A Systematic Review of Cracks and Patterns, and the Implementation of Artificial Intelligence in Photovoltaic Cells

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Abstract: Energy is a vital world need, currently several alternative energies have been developed, for example the development of renewable energy sourced from biomass. The analysis carried out in this paper concentrates on research that has developed on cracks, the influence of the gap energy produced due to the presence of these cracks, as well as the methods applied and the application of artificial intelligence to detect and overcome crack problems so far. The research questions in this paper include aspects of what types of cracks and crack patterns are in solar cells, what are the impacts if there are cracks in solar cells, and methods or implementation of Artificial Intelligence in detecting types of cracks and crack patterns. The method used is PRISMA. The review results show that the types of solar cell cracks and crack patterns in solar cells are categorized from various perspectives, namely linear, patchy, and linear and porphyritic. Another pattern is to take into account the number of cracks that occur, namely if more than 20% it is called a major crack and if it is less than 20 it is called a microcrack (vertical or horizontal). The overall impact of this crack is a decrease in energy gain from the solar cell. The methods applied to detect and classify solar cell cracks are Percolation Based Image Processing and Serre Standard Model, Halcon Based Solar Panel Crack Detection, Bluetooth, Image stitching technique, Convolutional Neural Network, YOLO, Multi-Scale Pyramid and Boost.

Keywords: Systematic Review, Cracks, Artificial Intelligence, Photovoltaic Cells, Solar Cells

1 Introduction

Energy is a basic world need, while energy sourced from fossil energy is decreasing [1]. Apart from that, excessive use of fossil energy will have an impact on the environment. Currently, several alternative energies have been developed, for example the development of renewable energy sourced from biomass [2], solar cells, wind, geothermal, hydro [3] and others. The use of renewable energy will have a very positive impact on the world and the preservation of our nature [4]. One of the efforts carried out and becoming an important issue is how to carry out reviews and efficiency in energy use, both on a small scale [5] and on a large scale. This efficiency is carried out by implementing technology that is currently highly developed, one of which is IoT [6].

Solar cells are an energy alternative that is reliable and has a long lifespan, of course they also have drawbacks and challenges. Research on solar cells is also now very developed [7]. The advantage of using solar cells is that the amount of sunlight is very abundant and very environmentally friendly [8]. The challenge of using solar cells is how to increase the efficiency of the solar cells so that maximum energy is obtained [9], besides that, another challenge is how to store the energy that has been obtained [10] so that it can be used wisely at the right time.

Research on solar cells has been widely developed to increase efficiency, including research on the materials used, and several parameter choices that are important in their implementation. The performance of this solar cell is influenced by several factors, including the environment around the solar cell (for example temperature and irradiation) and also the condition of the solar cell itself, for example the material [11], Maximum Power Point Tracking (MPPT) techniques and the DC-DC converters are used in converting [12]. However, there are several things that influence the energy obtained from solar cells, namely the surface condition of the solar cell. The energy results obtained are less than optimal if there are cracks on the surface. This crack can be caused by pressure on the surface of the solar cell or a certain temperature so that the surface of the solar cell becomes cracked [13].

The motivation for this in-depth review is to elaborate on all previous research findings on photovoltaic crack detection using Artificial Intelligence. This paper is expected to assist in determining the most appropriate method for determining next steps when a crack is detected.

The analysis carried out in this paper concentrates on research that develops cracks, the influence of the gap energy produced due to the presence of these cracks, as well as the methods applied and the implementation of artificial intelligence to detect and overcome crack problems so far. The research question in this paper covers the following aspects:

- What are the types of cracks and crack patterns in solar cells?

- What is the impact if there is a crack in the solar cell?

- Method or implementation of Artificial Intelligence in detecting crack types and crack patterns?

The contribution of this systematic review is to provide in-depth analytical information on cracks and their patterns in photovoltaics, as well as the application of Artificial Intelligence in detecting cracks in photovoltaics. Researchers can investigate and develop appropriate methods to improve energy efficiency. This in-depth analysis can also serve as a fundamental basis for determining appropriate and strategic next steps when photovoltaics have cracked.

This paper gives an overview on review of cracks, patterns, energy gaps, and implementation of artificial intelligence in photovoltaic cells. The structure of this paper consists of: part 1 which is the introduction of this paper; part 2 discusses material about cracks, gab energy, artificial intelligence in solar cells; section 3 explains the review method used in this paper; section 4 explains the detailed results and discussion to answer the research questions that have been set previously; and section 5 provides conclusions.

