

THE EFFECTIVENESS OF POLYVINYL ALCOHOL-BASED HYDROGEL AS A SOLAR PANEL SURFACE COATING

Jonathan Hendrik Tamboto¹, Galen Oswald Lynd², Rafael Alexander Susanto³

ABSTRACT

Climate change demands optimal use of solar energy. However, solar panel efficiency is still limited by light reflection on glass, necessitating the development of anti-reflective coatings. This study aims to examine the effectiveness of polyvinyl alcohol (PVA)-based hydrogel as a solar panel surface coating in reducing light reflectance and increasing solar panel output power. PVA hydrogel was tested in three variations, namely plain PVA hydrogel, PVA hydrogel with a mixture of TiO₂ nanoparticles, and PVA hydrogel with a mixture of ZnO nanoparticles. The method used in this research is a quantitative method with an experimental approach. The test was carried out by measuring the refractive angle of light using a photosynthesis light to determine the refractive index based on Snell's law, calculating the reflectance using Fresnel's law, and measuring the electrical power stored in the battery after the solar panel has operated for an hour. The results showed that plain PVA hydrogel had the lowest reflectance of 2.751% compared to PVA–ZnO hydrogel (4.647%) and PVA–TiO₂ hydrogel (5.925%). In addition, the solar panel with plain PVA hydrogel coating produced the highest electrical power with an average of 3,737 Wh, greater than the control panel and the panel with a mixture of nanoparticles. Based on these results, it can be concluded that plain PVA-based hydrogel is the most effective solar panel surface coating in this study. This study demonstrates the potential of PVA hydrogel as a simple and environmentally friendly anti-reflective coating to improve solar panel performance.

Keywords: PVA hydrogel, solar panel, reflectance, refractive index, renewable energy.

A. INTRODUCTION

Climate change is a global challenge with wide-ranging impacts, such as water crises and the increasing frequency of extreme weather phenomena. These conditions indicate that environmental degradation has reached an alarming stage. Therefore, concrete actions are needed to reduce the impacts of climate change. One such action is the transition from fossil energy to renewable energy.

Solar energy is one of the most promising renewable energy sources because of its abundant availability and its potential to be utilized in almost all regions of the

world. Solar panels are one of the technologies that harness solar power. Over the past few decades, solar panel technology has continued to develop and its use has become increasingly widespread. However, the efficiency of converting light into electrical energy still needs to be improved so that the potential of solar energy can be utilized optimally.

One aspect that needs to be improved in solar panels is the reflection of light on the glass surface of the panel. The glass surface can reflect part of the incoming light, preventing it from being absorbed by the solar cells and causing energy losses (Jones,



Law, & Walls, 2023). Therefore, anti-reflective coatings need to be developed to reduce light reflection and increase energy absorption in solar panels.

Nanoparticle composites can be used as anti-reflective coatings on solar panels (Afif, El-Khozondar, & Pfeifer, 2021). However, the number of studies combining hydrogels and nanoparticles to form anti-reflective coatings on solar panel surfaces is still limited. Thus, this study investigates the effectiveness of hydrogel–nanoparticle composites as anti-reflective coatings.

The first research question is: how does coating monocrystalline silicon solar panels with pure PVA-based hydrogel, PVA–TiO₂, and PVA–ZnO affect the light reflectance on the panel surface? This problem focuses on comparing reflectance among different hydrogel coating variations based on differences in their refractive indices. Therefore, this research question examines the relationship between hydrogel composition variations and the magnitude of light reflection from the solar panel surface.

The second research question is: which variation of PVA-based hydrogel coating produces the greatest reduction in light reflectance and the highest increase in electrical energy output of the solar panel? This study addresses this question through reflectance calculations using

Fresnel's equations and by measuring the electrical energy stored in a battery after the panel operates for a certain period. This question aims to identify the most optically and energetically effective hydrogel coating compared to an uncoated solar panel.

The objective of this study is to analyze the effect of pure PVA-based hydrogel and hydrogel mixed with TiO₂ and ZnO nanoparticles on the light reflectance of solar panel surfaces. In addition, this study aims to determine the type of hydrogel coating that is most effective in increasing the electrical energy generated by solar panels. The results are expected to provide insight into effective coating formulations for optimizing light absorption.

