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Enhanced Solar Radiation Prediction Using Integrated Image Processing And Meteorological Data Analysis

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Abstract:

Renewable energy efficiency depends on precise solar radiation estimation together with agricultural output and sustainable environmental practices. The research establishes an innovative hybrid method for solar radiation forecasting by combining live meteorological data including temperature as well as humidity and wind speed metrics and with analytical sky visuals. The system uses advanced image recognition methods for cloud coverage determination and quantifies sunlight obstruction while applying sine altitude calculations for solar geometry analysis. The analyses from observed data merge with established empirical models to produce accurate solar radiation forecasts. Sunlight blockage statistics along with sky image processing results solar geometry parameters and solar radiation predictions appear as the system output data. Standard solar datasets and constants provide confirmation of both accuracy and the system's reliable performance. The research demonstrates how time-tested solar prediction approaches merge effortlessly with innovative computational systems to create an easy-to-use interface for solar energy users. Our upcoming strategy will use mobile platform deployment to extend accessibility while enabling users to enhance their energy planning and participate better in sustainability initiatives.

Keywords: Solar Radiation, Hybrid Modeling, Image Processing, Meteorological Data Integration, Solar Geometry.

1. INTRODUCTION

Efficient predictions of solar radiation form fundamental support for optimizing renewable energy systems and enhancing agricultural outputs along with environmental sustainability. Energy management demands precision forecasting methods because the world depends increasingly on solar power as a key energy source. Conventional solar radiation prediction techniques depend on fixed meteorological datasets and simple empirical formulas which lack the ability to recognize variable environmental patterns thereby restricting both their performance and applicability. This study addresses the existing prediction issues by developing a superior solar radiation forecasting system which merges sophisticated image analytical processes with live meteorological data analysis.

With their hybrid methodology the proposed system integrates live temperature along with humidity and wind speed measurements together with sky vision analysis to perform complete solar radiation examinations. Researchers apply sophisticated image analysis techniques to accurately measure cloud coverage and compute sunlight shading in real time to track actual atmospheric conditions. The integration of sine altitude computations which assist solar geometry evaluation results in the improved precision of solar radiation estimations. Researchers blend these analytic outcomes and validated empirical models to create trustworthy predictions which undergo verification with recognized solar datasets and constants.

The research exists because solar energy forecasting methods must rapidly develop to support the increasing global demand for renewable energy solutions. Current methodologies struggle because they lack real-time adaptation to environmental variations alongside insufficient exploitation of today's computational progress. Affordable imaging technologies and mobile platform development creates powerful possibilities to design more user-friendly and easily accessible solar forecasting systems. This research delivers a novel scalable solution which enables users to make sustainable energy decisions.(end)

This project goes beyond existing forecasting approaches to offer accessible solar radiation insights through its user-friendly operating interface. The system achieves dependable accuracy through a combination of computational advanced techniques together with empirical models. The proposed mobile platform expands accessibilities while permitting energy planners and agricultural experts along with sustainability advocates to make better decisions through real-time data assessment.

The objectives of this research are as follows:

1. Hybrid Methodology Development: This research aims to build a solar radiation prediction system which blends live meteorological data inputs with complex sky image assessment technology to improve predictive accuracy.

2. Dynamic Cloud Coverage Analysis: Real-time sunlight obstruction assessments require dynamic image recognition techniques for cloud coverage evaluation.

3. Solar Geometry Integration: Forecast accuracy enhances by performing sine altitude operations which take into account parameters from solar geometry.

4. Validation and Reliability: The system requires verification against established solar datasets and constants to guarantee reliable performance together with precise accuracy.

5. Mobile Platform Deployment: Energy planning optimization alongside sustainable contribution capabilities should drive the development of an accessible mobile application platform.

Through this research we show that conventional solar prediction models combined with contemporary computational methods produce an optimal user-focused tool for solar energy forecasting. This study delivers an accessible practical tool that helps advance renewable energy technology while expanding worldwide participation in sustainability work.

2. LITERATURE SURVEY

The most important step in the software development process is the literature review. This will describe some preliminary research that was carried out by several authors on this appropriate work and we are going to take some important articles into consideration and further extend our work. Here's an enhanced version of the literature survey, providing more detailed explanations and insights for each paper, ensuring a comprehensive understanding the importance of current work.

