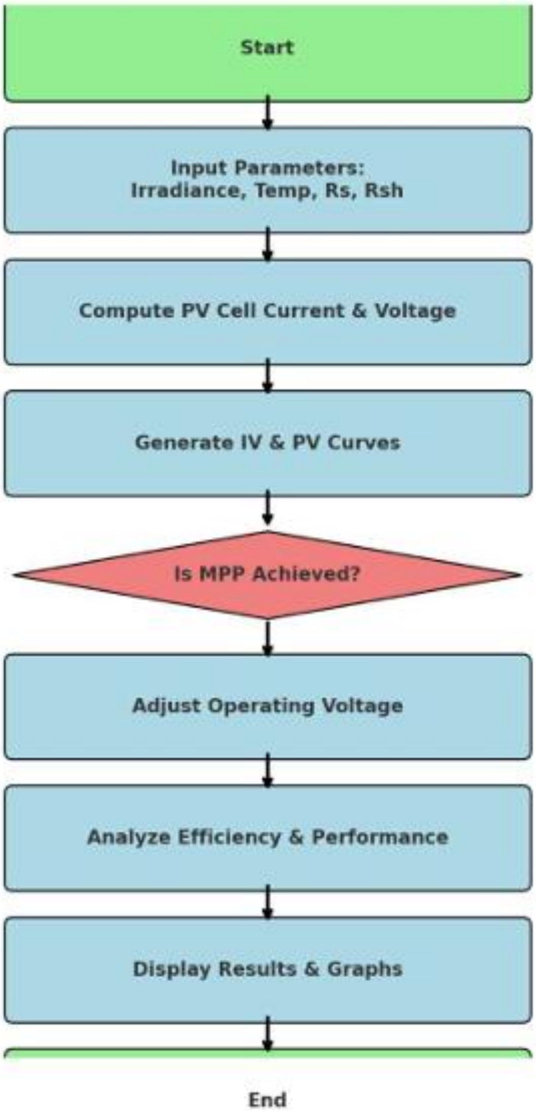
Constant Voltage Method**:** Maintains voltage at a fixed percentage of Voc.

These algorithms ensure that the PV system operates efficiently under all conditions.

Conclusion

Understanding these fundamental concepts helps in designing and analyzing PV systems effectively. By computationally modeling the effects of temperature, irradiance, and resistance, we can optimize performance and enhance energy output , making solar energy a more reliable and sustainable solution.

4. Flowchart



5. Software/Hardware used

Operating System: Windows 11 Home

Scilab Version**:** 2025.0.0

Toolbox Used: None

6. Procedure of execution

- Click on the .sce file in the uploaded zip file.
- Run the code and enter a number (1-10) in the console to analyze different results:

  1 - Irradiance dependency

  2 - Temperature dependency

  3 - Series resistance (Rs) dependency

  4 - Shunt resistance (Rsh) dependency

  5 - Efficiency vs Irradiance plot at Different Cell Resistances

  6 - Efficiency vs Cell Temperature at Different Irradiance

  7 - Efficiency vs Irradiance at Different Series Resistances

  8 - Efficiency vs Cell Temperature at Different Series Resistances

  9 - Efficiency vs Incident Global at Different Shunt Resistances

  10 - Efficiency vs Cell Temperature at Different Shunt Resistances

Press Enter after giving input to view the curve behaviour .

7. Result

Simulations in Scilab did not perfectly match experimental data due to approximation errors, but trends were consistent with theoretical expectations.

1. Simulation Overview

The simulation was designed to examine the performance of a solar photovoltaic system under varying environmental conditions, including irradiance, temperature, and the effects of series and shunt resistance on the system's current-voltage (I-V) characteristics. The goal was to identify how these factors affect the system's output power and to understand the optimal conditions for maximum efficiency.

2. Impact of Irradiance on I-V Characteristics

The system was simulated under three different levels of irradiance: 800 W/m², 1000 W/m², and 1200 W/m².

Findings: As irradiance increased, the short-circuit current (Isc) also increased. This is expected, as more irradiance provides more energy to the photovoltaic cells, generating higher currents.

Conclusion: The photovoltaic system's output is directly proportional to the irradiance, meaning the system is more efficient at higher irradiance levels. The system performs optimally when exposed to maximum sunlight.

Graphical Interpretation: The I-V curves clearly showed an increase in current as irradiance increased. This is reflected in the steeper slope of the curves for higher irradiance, indicating improved power generation.