The first hypothesis is that applying PVA-based hydrogel coatings, either pure or mixed with TiO₂ and ZnO nanoparticles, will reduce light reflectance compared to uncoated solar panels. This is because hydrogels can form transparent layers that reduce the refractive index mismatch between air and the glass surface of solar panels. Reducing this refractive index difference lowers light reflectance according to Fresnel's equations.

The second hypothesis is that PVA-based hydrogel mixed with ZnO nanoparticles will produce the lowest reflectance and the highest electrical energy output compared to

pure PVA hydrogel and PVA–TiO₂ hydrogel. This is presumably because the addition of nanoparticles can enhance the performance of the hydrogel layer by modifying light interactions at the panel surface. ZnO is expected to be more effective than TiO₂ because it has better transparency in the visible light range and is less likely to make the coating overly dense or opaque, allowing more light to enter the solar panel and generate energy more optimally.

Solar energy is a form of renewable energy obtained by converting light radiation into electrical energy using technologies such as solar panels (Dwisari, Sudarti, & Yushardi, 2023). Solar panels consist of semiconductor cells that absorb light radiation and generate electric current. Semiconductor materials have high chemical stability and relatively good conversion efficiency within the light spectrum (Fitriana, 2022). Solar panels operate based on the photovoltaic principle, which is the ability of semiconductor materials to generate electric current when exposed to light (Abidin, Alamsyah, & Hiendro, 2021).

When light strikes the surface of a solar panel, photons collide with electrons in the semiconductor structure and provide sufficient energy to free them from their bonds. These free electrons then flow through the semiconductor material, producing a direct current (DC). The basic structure of a solar

panel usually consists of two semiconductor layers: n-type (negative) and p-type (positive), forming a p–n junction. In this junction region, an internal electric field is created that drives electrons and holes in opposite directions, generating current when an external circuit is connected (Asnawi, Diningsih, Faiza, Firdaus, & Khoiro, 2021).

Solar panels are equipped with anti-reflective layers to minimize the amount of light reflected back and maximize the energy produced. Therefore, the efficiency of solar panels is strongly influenced by their surface coatings. The addition of nanoscale materials, such as nanoparticle layers, can improve the optical properties of solar panel surfaces and enhance photovoltaic performance (Prasetya & Utami, 2018).

Solar panels come in many types and specifications. This study uses monocrystalline silicon solar panels with dimensions of 136 × 136 mm. These panels are capable of producing 5 V, 2 W, and 390 mA under optimal conditions.

Hydrogels are polymeric materials with anti-reflective properties. These properties are indicated by light reflection below 4% when irradiated at a 50° angle (Abdullah et al., 2024). One way to increase solar panel efficiency is to reduce light reflection (Hadi, Notonegoro, & Soegijono, 2025).

There are many types of hydrogels, including natural,

synthetic, and hybrid. This study uses a synthetic hydrogel based on polyvinyl alcohol (PVA) crosslinked with citric acid. PVA is selected because PVA-based hydrogels form solutions with transparency up to 99.8% and an average refractive index of about 1.33 after gelation, so they do not interfere with visible light transmission to the solar panel (Barleany et al., 2024).

Nanoparticles are particles with sizes between 1–100 nanometers. TiO_2 and ZnO nanoparticles are wide-band-gap semiconductor oxides that are transparent to visible light (Ekarani, Prima, & Rusdiana, 2023). ZnO has a band gap of about 3.37 eV, while TiO_2 has about 3.2 eV. Both nanoparticles do not absorb visible light and are therefore suitable for surface coatings on solar panels. They also have relatively high refractive indices, namely about 2.5 for TiO_2 and 1.96 for ZnO (Setiawan, 2024).

These properties of TiO_2 and ZnO are beneficial for this study. Their high refractive indices can reduce light reflection between the panel surface and air. This behavior follows Fresnel's law, which states that reflectance increases as the difference in refractive index between two media increases. The glass on the surface of solar panels has a refractive index of 1.52 (Fuhaid, Ismail, & Nurhadi, 2016), while air has a refractive index of 1. Placing a hydrogel layer between glass and air reduces the refractive

index difference between each interface (El-Naas, Hussein, Surkatti, & van Loosdrecht, 2024).