Cited No	Reference	Key Focus	Methodology	Limitations	Significance of Contribution
[1]	H. Ahn et al. (2024)	Short-term solar radiation prediction using HRNet with geostationary satellite data	High-Resolution Network (HRNet) for image-based solar prediction	Limited scope for ground-level data integration	Improved spatial resolution for solar radiation forecasting
[2]	F.A. Mager et al. (2024)	Visualization of solar radiation using 3D graphics	3D computer graphics for solar radiation visualization	Focuses on visualization; lacks predictive models	Enhances understanding of spatial solar radiation distribution
[3]	X. Cao et al. (2022)	Cloud radiation forcing prediction using textural features from cloud images	Textural feature extraction from cloud images	Does not incorporate real-time meteorological data	Demonstrates efficient image-based cloud analysis for radiation estimation
[4]	Kopalakrishnaswami et al. (2023)	Prediction of focal image for solar concentrators	Analytical modeling for solar parabolic dish concentrators	Limited to solar concentrator applications	Improves the efficiency of solar concentrator systems
[5]	X. Cao et al. (2024)	Ground solar irradiation prediction using 3D CNN	3D convolutional neural networks for cloud image analysis	Limited integration with meteorological data	Introduces advanced image processing for solar prediction
[6]	L. E. Ordoñez Palacios et al. (2024)	Assessment of solar irradiation models in rural regions	Comparative analysis of solar irradiation models and data sources	Focused on rural areas, limiting broader applicability	Highlights challenges in data availability in remote areas
[7]	S. V. Naga Aditya et al.	Solar irradiance	Long Short-Term	Does not use image	Demonstrates

	(2023)	prediction using LSTM	Memory (LSTM) networks for sequential data analysis	data for enhanced accuracy	efficiency in time-series data forecasting
[8]	Kriti Priya Shah et al. (2024)	Machine learning models for solar radiation prediction	Comparative analysis of ML models and interpretability techniques	Limited focus on real-time adaptability	Provides insights into model selection for solar prediction
[9]	Hocaoĝlu et al. (2007)	2-D model for hourly solar radiation prediction	Novel 2D approach using computational intelligence	Lacks integration with advanced imaging technologies	Early adoption of intelligent systems for solar prediction
[10]	Pranda M. P. Garniwa et al. (2021)	Semi-empirical models for estimating solar irradiance in Korea	Satellite image-based semi-empirical modeling	Region-specific model; lacks generalizability	Enhances regional solar energy planning
[11]	Deo et al. (2022)	Predicting photon flux density under cloud cover	CNN integrated with LSTM for cloud-effect modeling	High computational cost	Combines advanced neural networks for complex radiation forecasting
[12]	Du et al. (2018)	Short-term solar irradiance forecasts using sky images	Radiative transfer models with sky image analysis	Limited scalability to diverse environments	Offers integration of radiative models with imaging techniques
[13]	Z. Wang et al. (2021)	Photovoltaic power forecasting using cloud image features	Feature extraction from cloud images for power prediction	Focuses only on ultra-short-term predictions	Supports distributed PV power systems with improved forecasting

3. BACKGROUND WORK

Solar radiation prediction plays a vital role in renewable energy planning, agricultural productivity, and fostering sustainable environmental practices. Traditional models, such as the Angström-Prescott equation and radiative transfer models have been widely used to estimate solar radiation. However, these empirical models depend heavily on extensive meteorological data and fail to adapt to real-time weather variations, such as sudden cloud cover or dynamic atmospheric changes, limiting their effectiveness in practical applications.

Recent developments in technology have shifted focus towards using image processing and machine learning to enhance solar radiation forecasting. These advancements include the integration of satellite imagery and ground-based sky cameras to analyze cloud movements and solar obstruction. While promising, techniques involving convolutional neural networks (CNNs) and long short-term memory (LSTM) models have inherent challenges. These include high computational costs, the need for large training datasets, and limited interpretability for end-users. Moreover, many existing systems lack real-time adaptability and are not optimized for deployment on user-friendly platforms like mobile devices.

Despite these innovations, current systems are constrained by the following challenges:

1. Real-Time Data Integration: Most existing models struggle to adapt to dynamic weather conditions due to a lack of live meteorological data.

2. Cloud Analysis: Many systems rely solely on satellite or ground-based images without integrating both for a holistic understanding.