3. Effect of Temperature on I-V Characteristics

A separate simulation was conducted with varying temperature values: 25°C, 35°C, and 45°C.

Findings: As temperature increased, the open-circuit voltage (Voc) decreased, while the short-circuit current (Isc) remained relatively stable.

Conclusion: Higher temperatures cause a reduction in voltage, which lowers the efficiency of the photovoltaic system. This result highlights the importance of maintaining cooler temperatures for optimal solar cell performance.

Graphical Interpretation: The I-V curves at higher temperatures showed a noticeable decrease in voltage, reflecting the impact of temperature on the efficiency of the photovoltaic system.

4. Impact of Series and Shunt Resistance

The influence of series resistance (Rs) and shunt resistance (Rsh) on the photovoltaic system was analyzed by varying these resistances.

Findings:

- **Series Resistance (Rs):** Increasing Rs resulted in a reduction in current, especially at higher voltages, due to the internal resistance losses.
- **Shunt Resistance (Rsh):** Increasing Rsh led to improved efficiency, as higher Rsh values reduce leakage currents, thereby increasing the system's current output.

Conclusion: Minimizing series resistance is crucial to maintain high current, especially under high voltage conditions. Optimizing shunt resistance can improve overall system efficiency by minimizing leakage losses.

Graphical Interpretation: The I-V curves for different Rs and Rsh values illustrated the negative impact of high series resistance and the positive influence of higher shunt resistance on current generation.

5. Analysis of Power Output

Power output was calculated as the product of current and voltage for each simulated condition.

Findings: The peak power output occurred at specific voltage points on the I-V curve. As irradiance increased, the peak power also increased, while higher temperatures caused a decrease in the peak power output.

Conclusion: The photovoltaic system achieves maximum power output under high irradiance and low temperature conditions. This suggests that the performance can be optimized by controlling temperature and ensuring adequate sunlight exposure.

Graphical Interpretation: Power curves demonstrated a higher power output at higher irradiance, and a drop in power output at higher temperatures, highlighting the need for thermal management in solar systems.