2 Literature Review

2.1 Solar Cell

Humans have been harnessing solar energy in their daily lives since 700 BC. The increasing development of solar energy utilization methods is evidenced by the fact that light could increase electric current when two metals were immersed in a conductive solution in the 18th century [14]. This discovery is a milestone in the discovery of renewable energy which is now widely used by humans. This technology is widely used in both large and household settings, in cities and villages. Its use spans various sectors of life. In agriculture, solar energy has been used to make farming more affordable for small-holder farmers [15], to power multipurpose agricultural robots [16], and to implement digitized, smart solar-powered agriculture systems [17]. Beyond agriculture, it is also widely applied in industry and other sectors [18].

The three main solar panel materials currently used are monocrystalline, polycrystalline, and thin film solar panels. Polycrystalline solar panels are known to have the advantage of being environmentally friendly, and their production costs are lower compared to monocrystalline and thin film solar panels. The disadvantage of using this material compared to other solar panels is that the cell efficiency is around 12% to 14%. Another weakness is that the usage period is shorter than other materials, where monocrystalline panel materials are estimated to be used for around 20 to 25 years. The technology for developing solar cell materials is currently very developed, for example the development of polyethylene glycol material by polydopamine and nano-copper particles [19], the development of high-temperature solar selective absorbers [20], and also the development of storage technology [21].

2.2 Crack

Cell efficiency and panel lifetime are determined by the percentage of active zones in the PV panel. One of the reasons that cause inactive zones is due to discontinuities or cracks that develop in the silicon over time due to thermal expansion and contraction. Some damaged zones are caused during the production process, due to the soldering process. Silicon which acts as a semiconductor in PV cells experiences a photoelectric effect and produces a DC current. The efficiency of the cell depends on the main ingredient, Silicon. Therefore, in this paper, we have discussed the behavior of discontinuities, i.e., cracks, that reduce cell efficiency in polycrystalline solar panels and investigated it with a numerical model considering the microstructure (grains), using peridynamics [22].

3 Method

Several methods can be applied when conducting deep analysis. One of them is the psychological approach, known as Cognitive Psychology (CP) [23], and another is PRISMA. This review analysis used the PRISMA method, which began with creating questions, identifying relevant references, evaluating the quality of articles, collecting evidence, and reporting findings. The five-step systematic review procedure followed the framework proposed by Khan et al. [24], the review reporting also followed the PRISMA 2020 statement [25], and the scoping review evaluating the uptake and impact of the PRISMA statement was used as an additional reference [26]. The first research question used Boolean expression keywords ("crack" OR "defect" OR "cracks") OR ("solar cell" OR "Photovoltaic Cells"). The keywords for the second research question were ("crack" OR "defect" OR "cracks") OR ("solar cell" OR "Photovoltaic Cells") OR ("impact" OR "effect" OR "influence"). While for the third research question was ("crack" OR "defect" OR "cracks") OR ("solar cell" OR "Photovoltaic Cells") OR ("method" OR "techniques") OR ("classification" OR "detection" OR "inspection").

There were 127 articles reviewed using the main search keywords, consisting of 24 papers for the first research question, 40 papers for the second research question, and 83 papers for the third research question. The second round of screening was carried out by looking for papers or references that had high quality. In the second screening, 12 papers were obtained for the first research question, 12 papers for the second research question, and 44 papers for the third research question. The third screening was carried out manually by selecting papers that really focused on answering the research question so that 5 papers were obtained for the first research question, 4 papers for the second research question, and 11 papers for the third research question. The PRISMA flow diagram is depicted in Figure 1.