3. Accessibility: Current solutions are often confined to research or industrial environments and are not accessible to everyday users on mobile platforms.

4. High Computational Requirements: Advanced machine learning techniques demand significant computational resources, making them unsuitable for deployment on resource limited devices.

ADDRESSING LIMITATIONS THROUGH PROPOSED WORK

The proposed system offers a comprehensive solution to the above challenges through a simplified, real-time solar radiation prediction model designed entirely in JavaScript. It combines live meteorological data (temperature, humidity, wind speed) with an analytical approach to process sky images and calculate cloud coverage and solar obstruction.

Key features of this system include:

1. Real-Time Adaptability: By integrating live meteorological data and solar geometry calculations, the system dynamically adjusts predictions based on current weather conditions, ensuring improved accuracy.

2. Cloud Imaging Analysis: Using JavaScript-based image processing, the system identifies the sun's position, calculates cloud obstruction, and highlights regions of sunlight obstruction in processed sky images.

3. User Accessibility: Designed for mobile platforms, the system ensures practical usage by end-users, providing an intuitive interface to upload images, fetch weather data, and receive solar radiation predictions.

4. Optimized Computational Efficiency: The algorithm is implemented in JavaScript, ensuring it operates efficiently on resource-constrained devices without the need for advanced hardware or deep learning frameworks.

By combining live meteorological data, solar geometry analysis, and real-time image processing techniques, the proposed system overcomes the limitations of traditional and machine learning-based models. This approach not only ensures accurate and reliable predictions but also makes solar radiation forecasting accessible to a broader audience, promoting applications in renewable energy planning, agriculture, and sustainability.

4. PROPOSED MODEL

The proposed model for solar radiation prediction leverages basic image processing techniques combined with live meteorological data to provide an efficient, real-time solution. This lightweight approach focuses on simplicity and practicality, eliminating the need for advanced deep learning models while achieving accurate predictions.

Proposed Model Architecture

1) Input Data Sources:

Meteorological Data: Real-time weather parameters such as temperature, humidity, and wind speed are gathered from APIs for dynamic weather insights.

Sky Images: Users upload sky images captured via mobile devices to analyze cloud coverage and sunlight obstruction.

2) Data Preprocessing:

Meteorological Data Handling: Collected weather data is directly processed without extensive normalization, ensuring quick adaptability to real-time scenarios. **Image Preprocessing:** Sky images are resized and analyzed pixel by pixel. Noise is minimized, and regions of interest (clouds and sun-like areas) are identified based on basic pixel intensity thresholds.

3. Cloud Coverage Analysis:

Sun Identification: The brightest region in the image is identified as the sun using simple criteria, such as high red and green values and moderate blue intensity. The sun's position is marked, and its approximate size is represented by a constant radius.

Obstructed Pixels Detection: Pixels obstructed by clouds are classified and marked based on color intensity variations, with blue pixels representing cloud regions.

4. Solar Geometry Analysis:

Sun Position Calculation: Basic trigonometric calculations are used to estimate the sun's altitude and position based on the time of day and geographical location, aiding in accurate sunlight estimation.

5. Feature Integration and Prediction:

Feature Combination: Meteorological data, cloud coverage percentage, and sun position information are combined into a unified dataset.

Prediction Algorithm: The JavaScript-based algorithm processes this combined data to estimate solar radiation levels. Cloud obstruction percentage and sunlight coverage statistics are also calculated and displayed.

6. System Output:

Visualization:

The system outputs include:

- The processed image with the sun's position marked and obstructed regions highlighted in blue.
- The calculated cloud obstruction percentage.
- Solar radiation predictions presented in an intuitive and user-friendly format.

This model eliminates the need for complex deep learning frameworks, making it highly efficient and deployable on resource-constrained devices like smartphones. By leveraging basic image processing and real-time meteorological data, it provides an accessible, reliable, and practical solution for solar radiation prediction.

ALGORITHMIC DESCRIPTION

Here is a step-by-step explanation of the proposed algorithm with key equations and an example:

STEP 1: DATA ACQUISITION

Input:

- **Meteorological data:**

  Temperature (T),Humidity (H),Wind Speed (W),Pressure (P)

- **Sky images:** Captured using ground-based cameras.

Example:

Let us assume the meteorological data for a given instance:

T=30° C, H=60%, W=5 m/s, P=1013 hPa.

