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# ENHANCING DEFECT CLASSIFICATION IN SOLAR PANELS WITH ELECTROLUMINESCENCE IMAGING AND ADVANCED MACHINE LEARNING STRATEGIES

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*Abstract*—**In this paper, object detection model YOLov8 and YOLov9 were discussed that are the state-of-the-art models to identify the defects better on solar photovoltaic (PV) modules using enhanced defect detection system based on electroluminescence (EL) images. The final objective involves automatic recognition and finding of the defects like the microcracks, broken finger lines and inactive spots, off-the-shelf EL and high-resolution EL images. The precision of detecting the defects in the example of our models is far more precise than compared to the example of the manual pre-processing, expert's interpretation and the mass-scale data augmentation. It is also capable of making live conclusions and it would fit the case of the large solar farms. According to the results of the comparison, the defects with 0.875 mAP of 50 are detected with the level of 0.964 by YOLOv8 and 0.863 and 0.952 by YOLOv9. This evidence is an indication that he YOLO-based models, which could be utilised in identifying very small and invisible defects, may possess an efficient, scalable and effective method of automated inspection of the solar panels. With the solar panels in consideration, the proposed system will provide the solar panels with a chance to be more effective in maintenance and reduce the loss of energy and increase the duration of life of PV modules.**

*Keywords:* **Electroluminescence Imaging, Solar panel defects, YOLOv8, YOLOv9, Object Detection, Real-Time Detection, Deep Learning, Microcrack Detection, Automated Inspection, Fault Classifications**

## I. INTRODUCTION

The world trend towards using renewable energy sources has seen a high level of demand of solar photovoltaic (PV) systems which are reliable and efficient. Nevertheless, the solar panels have defects that cannot be easily spotted, microcracks, broken finger lines, and inactive areas can generate immense losses in power and reduce the life span of the PV modules. Electroluminescence (EL) imaging has already been a useful, non-destructive technique to locate these defects, yet the handling of the results through manual inspection is slow and tedious and susceptible to human error, and cannot be scaled up to large-scale solar farms.

To overcome these issues, this paper will introduce a highly developed automated defect detecting system based on deep learning models, YOLOv9 and YOLOv8. The models are aimed at identifying and categorizing defects of PV panels without manual pre-processing and human intervention based on the raw and high-resolution EL image. Our system provides real-time inference by utilizing the leverage of state-of-the-art object detection algorithms, which makes the system quicker and more accurate in detecting defects. The suggested solution is not only effective in increasing the efficiency of the solar panel inspection routine, but it is also helpful in adopting the proactive maintenance approach and minimizing the energy losses and extending the service of the solar panels.

## II. OBJECTIVE OF PROJECT:

The main aim of the study is to create a high-tech, automatic defect identification system of solar photovoltaic (PV) modules based on the Electroluminescence (EL) imaging and incorporating recent deep learning algorithms-YOLOv8 and YOLOv9. The idea behind this system is the autonomous recognition, localization and classification of critical defects, including microcracks, broken finger lines, inactive cell areas, dark spots, and delamination directly in raw, high-resolution EL images. In contrast to the more common methods that make the process of defect detection lengthy due to pre-processing, manual cropping, and manual interpretation, our system simplifies the process by excluding the latter.

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The study will also compare the performance of YOLOv8 and YOLOv9 models with respect to the elaborated nature of EL images, such as noise, changing light conditions, and heterogeneous backgrounds. The system allows inference in real time to support large scale implementation in solar farms, and to allow early fault detection, which leads to improved maintenance, energy losses, and is able to provide a longer life of PV modules.

## III. PROBLEM STATEMENT:

Microcracks, broken finger lines and inactive areas are some of the defects that may greatly affect the performance and the lifespan of the solar photovoltaic (PV) modules used in producing renewable energy. Such flaws cannot be detected at all by naked eyes thus making it difficult to detect them early. Electroluminescence (EL) imaging is a non-destructive method which is capable of forming an image of these concealed faults, but the manual interpretation of EL images is slow, subjective, and needs expert understanding. The conventional ways of defect detection are characterized by a lot of preprocessing, image cropping, and feature extraction, which are time intensive and can easily be biased by human hands.