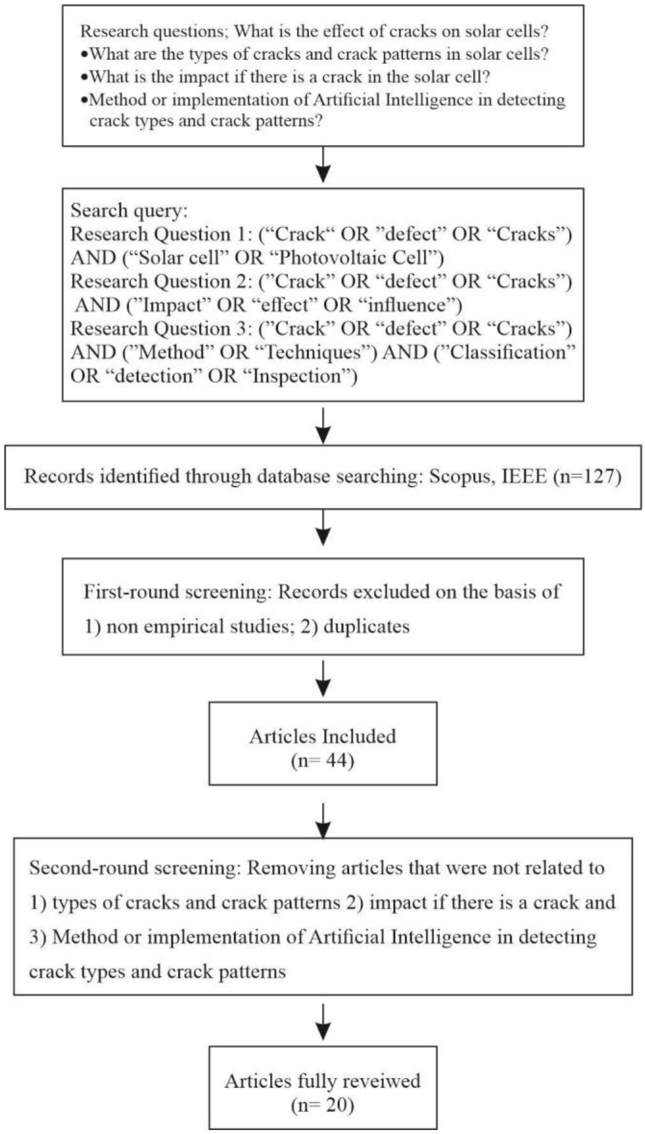

Figure 1
Prisma Flow Diagram

4 Results and Discussion

This section answers the questions of this systematic review, where section 4.1 answers the first systematic review question (the types of cracks and crack patterns in solar cells), section 4.2 answers the second systematic review question (the impact if there is a crack in the solar cell) while section 4.3 answers the third systematic review question (method or implementation of Artificial Intelligence in detecting crack types and crack patterns).

4.1 Cracks and fracture patterns in solar cells

Research [24] categorizes cracks into three types, namely linear, patchy, and linear and porphyritic which are depicted in Figure 2. While research by Srinivas [25] categorizes them into cracks and no cracks, this research attempts to classify solar cell images by involving 2000 images. Microcracks [26] are classified as major which is defined if the crack occurs more than 20% of the solar cell surface, and microcracks' are based on their orientation (vertical and horizontal). vertical µcracks are crucial, as well as dendritic ones and multiple orientations. About 6% of modules can have cracks after transportation.

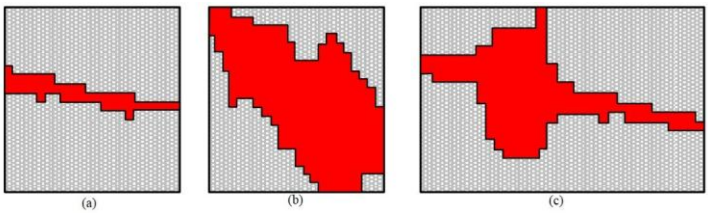

Figure 2
Crack types in solar cells (a) linier, (b) patchy, (c) linear and porphyritic

R. Del Prado Santamaria et al. [27] categorizes cracking of silicon solar cells into several categories, namely Mono-Si mini-module 1st stage of degradation 100%, Mono-Si mini-module 2nd stage of degradation 100%, Multi-Si mini-module 1st stage of degradation 100%, and Multi-Si mini-module 2nd stage of degradation 100%. This rift is depicted in Figure 3.