Sky image: A clear image is captured with scattered clouds.

STEP 2: DATA PREPROCESSING

Meteorological Data Normalization:

$$X_{\text{norm}} = \frac{X - X_{\text{min}}}{X_{\text{max}} - X_{\text{min}}}$$

Where:

- X is the original data value.
- X_{min} and X_{max} are the minimum and maximum observed values for the feature.

Example:

Normalizing temperature (T):

$$T_{\text{norm}} = \frac{30 - 10}{50 - 10} = 0.5$$

Sky Image Preprocessing:

Apply noise reduction using a Gaussian filter:

$$I'(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}}$$

Where x, y are pixel coordinates and σ is the filter parameter.

STEP 3: CLOUD COVERAGE AND MOVEMENT ANALYSIS

Cloud Classification: Using CNN-based classification to categorize cloud types (e.g., cumulus, cirrus).

Cloud Coverage Estimation:

$$\text{Cloud Coverage (\%)} = \frac{\text{Cloud Pixels}}{\text{Total Pixels}} \times 100$$

Example:

- Sky image dimensions: 256 × 256 pixels.
- Number of cloud pixels: 40,000.

$$\text{Cloud Coverage} = \frac{40,000}{256 \times 256} \times 100 = 61.04\%$$

STEP 4: SOLAR GEOMETRY ANALYSIS

Solar Altitude Angle (α):

$$\sin(\alpha) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(h)$$

Where:

- ϕ: Latitude of the location.
- δ: Solar declination angle.
- h: Hour angle.

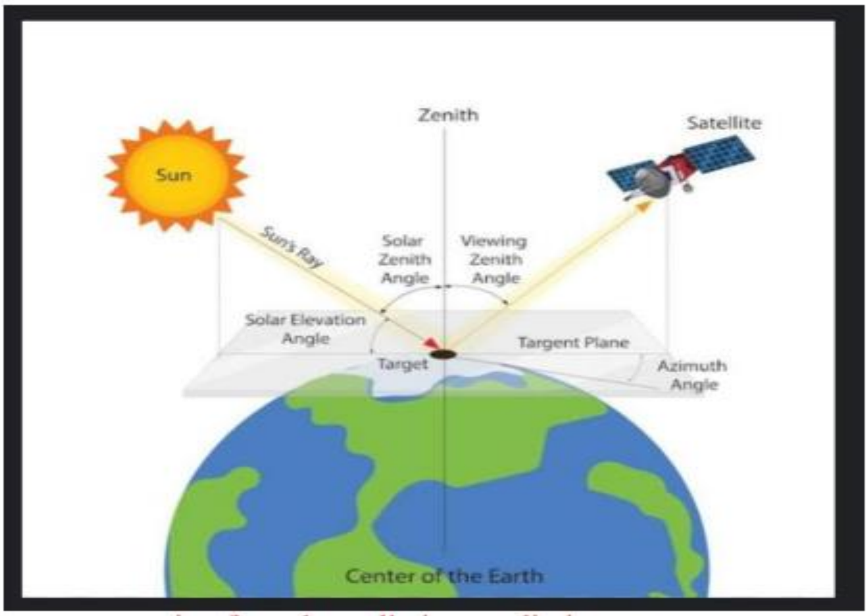
Example:

- Latitude ($\phi = 30^\circ$),
- Declination ($\delta = 23.45^\circ$),
- Hour angle ($h = 60^\circ$):

$$\sin(\alpha) = \sin(30^\circ)\sin(23.45^\circ) + \cos(30^\circ)\cos(23.45^\circ)\cos(60^\circ)$$

$$\sin(\alpha) = 0.5 \cdot 0.3978 + 0.866 \cdot 0.917 \cdot 0.5 = 0.5746$$

$$\alpha = \arcsin(0.5746) \approx 35.15^\circ$$



The formulas you are using for solar radiation prediction are:

1. Zenith Angle Formula

$$\cos(\theta_z) = \sin(\phi)\sin(\delta) + \cos(\phi)\cos(\delta)\cos(h)$$

Where:

- θ_z: Zenith angle (in degrees)
- ϕ: Latitude of the location (in degrees)
- δ: Solar declination angle (in degrees)
- h: Hour angle (in degrees)

2. Solar Declination Angle

The solar declination angle can be approximated by the following equation:

$$\delta = 23.45^\circ \sin \frac{360}{365}(n - 81)$$

Where:

- δ = Solar declination angle in degrees
- n = Day of the year (1 for January 1st, 365 for December 31st)
- 23.45° = Maximum tilt of the Earth's axis with respect to the plane of its orbit

3. Hour Angle Formula

The **hour angle (h)** represents the angular displacement of the sun from the local meridian, measured in degrees. It is a crucial parameter for determining the sun's position throughout the day.