B. METHOD

This study employs a quantitative method with an experimental approach. Quantitative methods focus on testing relationships between variables and building generalizations based on empirical evidence (Afgani, Fatimah, Septaria, Salsabila, & Siroj, 2024). The experimental approach is a research method conducted by applying specific treatments to independent variables and observing their effects on dependent variables under controlled conditions, so that cause-and-effect relationships can be clearly analyzed (Afgani et al., 2024). This study uses a quantitative experimental approach because it aims to objectively measure the effectiveness of polyvinyl alcohol (PVA)-based hydrogel as a surface coating for solar panels through the application of treatments and numerical measurement of solar panel performance variables, allowing causal relationships to be scientifically examined.

This study involves several variables classified into independent, dependent, and control variables. The independent variable is the treatment of PVA-based hydrogel mixtures crosslinked with citric acid. Each solar panel receives a different treatment. The first panel is not



coated with hydrogel and serves as the control panel. The second panel is coated with PVA-based hydrogel without nanoparticles. The third panel is coated with PVA-based hydrogel containing TiO_2 nanoparticles. The fourth panel is coated with PVA-based hydrogel containing ZnO nanoparticles.

The dependent variables in this study are the refractive index of each hydrogel treatment, the angle between the incident ray and the normal line for each hydrogel treatment, and the energy obtained from each solar panel after one hour of operation. Meanwhile, the control variables include the refractive index of air, the type, the angle between the refracted ray and the normal line, brand, and model of the solar panel, as well as the batteries, resistors, wires, modules, and switches used. Each experimental repetition is conducted at the same time and placed under a photosynthesis lamp.

The instruments used in this study are a magnetic stirrer, doctor blade, laboratory oven, multimeter, lux meter, and photosynthesis lamp. The magnetic stirrer is used to prepare PVA-based hydrogel and its nanoparticle variations. The doctor blade is used to apply the hydrogel layer onto the surface of the solar panel. The laboratory oven is used to ensure that the citric acid crosslinking process proceeds properly.

The photosynthesis lamp is used to determine the refractive

index of each hydrogel mixture variation. Measurements are carried out using Snell's Law so that changes in the direction of light propagation through each mixture can be quantitatively analyzed.

The multimeter is used for two main purposes: testing the output of the solar panel under standard operating conditions and measuring the voltage and current of the battery. The measurement data are then used to determine the amount of electrical energy stored in watt-hours. Meanwhile, the lux meter is used to measure the light intensity incident on each panel in every experiment. The results are recorded in units of lux (lumens/m²). The photosynthesis lamp serves as a substitute for natural sunlight.

This study is conducted in three main stages. The first stage is the preparation of PVA-based hydrogel and its nanoparticle variations. Plain PVA hydrogel is prepared by dissolving polyvinyl alcohol powder in hot distilled water, followed by stirring and heating using a magnetic stirrer for two hours and thirteen minutes. The temperature of the hydrogel is then reduced to room temperature and the mixture is placed in a refrigerator for 21 hours.

After being removed from the refrigerator and returned to room temperature, the magnetic stirrer and heater are turned on again until the hydrogel reaches 50°C. Citric acid dissolved in distilled water is then added and allowed to mix into

the hydrogel for 15 minutes. A portion of this hydrogel is applied to the surface of a solar panel as the plain PVA hydrogel sample using a doctor blade.

The remaining hydrogel is divided into two separate beakers. TiO_2 and ZnO nanoparticles dissolved in distilled water are added to each beaker. The nanoparticle-mixed hydrogels are then applied to the surfaces of the corresponding solar panels. After all panels are coated, they are placed in a laboratory oven at 80°C for one hour to facilitate proper citric acid crosslinking.

The second stage is data collection and classification. The first data collected are the refracted angles of each type of hydrogel. Samples from each hydrogel type are formed into thin, uniform layers. These layers are placed horizontally, and a photosynthesis lamp is directed at an angle of 60° . The refraction angle of the light passing through the hydrogel layer is measured using a protractor relative to the normal line.

After each test, the voltage and current of each battery are measured. The data are then grouped according to the type of coating on each solar panel.

The third stage is the calculation of battery energy increase, refractive index, and reflectivity. Battery energy is calculated using the formula $E = V_{\text{Average}} \times I \times t$, where E is the stored electrical energy (watt-hours),

V_{Average} is the average voltage between the voltage before and after testing (volts), I is the battery current (amperes), and t is time (hours).

The refractive index of each hydrogel mixture was calculated using Snell's law. The Snell's law equation applied is $n_{\text{air}} \sin\theta_1 = n_{\text{hydrogel}} \sin\theta_2$ which can be arranged to $n_{\text{hydrogel}} = n_{\text{air}} \frac{\sin\theta_1}{\sin\theta_2}$.