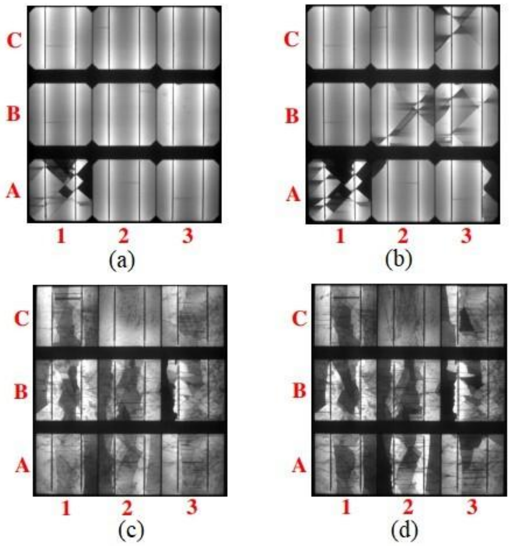

Figure 3

(a) Mono-Si mini-module 1st stage of degradation 100% (b) Mono-Si mini-module 2nd stage of degradation 100% (c) Multi-Si mini-module 1st stage of degradation 100% (d) Multi- Si mini-module 2nd stage of degradation 100% [27]

Research [28] categorizes the condition of solar cells into several categories, namely healthy modules, one hotspot modules, two hotspot modules, more than two hotspot modules, and micro crack modules. Each condition has its own value.

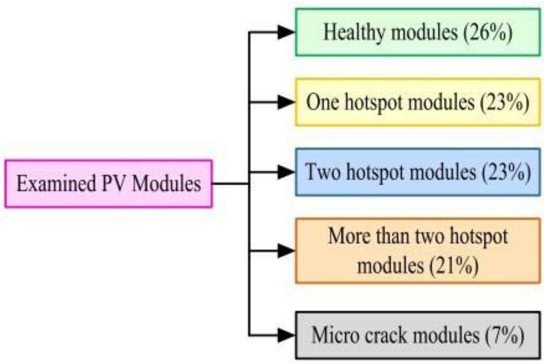

Figure 4
Method for checking solar cells [28]

The results of this first step show that rear-side solar array cables with small cracks, separated by a gap of 1 mm, can cause damaging arcs under electrical conditions and realistic environment. There is no noticeable difference between the cables tested because the PSA occurs at the same value [29].

The research results show that cell cracks are mainly caused by a reduction in the cell's maximum power point current, and this will cause power loss. Analysis of the dark I-V curve also explains the evolution of diode parameters in the cell at the cracked section (increased degradation rate) [30]. Experimental results in detecting five categories of damaged and undamaged panels using a neural network and SVM showe very satisfactory results. An average accuracy of 87% was achieved for the feed-forward backpropagation neural network and 99% accuracy when implementing the SVM [31].

4.2 The impact that occurs if there is a crack in the solar cell

The results of this first step show that rear-side solar array cables with small cracks, separated by a gap of 1 mm, can cause damaging arcs under electrical conditions and realistic environment. There is no noticeable difference between the cables tested because the PSA occurs at the same value [29].

Research discussing the impacts of cracks also considers various perspectives, but the general outline of all cases of cracks in solar cells results in energy being obtained [32]. Based on the results of the review and various expert opinions, even though the solar cell has cracks or bumps or scratches, this solar cell can still produce most of the voltage. The output power of the solar cell produced depends on how many cells are damaged or cracked, and this energy will affect 10-20% of the damaged cells.

Cracks in solar cells may cause little problem in new solar panels, but once they open, they can lead to thermal cycling and cyclic loading. These hidden cracks often cause numerous lattice line disruptions [33]. Another impact of cracking is that open cracks in heterojunctions for depths ranging from 0 to 5 µm cause a linear decrease in the short-circuit current. This also causes a significant decrease in the open-circuit voltage found between depths of 0 and 0.25 µm. The efficiency decreases from 19.97% to 12.94%, at a crack depth of approximately 5 µm [34].

It was also revealed that the effect of mechanical damage on some CdTe photovoltaic panels showed that insignificant mechanical damage (slight cracks in the initial condition), such as cracks, does not significantly affect the panel's efficiency level. However, this becomes a problem when the cracks become more open and moisture penetrates the panel [35].

As long as the solar cell is still in good condition, the solar cell can usually still be used in the panel. It is necessary to measure the voltage of all parts of the solar cell that are exposed to full sunlight. Of course, the output power produced depends on the percentage of the solar cell area that has been cut off.

4.3 Method/Implementation of Artificial Intelligence in detecting crack types and crack patterns

Method/Implementation of Artificial Intelligence in detecting crack types and crack patterns. Based on the methods used, most studies use image processing and artificial intelligence, both machine learning and deep learning.

The methods that have been applied to detect and classify solar cell cracks from the reviewed papers are Percolation-Based Image Processing and Serre Standard Model, Halcon-Based Solar Panel Crack Detection, Bluetooth, Images stitching technique, Convolutional Neural Network, YOLO, Multi-Scale Pyramid and Improved Region Growing, and Machine Learning to Electroluminescence Images.