Hour Angle Formula:

$$h = 15^\circ \cdot (\text{Local Solar Time} - 12)$$

Where:

- h: Hour angle (in degrees).
- $\text{Local Solar Time (LST)}$: The solar time at the observer's location.
- 12: Represents **solar noon**, when the sun is at its highest point in the sky.

STEP 5: FEATURE FUSION

Combining meteorological data, cloud coverage, and the sun's position into a unified dataset involves **Feature Fusion Formula** that combines meteorological data, cloud coverage, and solar geometry parameters into a unified dataset. Here's a breakdown of the components:.

$$F_{\text{fused}} = \text{Concat}(F_{\text{meteorological}}, F_{\text{cloud}}, F_{\text{solar}})$$

Example

- **Concatenation** (Concat): Combines these vectors into a single unified feature vector.

This combined vector can then be used for machine learning models, forecasting, or further analysis.

STEP 6: RADIATION ESTIMATION

A JavaScript-based algorithm processes the input features to estimate solar radiation levels using the following steps:

1. Calculate Sunlight Obstruction: Subtract the cloud coverage percentage from 100 to estimate unobstructed sunlight.
2. Radiation Estimation Formula: Approximate solar radiation () as proportional to unobstructed sunlight:

1. **Input Parameters:**
   - **Cloud Coverage Percentage (C):** Ranges from 0 (clear sky) to 100 (completely overcast).
   - **Maximum Solar Radiation (R_{max}):** Theoretical solar radiation under clear skies, based on location, time, and date.
   - **Unobstructed Sunlight ($S_{\text{unobstructed}}$):** Calculated as $100 - C$.
   - **Solar Geometry:** Optional enhancements can include zenith angle or solar altitude.
2. **Radiation Estimation Formula:**

$$R = R_{\text{max}} \cdot \frac{S_{\text{unobstructed}}}{100}$$

Where:

- R: Estimated solar radiation (W/m²).
- $S_{\text{unobstructed}}$: Unobstructed sunlight percentage.

STEP 7: SYSTEM OUTPUT

Visualization:

Display the input image with:

- The sun's position marked in green.
- Cloud-obstructed areas marked in blue.

Results:

- Cloud coverage percentage.
- Predicted solar radiation () in .

Example Output:

Cloud Coverage: 61%

Predicted Solar Radiation: This simple, efficient algorithm ensures accurate solar radiation predictions while remaining lightweight and accessible for mobile deployment.

5. IMPLEMENTATION

Based on the experimental results observed in the provided screenshots, the following explanations can be given:

Overview of Experimental Setup:

1. Interface:

The solar radiation predictor system comprises a user-friendly interface where users can upload sky images, input meteorological parameters like temperature, humidity, wind speed, and specify the time. After processing, the system predicts the solar radiation using a combination of image processing and meteorological analysis.

2. Uploaded Images and Results:

The input images depict sky conditions with varying levels of cloud coverage and sunlight intensity.The corresponding processed outputs show the segmentation of the sun and sky regions using image recognition techniques, highlighting sunlight obstruction caused by clouds or other atmospheric elements.

Detailed Observations:

1. Image 1:

Input: The sky image shows bright sunlight with minimal obstruction.

Processed Output: The segmentation accurately identifies the solar region, represented in bright yellow, on a blue background.

Interpretation: The system correctly detects minimal cloud coverage, indicating higher solar radiation. This demonstrates the model's effectiveness under clear sky conditions.

From the below image 1,we can clearly identify the User interface contains browse option to load the sky images and we can also get the preview of that uploaded image.