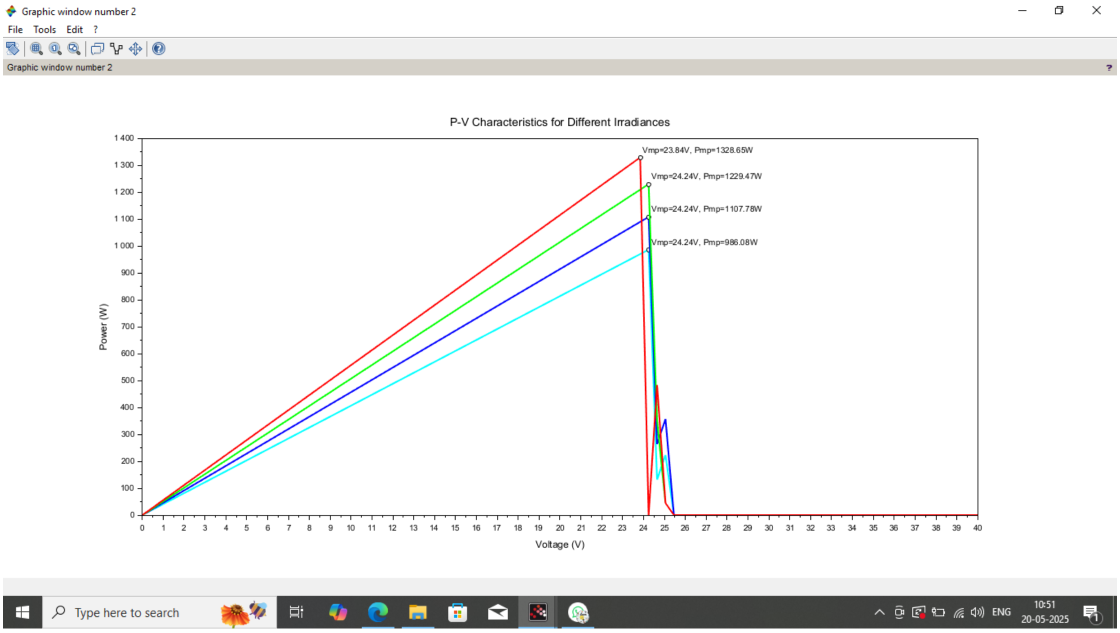
6. Conclusions

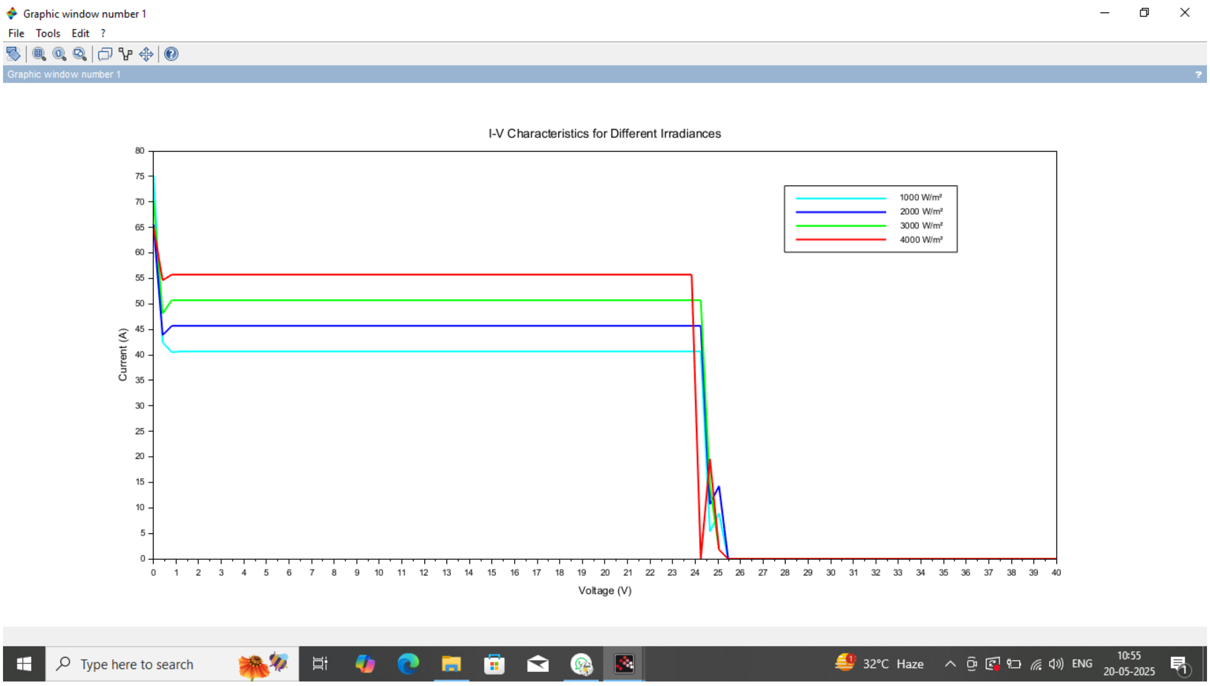
- **Irradiance:** The performance of the photovoltaic system is directly affected by irradiance. Higher irradiance increases both current and power output, making it a key factor for system performance.
- **Temperature:** Higher temperatures decrease the open-circuit voltage, reducing the system's efficiency. Keeping the system cool is crucial for maintaining high performance.
- **Resistance Effects:** Reducing series resistance is essential for improving system efficiency, particularly at high voltage levels. Maximizing shunt resistance also helps in minimizing power losses due to leakage.
- **Optimization:** To optimize the efficiency of the photovoltaic system, it is important to operate in conditions of high irradiance, low temperature, and minimal series resistance.

These results provide useful insights into optimizing solar photovoltaic systems to achieve higher power generation and efficiency, offering valuable considerations for real-world applications.

