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Research Article

# EFFICIENCY ANALYSIS OF PEROVSKITE-BASED SOLAR PANELS IN TROPICAL CLIMATES

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**Abstract**

The decline in efficiency of conventional silicon-based solar panels in tropical climates has become a significant concern in the advancement of renewable energy technologies. Environmental factors such as high temperatures, extreme humidity, and intense ultraviolet (UV) radiation contribute to material degradation, leading to reduced long-term performance. In response to these challenges, perovskite materials have emerged as a promising alternative, offering high efficiency and lower production costs. This study aims to analyse the efficiency performance of perovskite-based solar panels in tropical environments, identify the key environmental factors affecting their performance, and compare their resilience with that of conventional silicon panels. A qualitative case study approach was employed, using data collection techniques such as in-depth interviews, direct observation of test units, and technical documentation over a one-year monitoring period. The findings indicate that perovskite solar panels maintained up to 85% of their initial efficiency after one year of deployment, despite performance degradation caused by high humidity levels and prolonged UV exposure. Compared to silicon panels, perovskite panels demonstrated better adaptability to tropical conditions, although improvements in material durability are still needed. These results highlight the significant potential of perovskite materials for energy applications in tropical regions and underscore the importance of further research into protective coating technologies and material stabilisation strategies to enhance their long-term performance and reliability.

**Keywords**: Energy Efficiency, Perovskite Material, Solar Panel

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## INTRODUCTION

In recent years, the use of solar panels as a renewable energy source has been growing, including in tropical climates (Apriliyanti & Rizki, 2023; Belva & Raspati, 2024; Dwisari dkk., 2023). Conventional silicon-based solar panels have been the main choice in various solar energy applications. However, in tropical climates known for their high temperatures, extreme humidity, and high UV radiation intensity, silicon-based panels show a significant decrease in efficiency. As an alternative, perovskite materials offer the potential for higher energy efficiency and lower production costs compared to silicon. However, studies that specifically assess the performance of perovskite-based solar panels in tropical environments are still minimal. The unique tropical climate conditions present additional challenges such as extreme daily temperature variations and high rainfall, affecting material stability and device performance. Therefore, this study is important to analyze the efficiency of perovskite-based solar panels in tropical climates and identify the main factors that affect their performance.

Previous studies have extensively discussed the development of perovskite materials in the context of high efficiency under ideal laboratory conditions. However, when applied in the field with uncontrolled environmental conditions, especially in tropical regions, the performance of this material is not fully understood. Most theories and models of perovskite solar panel performance are still based on the assumption of moderate temperature and low humidity, so they cannot fully explain how perovskites will behave in extreme climates. In addition, there is no strong scientific consensus regarding the long-term resistance of perovskites to degradation due to exposure to tropical factors. This fact emphasizes the existence of a knowledge gap that needs to be bridged through research based on real conditions in tropical regions to strengthen the scientific and technical basis for the development of this technology.

This study aims to analyze the energy efficiency level of solar panels made of perovskite material in tropical climates. In addition, this study is also directed to identify specific environmental factors, such as high temperature, humidity, rainfall, and UV intensity, which have the potential to affect the performance of perovskite solar panels. Not only that, this study will compare the performance of perovskite solar panels with conventional silicon solar panels under similar conditions, to obtain a comprehensive picture of the advantages and challenges of using this material in tropical climates. With this aim, it is hoped that the results of this study can be the basis for the development of more adaptive and efficient solar panel technology in tropical areas.

Based on the facts of tropical environmental conditions and gaps in scientific literature, this study is expected to prove that perovskite-based solar panels have high potential to be applied in tropical climates, despite the quite severe environmental challenges. The hypothesis proposed is that the efficiency of perovskite solar panels can remain competitive or even superior to conventional silicon, provided that the materials and system design are adapted to deal with tropical conditions. The importance of this study lies in its contribution to providing a deeper understanding of the actual performance of perovskites in the field while opening up opportunities for the development of more sustainable solar energy technology solutions for tropical countries.

Solar panels, also known as photovoltaic modules, are devices designed to convert sunlight energy into electrical energy through the photovoltaic effect (Irawati dkk., 2023; Pratama & Asnil, 2021; Siagian, 2022). In general, solar panels consist of several solar cells arranged in a single structure to optimize light absorption and produce electric current (Arya & Mahajan, 2023; Awan dkk., 2025; Phogat dkk., 2024). The working principle of solar panels is based on the phenomenon in which certain semiconductor materials release electrons when exposed to sunlight, thereby producing electric current (Lubis dkk., 2024; Rohmani, 2022; Soetadji & Khoirudin, 2024). In the development of renewable energy technology, solar panels have become one of the key components in efforts to decarbonize the global energy sector. Their use extends from small-scale installations for households to large-scale solar power generation projects, making solar panels an important solution in the transition to clean energy.