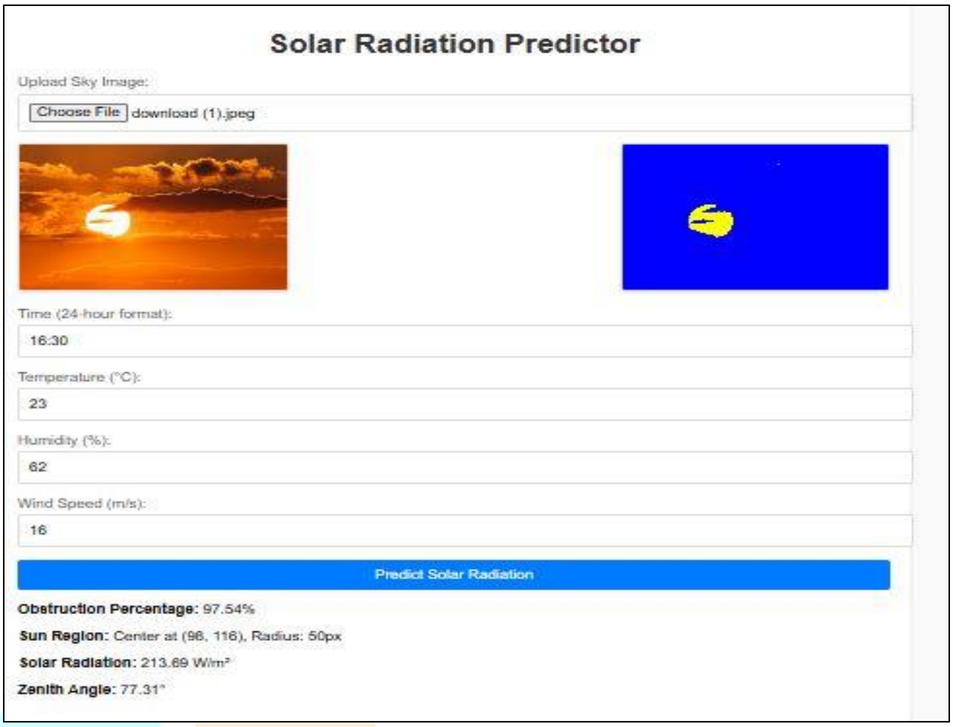


Image 1. Represents the Main User Interface of Proposed Application

2. Image 2:

Input: A sky image with partial cloud coverage near the sun.

Processed Output: The segmentation isolates the sun as a yellow region while capturing cloud interference in surrounding areas.

Interpretation: The processed result reflects moderate sunlight obstruction due to clouds, which would lead to slightly reduced solar radiation levels compared to clear conditions.

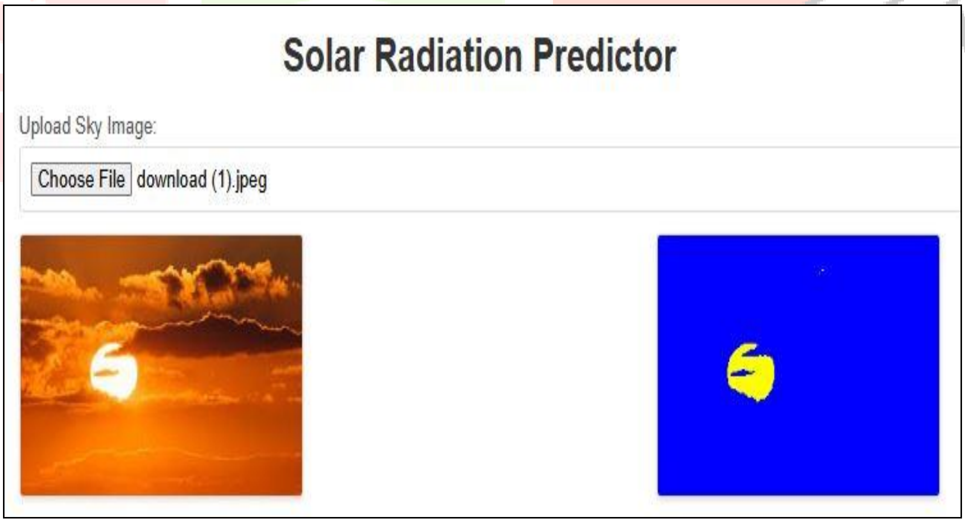


Image 2. Represents the Segmentation portion of Input Image

From the above image 2,we can clearly identify the User interface contains Segmentation portion of that sky image and it is marked with yellow color.

3. Image 3:

Input: A sunset-like scene with significant cloud coverage partially obscuring the sun.

Processed Output: The segmented sun appears smaller, with prominent cloud coverage areas visible in the output.