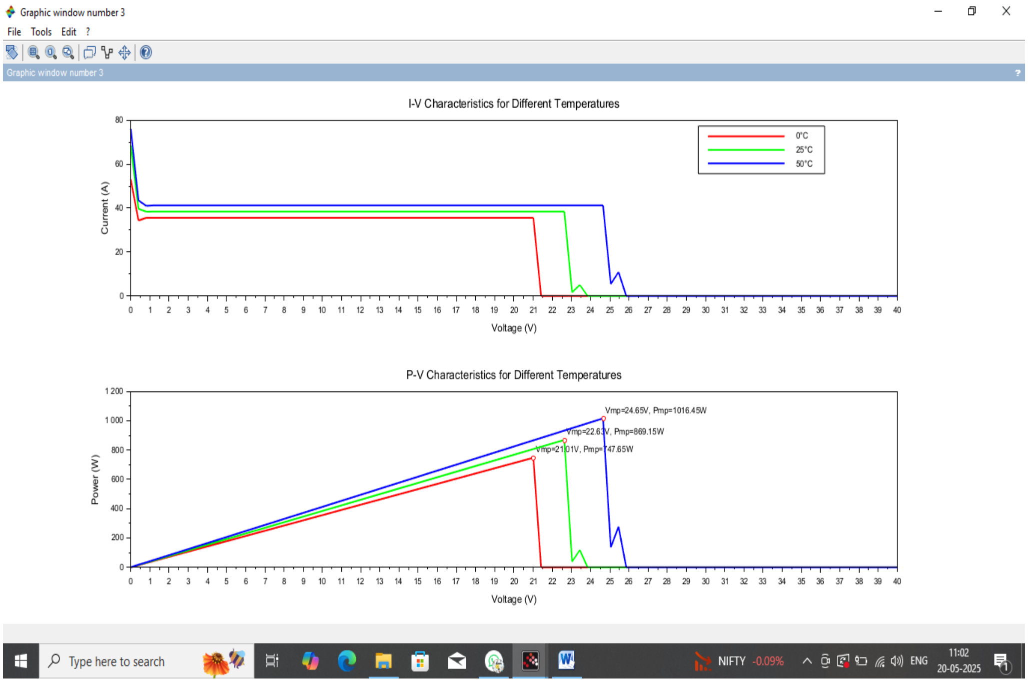
Here are the results through scilab code:

1. For irradiance dependence

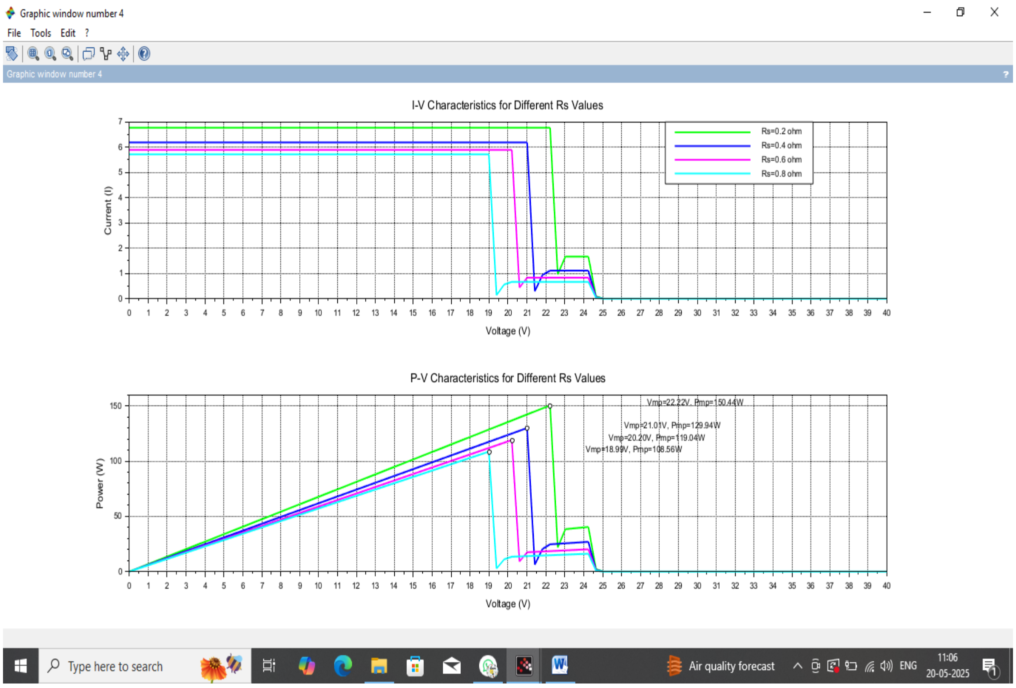




2. For Temperature dependence



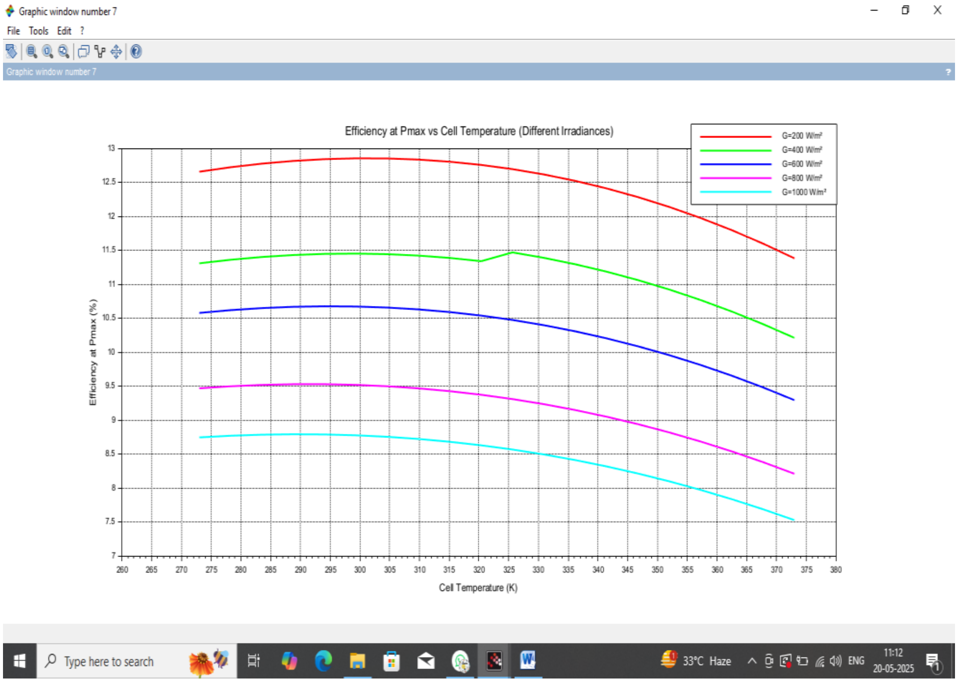
3. For Series Resistance (Rs) dependency:



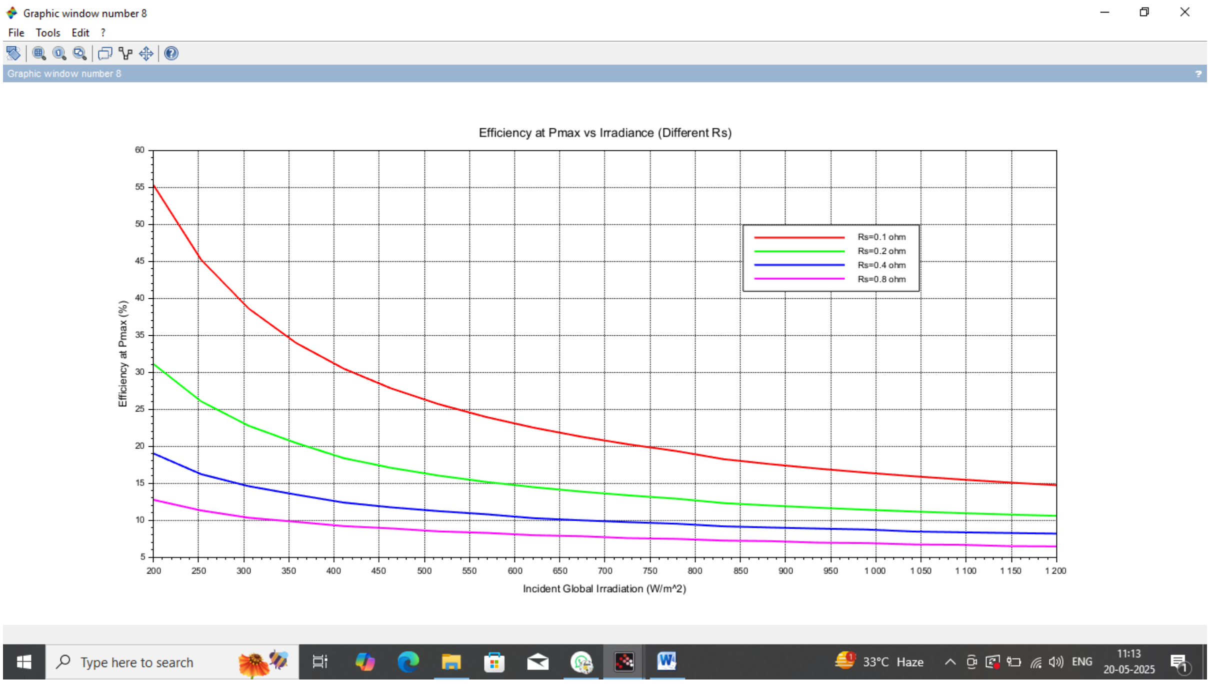
4. Shunt Resistance dependency:

5. Efficiency vs irradiance plot:

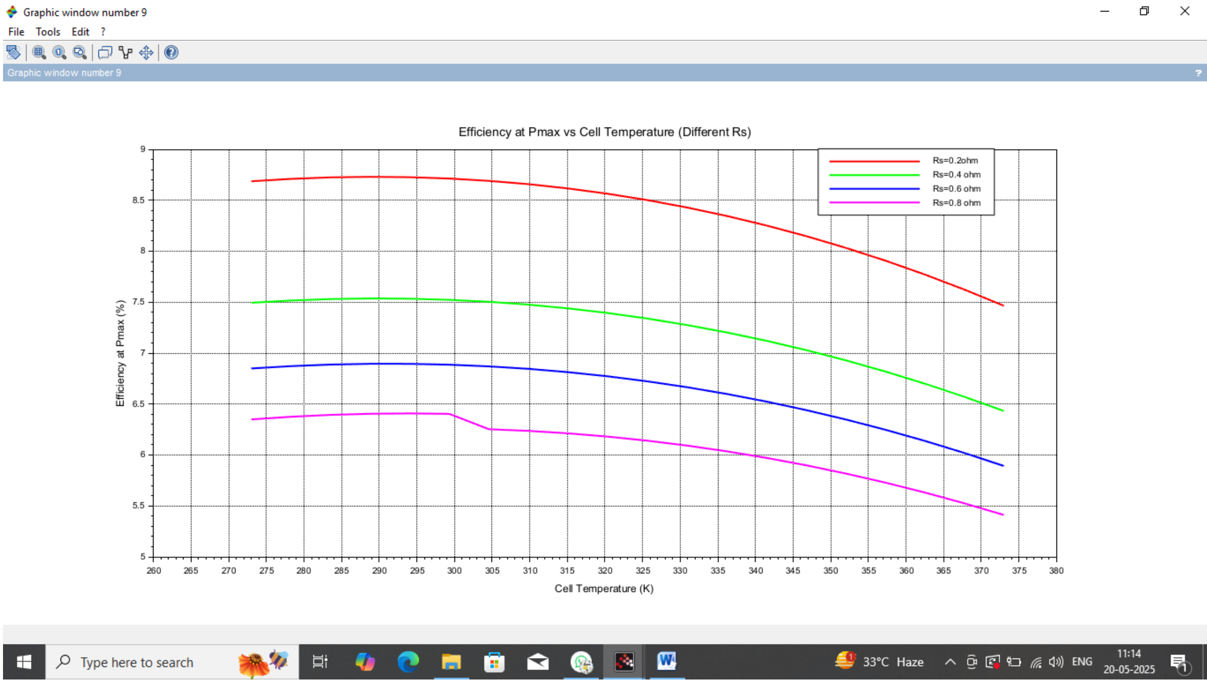
6. Efficiency vs Cell Temperature at different radiance



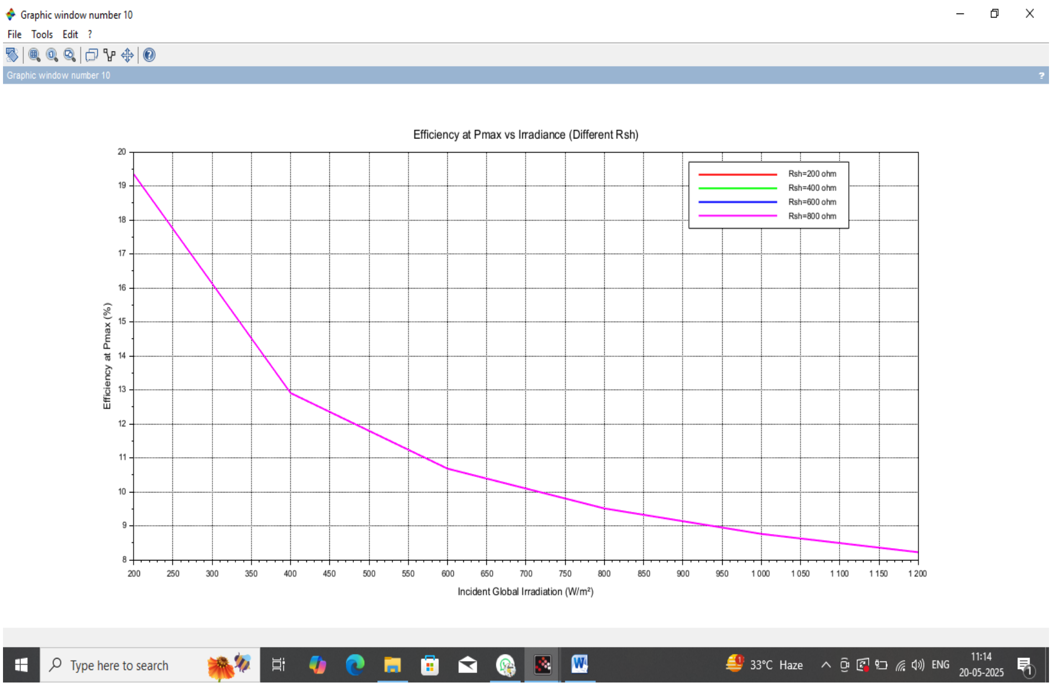
7. - Efficiency vs Irradiance at Different Series Resistances