The manifestation of solar panel technology has undergone significant developments with advances in materials science and manufacturing techniques. In general, solar panels can be categorized into three main types, namely crystalline silicon panels (monocrystalline and polycrystalline), thin-film panels, and new-generation panels made of innovative materials such as perovskite (Hosseini dkk., 2024; Järvinen dkk., 2025; Kamble dkk., 2024; Yusuf dkk., 2024). Crystalline silicon panels are the most common form and have dominated the market for decades due to their high conversion efficiency and long-term reliability. Meanwhile, thin-film panels offer design flexibility and lower production costs, although with lower efficiency. The new-generation category, including perovskite panels, is now a major focus of research because it promises a combination of high efficiency, material flexibility, and potentially lower production costs, opening up new opportunities in the development of solar energy technology.

Perovskite materials, in the context of solar technology, refer to a group of materials that have a crystal structure resembling the mineral perovskite ($CaTiO_3$), with the general formula $ABX_3$, where A and B are cations of different sizes and X is an anion. These materials have attracted extensive attention in photovoltaic research due to their excellent optoelectronic characteristics, such as high light absorption coefficient, good charge diffusion, and a wide range of energy bands that can be tuned. In solar panel applications, perovskites are used as active layers to absorb light and produce electron-hole pairs that are then separated to generate electric current (Ganesh, 2025; Islam & Bag, 2025; Wang dkk., t.t.). Another advantage is the ease of synthesis of these materials, which allows production by simple techniques such as spin-coating or printing, thus promising lower manufacturing costs compared to conventional silicon.

In terms of manifestation, perovskite materials used in solar panels can be classified based on chemical composition and device structure. Based on composition, there is lead-based perovskite which is currently the most commonly used due to its high performance, although toxicity issues are a concern. Another alternative being studied is lead-free perovskite which is more environmentally friendly but still faces stability challenges. Based on device structure, there are two main types, namely planar and mesoporous structures, each with a different approach to optimizing charge transport. In addition, the combination of perovskite with other technologies such as perovskite-silicon tandem is starting to be developed to achieve higher efficiency, showing how flexible this material is in supporting solar panel technology innovation.

Energy efficiency, in the context of solar panels, refers to the ratio of the electrical energy produced by a panel to the light energy received by it under given conditions (Avasthi dkk., 2025). This concept is a key indicator in assessing the performance of a solar panel because it determines how effectively the device converts natural energy sources into usable energy. Efficiency is influenced by various factors such as the nature of the active material, the structural design of the device, environmental conditions (including temperature and light intensity), and fabrication techniques. In the development of solar energy technology, increasing energy efficiency is one of the main goals, because the higher the efficiency, the greater the electrical output that can be generated from the same surface area, thereby increasing the economic and technical feasibility of solar installations, especially in areas with limited space or challenging environmental conditions.

The manifestation of energy efficiency in solar panels is reflected through various technical parameters and measurement approaches. Some important indicators include power conversion efficiency (PCE), temperature coefficient, and long-term stability. First-generation solar panels, such as monocrystalline silicon, achieve efficiencies of around 20–22% in commercial applications, while thin-film generally has lower efficiencies of around 10–15%. Perovskite materials, although still in the development stage, have demonstrated laboratory efficiencies above 25% in a relatively short time, matching or even surpassing conventional silicon. However, challenges such as material degradation due to exposure to humidity, high temperatures, and UV radiation are important factors that affect actual efficiency in the field, especially in tropical climates. Therefore, developing strategies to maintain high efficiency under extreme environmental conditions is a major focus in current perovskite technology research.

## RESEARCH METHOD

The object of this research focuses on solar panels based on perovskite materials operated in tropical climate conditions, taking into account the specific environmental challenges inherent in the region. In recent years, the use of solar panels as a renewable energy source has grown rapidly, including in tropical areas that have high solar energy potential throughout the year. However, conventional silicon-based solar panels show a decrease in efficiency due to exposure to high temperatures and extreme humidity. Perovskite materials have emerged as a new alternative that offers the potential for higher efficiency and lower production costs. However, studies on the performance of perovskite solar panels in tropical climates are still minimal, considering that this environment poses additional challenges such as high UV intensity, extreme temperature fluctuations, and heavy rainfall. Therefore, this study was conducted to examine the energy efficiency of perovskite solar panels in tropical environments and to identify environmental factors that affect their performance in depth.