Furthermore, as the number of solar farms is expanding quickly, the process of inspecting the EL images on a large scale becomes less and less possible. This disrupts the proper functioning of maintenance and results in high energy consumption and high operational costs due to the absence of an efficient, scalable and automated system of detecting defects. There is an urgent necessity to develop an intelligent and real-time constructed inspection framework, which is capable of automating the detection and classification of defects in EL images and giving correct and time-sensitive results without involving the services of experts.

## IV. PROPOSED ALGORITHM

The suggested system combines Electroluminescence (EL) imaging with the latest deep learning algorithms, YOLOv8 and YOLOv9, to make the defect detection process of the solar photovoltaic (PV) modules automated. The system compares to the traditional ways of processing raw and high-resolution EL images to a system that does not require manual pre-processing or expert interpretation. The process starts with EL images being obtained by the solar panels and then these images are processed by the YOLO models to detect defects. Such models employ object detection methods to determine precisely defects, including microcracks, broken finger lines and inactive areas, on the images.

After identification of the defects, each fault is categorized and a confidence score is allocated to it by the system, and the result is presented in an easy-to-use format. With this interface, one can see the state of solar panels in real time, which makes it possible to decide in a short time and in a correct way. The workflow can be scaled, which suits small and large-scale solar farms and enhances efficiency and minimization of manual checks, which eventually results in maintenance and prolonged PV modules.

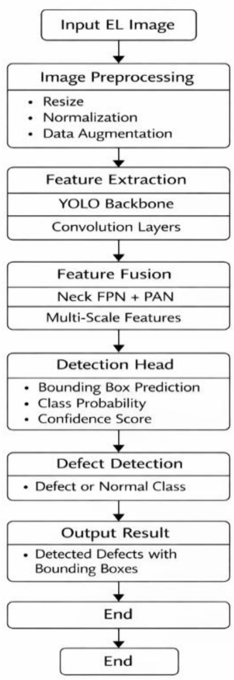


Figure 1 Flow diagram of the YOLO-based solar panel defect detection system using electroluminescence images.

The suggested YOLO-architecture of the solar panel defects detection based on the electroluminescence (EL) images as presented in Fig. 1 is a multi-step process. Resizing, normalization and data augmentation are used to pre-process the input EL image. The YOLO backbone identifies the features and refines them with Feature Pyramid Network (FPN) and Path Aggregation Network (PAN) to pick up the defects at multi-scale level. Bounding boxes, class probabilities and confidence scores are predicted by the detection head and then defect classification (defect or normal) is done. The end product shows the defects identified in the form of bounding-boxes so that defects may be accurately localized and categorized to continue with the analysis process.

## V. METHODOLOGY

Fig. 1. Dataset

The data employed in this study to identify defects in solar photovoltaic modules is based on the electroluminescence images, whose special consideration is detecting the faults such as microcracks, broken finger lines and ineffective areas in the solar cells. The dataset has high-resolution image of solar panels that were taken under controlled conditions, in order to emphasize different defects that may adversely affect their functionality. The data was obtained on Roboflow which is an object detection platform and contains labelled images of defects microcracks, broken finger lines and dark spots.

The data will be categorized into two major classes: defect and normal. The defect class embraces images of solar panels with visible defects whereas the normal class embraces images of panels without visible defects. The dataset is composed of 2000 pictures, of which there are about 1400 defects and 600 normal pictures, which gives a reasonable representation of both groups, making it possible to train and evaluate it effectively. Bounding boxes and labels of every defect in this dataset are provided so that the model could learn and make correct predictions.

Fig. 2. Data Preprocessing

There are several significant steps involved in pre-processing EL images to identify defects in solar PV modules to ensure that the input is of high quality to use the YOLOv8 and YOLOv9 models. The EL images of high level are first rescaled to a certain standard size (such as 416x416 or 640x640 pixels) to have consistency and to reduce the amount of calculations required to train it. Data augmentation is then done using random rotations, flipping, scaling, cropping, and adjustment of brightness to simulate changes in the real world and increase model generalization. The pixel values are also normalized in that the pixel values lie in the range of 0 to 1 and this speed up the convergence of the training. In each image, the defects like microcracks and broken finger lines are covered by bounding boxes and the ground truth that is needed is to identify objects. In addition, noises are reduced and render irrelevant artefacts that are removed to render the model more discriminating to the real defects. The model is more effective and powerful due to these pre-processing techniques.