8. Efficiency vs Cell Temperature at Different Series Resistances



9. Efficiency vs Incident Global at Different Shunt Resistances

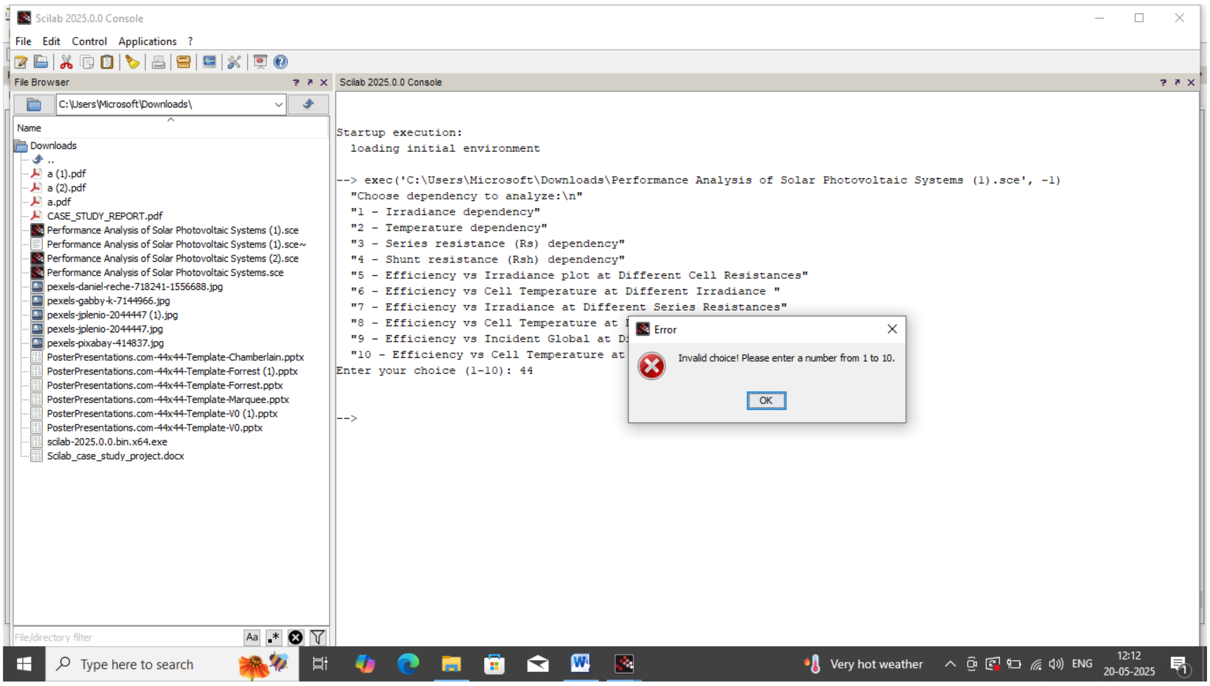


Only one graph is visible because all the graphs are overlapping . Behavior at all the conditions is approximately the same.

10. Efficiency vs Cell Temperature at Different Shunt Resistances

Only one graph is visible because all the graphs are overlapping . Behavior at all the conditions is approximately the same.

If an user enters the number out of the specified range (1-10) , the program will give the prompt to the user to enter the input in the specified range.



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