The type of research used in this study is qualitative research with a case study approach, which aims to understand the phenomenon in depth through investigations on one specific unit of analysis. This study relies on primary data obtained from in-depth interviews with various key informants who are directly related to the use and development of perovskite solar panels in tropical areas. In addition, secondary data was collected from relevant literature, including scientific journals, technical reports, and previous research results discussing solar panels, perovskite materials, and energy efficiency. With this combination of primary and secondary data sources, the study aims to build a comprehensive understanding of the phenomenon being studied, as well as fill the gap in the literature related to the performance of perovskite solar panels in extreme tropical conditions.

Participants in this study were selected purposively to ensure that they had sufficient relevance and knowledge related to the research object. Key informants included energy technicians and engineers working in renewable energy research institutions, who provided technical insights related to the performance of perovskite solar panels. In addition, managers of solar panel installation projects in tropical areas were included to gain perspectives on practical implementation in the field. Material experts who focus on perovskite material development research are also important sources of information, especially in terms of material characteristics and stability under extreme conditions. Equally important, solar panel users in tropical areas were also involved in completing field data based on their daily usage experiences. The diversity of participant backgrounds is expected to provide a holistic perspective on the performance of perovskite solar panels in tropical climates.

This research process was conducted through several structured and systematic stages. The initial stage involved research planning, including the preparation of interview instruments and observation lists. The main data collection techniques used included semi-structured in-depth interviews with selected participants to explore detailed qualitative information. In addition, participant observation was conducted at the solar panel installation site to directly observe operational conditions and technical challenges in the field. Documentation was also used to complement the data obtained, by reviewing project reports, installation photos, and other relevant technical documents. Each stage of data collection was carried out by considering the principles of research ethics, such as participant consent and maintaining confidentiality of information, to ensure the integrity of the research results.

The data analysis technique in this study uses the Miles and Huberman model, which includes three main stages: data reduction, data presentation, and drawing and verifying conclusions (Erduran Tekin, 2024; Yagmur dkk., 2024). In the data reduction stage, information obtained from interviews, observations, and documentation is filtered to identify key themes that are relevant to the research objectives. Data presentation is done by organizing information in the form of tables, matrices, and descriptive narratives to facilitate interpretation. Conclusions are then drawn based on patterns that emerge from the data that has been presented, accompanied by ongoing verification to improve the accuracy of interpretation. Data validity is checked through credibility, dependability, transferability, and confirmability techniques. This approach ensures that the results of the analysis are valid and can make a meaningful contribution to the development of science around the efficiency of perovskite solar panels in tropical climates.

## RESULTS AND DISCUSSION

Interviews with technicians, material experts, field observations and technical documentation show that perovskite solar panels have attractive performance characteristics in the context of tropical climates. In laboratory conditions, the energy efficiency of perovskite panels is recorded at 20–24%. However, when used in tropical outdoor environments, this efficiency decreases to 18–20%. In addition, observations show that even in cloudy weather the panels are still able to generate electricity, their efficiency drops by around 5–7% compared to fully sunny conditions. Energy documentation shows a relatively stable daily production graph despite weather changes. Physically, observations found micro-cracks on the panel surface after six months of exposure to high heat, while visual documentation showed colour changes in the perovskite layer after more than six months of use. In terms of design, perovskite panels are proven to be lighter and more flexible than conventional silicon panels, making them easier to install on various types of buildings in tropical areas.

Further elaboration of the data shows that although perovskite panels show high-efficiency potential, extreme tropical climate conditions significantly affect their performance. High humidity and extreme temperatures are the main challenges, as confirmed by interviews with material experts who stated that material degradation is the main factor of performance degradation. The use of encapsulation technology is recommended to slow down this degradation. In terms of energy performance, although there is a decrease in efficiency in cloudy conditions, perovskite panels still show superior adaptation to low light intensity, by daily and monthly energy production observation data. Documentation data shows that despite fluctuations, perovskite panels can maintain around 85% of their initial capacity after one year of use.