In this equation, n represents the refractive index of air and hydrogel, with $n_{\text{hydrogel}} \approx 1$. θ_1 is the angle between the incident ray and the normal line, while θ_2 is the angle between the refracted ray and the normal line. The refractive index of each tested hydrogel mixture is expressed as n_{hydrogel} .

The refractive index was determined by directing light at an incident angle of 60° and measuring the refracted angle using a protractor. This method is subject to relatively large measurement uncertainty because the hydrogel surface may not be perfectly flat, alignment of the light beam may vary, and manual angle readings can introduce human error. Even a small deviation of about $\pm 1^\circ$ in the measured angle can cause a noticeable change in the calculated refractive index due to the nonlinear relationship in Snell's law. Ideally, multiple measurements should be taken and reported using statistical indicators such as the mean and standard deviation to quantify

variability. However, this study did not include repeated measurements, uncertainty analysis, or error propagation calculations. Therefore, the reported refractive index values may appear more precise than the experimental method actually supports and should be interpreted as approximate estimates rather than exact values.

The reflectance of each hydrogel mixture was calculated using Fresnel's law. The equation used is $R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \times 100\%$. In this equation, R is the reflectance. A lower reflectance indicates that less light is reflected from the surface of the solar panel. For the calculation of $R_{\text{air-hydrogel}}$, n_1 represents the refractive index of air and n_2 represents the refractive index of the hydrogel. Meanwhile, for the calculation of $R_{\text{hydrogel-glass}}$, n_1 represents the refractive index of the hydrogel and n_2 represents the refractive index of the glass.

It should be noted that the reflectance calculation in this study uses a formula that is valid for light hitting the surface straight on (0°). In this experiment, however, the light was directed at an angle of 60° . At such angles, reflectance depends on the light's polarization, which can produce different reflection values. Because the light source used was not polarization-controlled, this effect was not included in the calculations. Therefore, the reflectance values obtained are simplified estimates and may not be

fully accurate, which should be considered as a limitation of this study.

C. RESULTS AND DISCUSSIONS

The experimental data are presented in the form of tables and bar charts.

1. Refractive Index of Hydrogel Calculation

Table 1. Results of Refractive Index Calculation

Hydrogel Treatment	θ_1	θ_2	n
Plain PVA	60°	39°	1.376
TiO ₂	60°	32°	1.634
ZnO	60°	34°	1.549

This table shows that plain PVA hydrogel has a refractive index of 1.376, while the addition of TiO₂ increases the refractive index to 1.634. Meanwhile, the hydrogel with ZnO has a refractive index of 1.549. These results indicate that the addition of inorganic materials to PVA hydrogel affects its optical properties, with TiO₂ providing the most significant increase in refractive index. This increase in refractive index has the potential to increase light deflection, thus contributing to the effectiveness of the hydrogel as a solar panel surface coating.

2. Reflectance Calculation

Table 2. Results of Reflectance Calculation

Solar Panel Treatment	$R_{\text{air-hydrogel}}$	$R_{\text{hydrogel-glass}}$	R_{total}
	$R_{\text{air-glass}}$ (Just for Control)		
Control	4.258%		4.258%
Plain PVA	2.504%	0.247%	2.751%
PVA + TiO_2	5.794%	0.131%	5.925%
PVA + ZnO	4.639%	0.008%	4.647%

This table shows that plain PVA hydrogel has the lowest reflectance of 2.751%, followed by control (4.258%), PVA + ZnO (4.647%), and PVA + TiO_2 with the highest value of 5.925%. This difference indicates that the increase in refractive index due to the addition of TiO_2 and ZnO particles increases the difference in refractive index with air, thus increasing reflectance.

3. Light Intensity Calculation

Table 3. Light Intensity Calculation Results

Attempt Number	Photosynthesis Light Intensity (Lux)
1	12360
2	12365
3	12381

4	12370
5	12379

4. Battery Energy Calculation

In this experiment, the current was fixed at 1 A for all trials rather than measured dynamically during charging. This indicates that the calculation assumes a constant current condition and does not account for real-time variations in current supplied by the solar panel. Since the solar panels used are rated at approximately 2 W, they may not realistically sustain a 1 A output for one hour under the given operating conditions without additional circuitry or energy buffering. Therefore, the calculated energy values should be interpreted as theoretical estimates based on the assumed current, rather than precise measurements of the actual electrical energy delivered solely by the panels. This assumption represents a limitation of the electrical analysis and should be considered when evaluating the results.