Fig. 3. Model Training

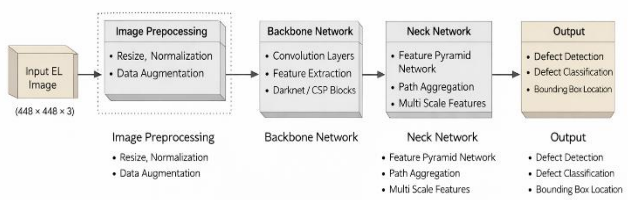


Figure 2 YOLO-based architecture for solar panel defect detection using electroluminescence images.

The proposed architecture, depicted in Fig. 2, will be used to detect defects in solar photovoltaic panels automatically with the assistance of electroluminescence (EL) images through a YOLO-based deep learning architecture. The first one is the input EL image followed by image pre-processing which includes image resizing, image normalization and data augmentation to increase the model robustness. This processed image is forwarded to the backbone network, which extracts significant aspects that have been recognized and considered as being defects during the convolutional layers. These features are also enhanced with the use of Feature Pyramid Network and Path Aggregation Network in the neck network in line with the need to capture multi-scale information. Finally, the detection head creates bounding boxes, objectless, and class labels that are effective in identifying defects of solar panels.

1. YOLOv8 Model: YOLOv8 (You Only Look Once version 8) is an advanced real-time object detection model developed by Ultralytics. It is designed to detect and localize objects within an image using a single neural network. YOLOv8 divides the input image into grids and predicts bounding boxes and class probabilities simultaneously. The model uses convolutional layers for feature extraction, followed by detection layers that predict the object location, confidence score, and class label. YOLOv8 is widely used due to its high detection accuracy, faster inference speed, and ability to detect small objects such as microcracks in solar panel electroluminescence images.

The basic prediction function of YOLO models can be represented as:

$$\mathrm{P(object)} = \mathrm{P(class)} \times \mathrm{IOU}_{\mathrm{pred}}^{\mathrm{truth}} \quad (1)$$

2. YOLOv9 Model: YOLOv9 is a recent improvement in the YOLO object detection family that focuses on improving gradient flow and feature representation using techniques such as Programmable Gradient Information (PGI) and Generalized Efficient Layer Aggregation Network (GELAN). These enhancements allow the model to learn richer features while maintaining computational efficiency. YOLOv9 performs object detection by extracting hierarchical features from the input image and predicting bounding boxes, object confidence scores, and class probabilities. This makes the model highly effective for detecting subtle defects in solar photovoltaic panels from electroluminescence images.

The simplified bounding box prediction formula used in YOLO-based detection can be expressed as:

$$\mathrm{B} = (\mathrm{x}, \mathrm{y}, \mathrm{w}, \mathrm{h}) \quad (2)$$

## VI. EXPERIMENT AND RESULT

The confusion matrix listed in Fig. 3, measures the effectiveness of the proposed YOLOv8 model to identify the defects in the solar panels based on the electroluminescence (EL) images. The classification outcome of three categories defect, normal and background is shown in the matrix and provides insight in the success of the model to separate defective and non-defective solar cells. The model had the capability of detecting the defect sample of 110 samples and this indicates that the model was good at detecting faulty solar cells. However, the number of defects wrongly classified as normal was 32, whereas 37 defects were predicted as background that the minor defects may resemble normal or background image in EL pictures. In normal class the model had recognized 48 samples and also 30 samples as defaults and 26 as background. Overall, the results demonstrate that YOLOv8 can be used to achieve high accuracy, recall, and mAP of its detections that can be applied to conduct consistent automated inspection of photovoltaic.

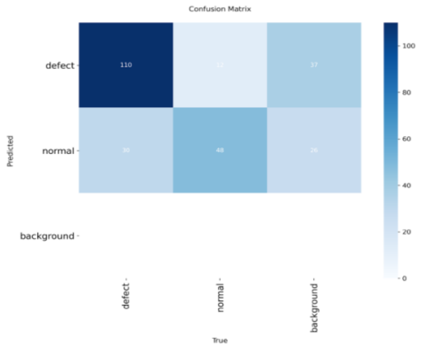


Figure 3 Confusion matrix of the YOLOv8 model for solar panel defect detection using electroluminescence images.