The relationship between the description and explanation of data on solar panels with the reality of the research problem shows a gap that needs to be addressed. The challenges of the tropical environment, such as high rainfall and UV intensity, do have an impact on the physical durability and long-term performance of perovskite panels. These results emphasize the need to develop additional protective technology innovations to improve panel reliability in tropical conditions. Data obtained through interviews, observations, and documentation prove that although perovskite panels have the potential to adapt to tropical environments, there are environmental factors that must be taken into account more seriously in their development and application.

Based on the results of interviews, observations, and documentation, the perovskite material used in the manufacture of solar panels shows several advantages as well as disadvantages in application in tropical climates. In terms of advantages, perovskite can adapt to the low light intensity that often occurs in cloudy conditions, and its lightweight and flexibility make it easy to install. However, from the results of observations, physical damage was found in the form of micro-cracks that appeared after six months of use, and changes in the colour of the perovskite layer due to exposure to high UV intensity. Interviews with material experts revealed that the nature of perovskite material which is relatively sensitive to humidity and extreme temperatures is still a major challenge in its development.

Further explanation of perovskite material data shows that although this material has great potential in renewable energy development in tropical climates, its resistance to external factors still needs to be improved. Encapsulation technology is mentioned as a potential solution to overcome material degradation. Field observations show that even though there is micro-damage, energy performance does not experience a drastic decrease in the short term, as indicated by relatively stable energy production data. Thus, despite challenges related to material stability, perovskites still offer promising prospects for applications in tropical climates, with the note that additional innovations are needed in the material protection aspect.

The relationship between the description and explanation of perovskite materials with the reality of research problems shows that although the theoretical potential of this material is high, its application in the field faces real practical obstacles. Tropical environmental factors such as high humidity and UV exposure are key variables that affect the durability and efficiency of perovskite panels. The empirical data obtained indicate that further development of material protection technology is needed to optimize the use of perovskites in tropical climates. This is in line with the research objective to identify environmental factors that affect the performance of perovskite solar panels and compare them with conventional silicon panels.

In terms of energy efficiency, the results of interviews and observations show that perovskite solar panels can maintain fairly stable performance even in changing tropical climate conditions. Based on documentation data, the daily energy production graph shows that output fluctuations are not too extreme, even though there are changes in the weather. In general, perovskite panels maintain about 85% of their initial capacity after one year of use, better than conventional silicon panels which only maintain about 80% in the same period. Interviews with technicians emphasized that the ability of the panels to continue operating at decent efficiency even in cloudy conditions is one of the main advantages of perovskite technology.

Explanation of energy efficiency data shows that although perovskite panels experience efficiency degradation in cloudy conditions or after long exposure to extreme environmental factors, the scale of the degradation is still within acceptable limits for renewable energy applications in tropical areas. Adaptability to low light intensity is a distinct advantage that strengthens the applicability of this panel in facing tropical weather variability. In addition, the success of maintaining efficiency over a year with relatively lower degradation compared to silicon panels shows that perovskite panels have strong potential to become a sustainable energy solution in areas with similar climate characteristics.

The relationship between the description and explanation of energy efficiency with the reality of the research problem confirms the importance of this research. The data obtained show that the use of perovskite solar panels in tropical climates allows for competitive energy efficiency, although special attention is needed to environmental factors that can cause material degradation. This fact supports the initial argument of the study that studies on perovskite solar panels in tropical environments have not been widely developed and that there is great room for further innovation. By understanding the relationship between panel characteristics, perovskite materials, and energy efficiency in the context of tropical climates, this study provides an important empirical basis for the development of future solar panel technology. The following researchers present the research findings in the form of tables, based on the results of interviews with participants, the results of direct observations in the field, and the results of documentation studies.

Table 1. Research Findings

| No. | Research Purposes | Key Findings | Explanation |
|---|---|---|---|
| 1 | Analyzing the energy efficiency level of perovskite-based solar panels in tropical climates | Perovskite panels maintain 85% efficiency after one year of use | Initial efficiency in the laboratory is 20–24%, dropping to 18–20% in the tropical field, but remaining stable in changing weather. |
| 2 | Identifying environmental factors that affect the performance of perovskite solar panels | High humidity, extreme temperatures, high UV intensity and heavy rainfall | These factors cause material degradation, micro-cracking, discoloration and decreased performance. |
| 3 | Comparing the performance of perovskite solar panels with conventional silicon solar panels in tropical environments | Perovskite panels show better durability than conventional silicon | After one year, perovskite panels retained 85% of their capacity, while silicon panels dropped to 80%. |

Based on the research results obtained through interviews, observations, and documentation, perovskite solar panels show quite high energy efficiency performance in tropical climates, although there is a decrease in performance due to extreme environmental factors such as high temperature and humidity. Adaptation to low light and material flexibility are the advantages of this panel, while the main challenge is material degradation which accelerates the decline in physical performance. Compared to conventional silicon panels, perovskite panels can maintain a more stable energy production capacity after one year of use. This energy stability, even when faced with dynamic tropical weather conditions, shows that perovskite panels have promising prospects for further development in similar climates.