Algorithm of Percolation-Based Image Processing and Serre Standard Model is explained in Figure 5. Image denoising is performed through percolation-based image processing, followed by feature matching. The resulting feature vectors are classified using SVM.

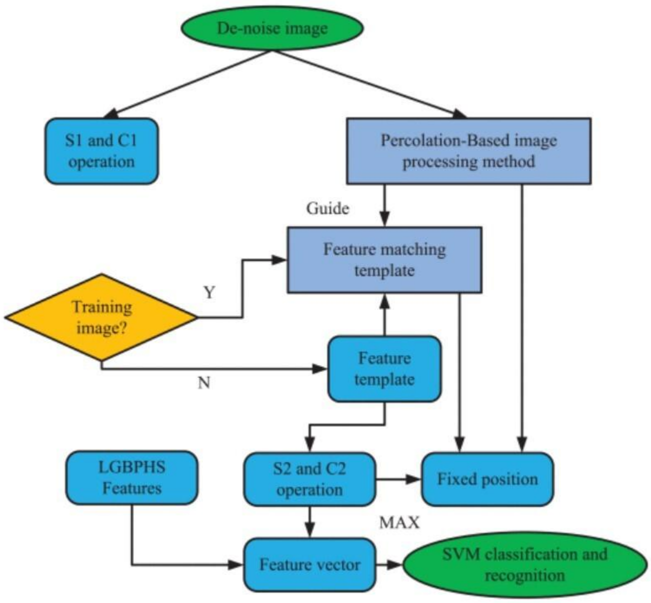

Figure 5
Algorithm of Percolation-Based Image Processing and Serre Standard [27]

In general, the entire process of detection, classification, and inspection obtained results with satisfactory accuracy. However, the findings of detection, classification, and inspection must be followed up so that the power produced is maximized. If cracked or damaged parts are known, an analysis of the disconnected solar cell parts can be carried out.

Solar panel crack detector based on deep learning algorithm and implementing Halcon method shows effective results in detecting cracked solar panels, thus reducing the product defect rate at the final stage and improving the quality of solar cell production results at the final stage of production [36].The follow-up is that repairs must be made to these parts. Several methods can be used to effectively classify and detect cracks using neural network-based pattern recognition [37]. If large data sizes are difficult to achieve, **dimensionality reduction can be achieved using unsupervised learning** [38].

The reviewed papers and applications of Percolation-Based Image Processing and Serre Standard Model, Halcon-Based Solar Panel Crack Detection, Bluetooth [39], Images stitching technique [40], Convolutional Neural Network [41], YOLO [42], Multi-Scale Pyramid and Improved Region Growing, and Machine Learning to Electroluminescence Images methods do not explain that these excellent results are caused by overfitting during the learning process. So all applications of these methods have used the right and appropriate parameters for each method.

The use of Convolutional Neural Network provides excellent results in detecting and classifying cracks. This method of freedom is also a case of traffic sign classification in Germany, where the experimental results show very satisfactory results, failure only in images that have very low quality [43]. Some recommendations in classifying solar cell cracks can also use K-Means where this method has successfully accelerated the learning process by reducing the number of iterations [44]. In addition, it can also be combined with an XOR-based detector which is used to optimize the number of opposing decisions from the FNN and wk-NN models and is able to work in parallel [45].

5. Conclusions

This review aims to examine papers relating to the types of solar cell cracks and crack patterns in solar cells, analyze the impact if there are cracks in solar cells, and discuss methods or implementation of Artificial Intelligence for detecting types of cracks and crack patterns.

The review results show that the types of solar cell cracks and crack patterns in solar cells are categorized from various perspectives, namely linear, patchy, and linear and porphyritic. Another pattern is to take into account the number of cracks that occur, namely if more than 20% it is called a major crack and if it is less than 20 it is called a microcrack (vertical or horizontal).

The overall impact of this crack is a decrease in the energy production of the solar cell. The methods applied to detect and classify solar cell cracks are Percolation-Based Image Processing and Serre Standard Model, Halcon-Based Solar Panel Crack Detection, Bluetooth, Images stitching technique, Convolutional Neural Network, YOLO, Multi-Scale Pyramid and Improved Region Growing, and Machine Learning to Electroluminescence Images.

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