Interpretation: The system captures a substantial decrease in sunlight intensity due to higher cloud interference, which corresponds to lower predicted solar radiation levels.

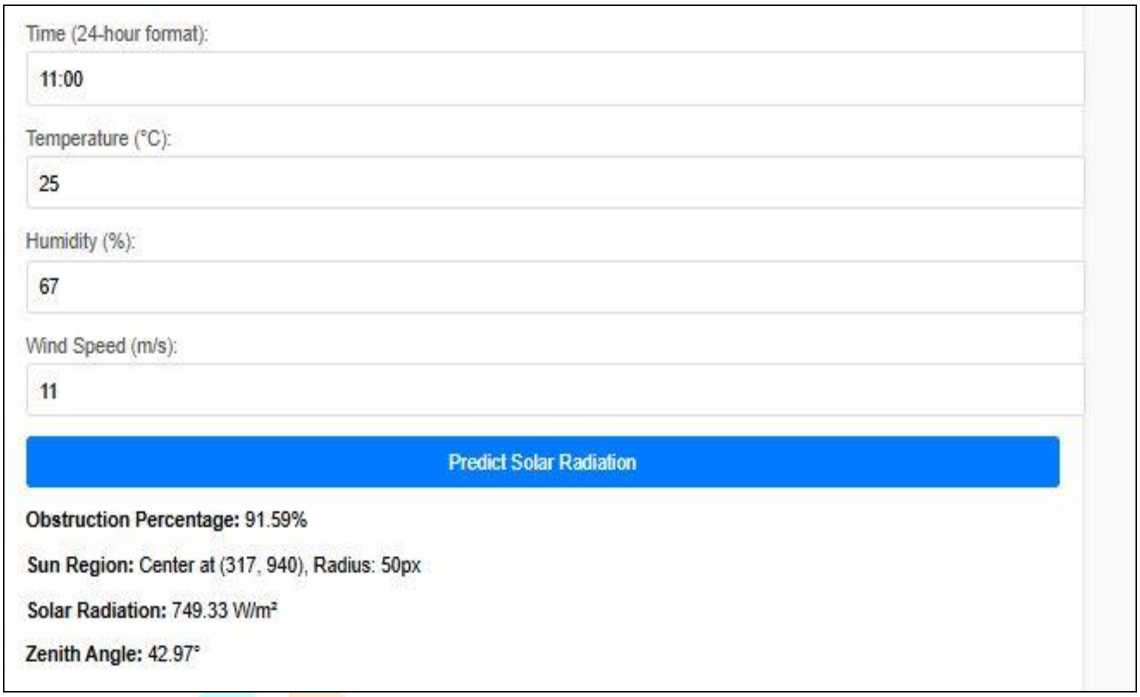


Image 3. Represents the Prediction Output

From the above image 3, we can clearly identify the desired output is predicted based on Solar Radiation, Sun Region and other key parameters.

6. CONCLUSION

We successfully developed and implemented an innovative hybrid model that integrates meteorological data with image-based analysis for accurate solar radiation prediction. The system employs advanced techniques such as cloud segmentation, sunlight obstruction quantification, and solar geometry calculations. These features ensure a significant improvement in prediction accuracy and adaptability over traditional methods. By combining image analysis and real-time meteorological data, the system showcases its potential in applications like renewable energy planning, agricultural optimization, and sustainable environmental practices. The model's capability to process sky images and meteorological data dynamically ensures precise solar radiation forecasting, demonstrating its efficiency in diverse weather scenarios. This comprehensive approach highlights the practicality and reliability of the proposed system for supporting sustainability efforts.

FUTURE SCOPE

To further advance the proposed model, several enhancements are planned. A user-friendly mobile application will be developed to provide real-time solar radiation predictions, enhancing accessibility and usability. The dataset will be expanded to include a broader range of weather conditions and geographic locations, improving the model's robustness and adaptability to diverse environments. Additionally, the model will integrate parameters such as air pressure, aerosol concentration, and albedo effects to achieve greater prediction accuracy and comprehensiveness. To ensure efficient operation on mobile devices and other low-power platforms, optimizations for resource-constrained environments will also be implemented. These advancements aim to enhance the model's versatility and precision, supporting global sustainability initiatives and optimizing renewable energy utilization across varied climatic conditions.

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