In the context of other research, several previous studies have shown that perovskite panels tend to have stability issues when applied outdoors, especially in high-humidity environments. However, this study confirms that there is a greater opportunity for adaptation in tropical climates compared to previous studies, thanks to more advanced encapsulation technology and material production techniques. These results strengthen the position of this study as a significant contribution to the scientific literature, by showing that even though environmental challenges remain, perovskite materials can maintain better performance than previously thought. Thus, this study broadens the horizon of knowledge about the potential application of perovskite panels in more extreme real-world conditions.

Reflections from the results of this study indicate that the use of perovskite materials in solar panels not only provides an alternative renewable energy solution in tropical areas but also opens up great opportunities for innovation in the field of energy technology. The purpose of the study is to analyze efficiency, identify environmental factors, and compare the performance of perovskite materials with silicon, all lead to the conclusion that perovskite is a strong candidate for the future of clean energy in tropical areas. This reflection marks the importance of investing in the development of materials that are resistant to humidity and extreme temperatures as a crucial next step.

The implications of this research point to the importance of developing advanced protection technologies for perovskite solar panels. The renewable energy industry can benefit from these findings by accelerating the adoption of perovskite panels in tropical regions while encouraging further research in encapsulation and structural modification of the material to improve durability. In addition, energy policies in tropical countries can be directed to support innovation and adoption of perovskite-based technologies, which in the long term will accelerate the clean energy transition while reducing dependence on fossil fuels.

The phenomenon of the results of this study, where perovskite panels are able to maintain performance even in extreme tropical environmental conditions, can be explained by the intrinsic properties of perovskite materials that have a tunable band gap and high light absorption efficiency. However, long-term durability is still affected by external factors such as UV exposure and humidity, which accelerate degradation. The performance variations found also indicate that production conditions, encapsulation methods, and manufacturing quality greatly affect the durability and efficiency of panels in real-world use.

Based on the results of this study, actions that need to be taken include strengthening innovation in encapsulation technology to extend the service life of perovskite panels in tropical climates, developing a pilot project program for installing perovskite panels in tropical areas to collect long-term data, and preparing specific technical standards for outdoor applications of perovskite solar panels. In addition, it is also important to educate and socialize end users about the maintenance of perovskite panels to optimize efficiency and extend the service life of the panels. These actions are expected to accelerate the acceptance of perovskite technology in the global renewable energy system, especially in tropical areas.

## CONCLUSION

The study revealed a surprising finding that solar panels made from perovskite materials were able to maintain energy efficiency of up to 85% of their initial capacity in tropical climate conditions after one year of use, an achievement that exceeded initial concerns about the durability of this material in extreme environments. Despite high UV exposure, extreme temperatures, and excessive humidity being real challenges, perovskite panels showed impressive performance adaptation, even exceeding the output stability of conventional silicon panels over the same period of use. This indicates that the potential for perovskite panels to be applied in tropical areas is much greater than previously thought.

The added value of this research lies in its contribution to scientific development both theoretically and practically. Theoretically, this research expands the knowledge base on the characteristics of perovskite materials in renewable energy applications in tropical climates, offering a new framework for understanding the relationship between environmental factors and material degradation. Practically, this research provides concrete insights for the development of solar panel protection technology and installation strategies in extreme climate areas. The results of this research are also an important reference for the renewable energy industry and policymakers in designing clean energy projects that are more adaptive to climate change.

Although this study has successfully revealed the great potential of perovskite materials, there are still limitations that open up opportunities for further research development. The focus of this study is limited to one year of observation, so it does not fully capture the long-term impact on panel stability in multi-year use. In addition, this study focuses on a specific tropical environment, so there is a great opportunity to explore the performance of perovskite panels in various tropical microclimate variations. Further research is expected to expand the scope of time and location, as well as explore further innovations in encapsulation technology to optimize the durability of perovskite materials on a global scale.

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