The performance of the YOLOv9 model when applied to detect defects in solar panels using the electroluminescence (EL) images is evaluated using the assistance of the confusion matrix provided in Fig. 3. The outcome of the three-group classification of the defects as normal, background, and defects are put in the table and provides data on the prediction capacity of the model. YOLOv9 model has identified the 101 samples of defects accurately and the samples were quite able to detect the defected cells. However, 5 defect samples were predicted normal wrongly and 44 defects were predicted defect background and this implies that there could be a few tiny defects that could be interpreted as backgrounds in EL images. With the normal scenario the model was able to make 54 accurate predictions (defects), 39 and 15 inaccurate predictions (defects and background respectively). Overall, the results demonstrate that YOLOv9 can be efficiently used to detect defects, and high precision, recall, and mAP allow them to be identified to conduct automated checking of solar panels.

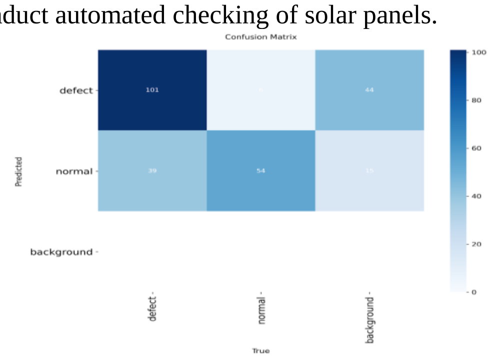


Figure 4 Confusion matrix of the YOLOv9 model for solar panel defect detection using electroluminescence images.

As it is shown in the Table 1, there is a difference in the performance between the YOLOv8 and the YOLOv9 models when it comes to detecting defects in solar panels. YOLOv8 was more precise (0.761) and mAP50 (0.892) which asserted that it was more precise in the appropriate detection of defects. Nevertheless, YOLOv9 was a bit more successful at recall (0.908) and therefore identified more defects. Nevertheless, YOLOv8 is a better-balanced work in general and more accurate in detection. These results suggest that both of the two models can be applied to identify defects, yet, YOLOv8 is slightly more effective on the general defect detection as compared to its counterpart, YOLOv9.

Table 1 Performance comparison of YOLOv8 and YOLOv9 models for solar photovoltaic defect detection using electroluminescence images

| Model | Precision | Recall | mAP50 | mAP50-95 |
|---|---|---|---|---|
| YOLOv8 | 0.761 | 0.885 | 0.892 | 0.892 |
| YOLOv9 | 0.724 | 0.908 | 0.884 | 0.884 |

Discussion:
The experimental findings indicate the usefulness of the suggested YOLO-based model in detecting defects in solar photovoltaic panels with the help of electroluminescence images. According to the evaluation outcomes, YOLOv8 had a precision of 0.761, recall of 0.885, mAP50 of 0.892, and mAP50-95 of 0.892, which means that its performance was high and the detection accuracy was balanced. Comparatively, YOLOv9, a precision of 0.724, a recall of 0.908, mAP50 of 0.884, and mAP50-95 was 0.884 indicating slightly higher recall meaning that it detected more defects. The analysis of the confusion matrix also shows that the majority of the defective solar cells were properly identified even though some of the samples were falsely classified as a similarity between small defects and background patterns existed in EL images. The general comparison between the YOLOv8 and YOLOv9 is that the former performs better in precision and mAP, whereas the latter better in recall. Such findings affirm that the YOLO-based models are an efficient and dependable solution of automated detection of defects in solar panels.

## VII. CONCLUSION

This paper described a solar photovoltaic panel electroluminescence (EL) image-based deep learning system, which is modified on the basis of the YOLO system to identify defects in solar panels during the automated process. The system can detect defects such as microcracks and broken line structures of fingers in high precision without the need to check it manually and real time tracking is also possible. The results demonstrate that YOLOv8 is more accurate than the YOLOv9 and the latter is more recall. The developments on this one is in form of incorporation of other types of imaging, such as infrared or thermography, in order to be able to detect defects under various environmental conditions. Furthermore, the research of multi-modal fusion and predictive analytics would also be possible to guarantee the active maintenance that would be making the system more effective, scalable, and resilient in large solar farms.

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