Table 4. Results of Control Solar Panel Experiments

Attempt Number	Beginning Voltage (V)	Ending Voltage (V)	Average Voltage (V)	Current in Battery (A)
1	3.62	3.7	3.66	1
2	3.62	3.71	3.665	1



3	3.62	3.75	3.685	1
4	3.62	3.72	3.67	1
5	3.62	3.74	3.68	1

Table 5. Calculation Results of Control Solar Panel Battery Energy

Attempt Number	$V_{Average} \times I \times t$	Watt hour (Wh)
1	3,66 x 1 x 1	3,66
2	3,665 x 1 x 1	3,665
3	3,685 x 1 x 1	3,685
4	3,67 x 1 x 1	3,67
5	3,68 x 1 x 1	3,68
Average		3,672
Standard Deviation		0.0102

Table 6. Results of Plain PVA Solar Panel Experiments

Attempt Number	Beginning Voltage (V)	Ending Voltage (V)	Average Voltage (V)	Current in Battery (A)
1	3.62	3.83	3.725	1
2	3.62	3.84	3.73	1
3	3.62	3.87	3.745	1
4	3.62	3.86	3.74	1

5	3.62	3.87	3.745	1
---	------	------	-------	---

Table 7. Calculation Results of Plain PVA Solar Panel Battery Energy

Attempt Number	$V_{Average} \times I \times t$	Watt hour (Wh)
1	3.725 x 1 x 1	3.725
2	3.73 x 1 x 1	3.73
3	3.745 x 1 x 1	3.745
4	3.74 x 1 x 1	3.74
5	3.745 x 1 x 1	3.745
Average		3.737
Standard Deviation		0.0087

Table 8. Results of TiO₂ Solar Panel Experiments

Attempt Number	Beginning Voltage (V)	Ending Voltage (V)	Average Voltage (V)	Current in Battery (A)
1	3.62	3.67	3.645	1
2	3.62	3.69	3.655	1
3	3.62	3.73	3.675	1
4	3.62	3.72	3.67	1
5	3.62	3.72	3.67	1

Table 9. Calculation of TiO₂ Solar Panel Battery Energy

Attempt Number	$V_{Average} \times I \times t$	Watt hour (Wh)
1	3.645 x 1 x 1	3.645
2	3.655 x 1 x 1	3.655
3	3.675 x 1 x 1	3.675
4	3.67 x 1 x 1	3.67
5	3.67 x 1 x 1	3.67
Average		3.663
Standard Deviation		0.012

Table 10. Results of the ZnO Solar Panel Experiment

Attempt Number	Beginning Voltage (V)	Ending Voltage (V)	Average Voltage (V)	Current in Battery (A)
1	3.62	3.7	3.66	1
2	3.62	3.7	3.66	1
3	3.62	3.74	3.68	1
4	3.62	3.71	3.665	1
5	3.62	3.73	3.675	1

Table 11. Calculation of ZnO Solar Panel Battery Energy

Attempt Number	$V_{Average} \times I \times t$	Watt hour
----------------	---------------------------------	-----------

		(Wh)
1	3.66 x 1 x 1	3.66
2	3.66 x 1 x 1	3.66
3	3.68 x 1 x 1	3.68
4	3.665 x 1 x 1	3.665
5	3.675 x 1 x 1	3.675
Average		3.668
Standard Deviation		0.0084

The experimental results show that pure PVA-based hydrogel has a refractive index of approximately 1.376 and the lowest reflectance of 2.751%, compared to PVA hydrogel mixed with ZnO, which has a refractive index of 1.549 and a reflectance of 4.647%, and PVA hydrogel mixed with TiO₂, which has a refractive index of 1.634 and a reflectance of 5.925%. In line with these results, measurements of the electrical energy stored in the battery indicate that the solar panel coated with pure PVA hydrogel produced the highest energy output, with an average of 3.737 Wh. This value is higher than that of the control solar panel (3.672 Wh), the panel coated with PVA-TiO₂ (3.663 Wh), and the panel coated with PVA-ZnO (3.668 Wh). These findings indicate a correlation between refractive index, reflectance, and the electrical energy produced by the solar panel.

The panel coated with plain

PVA hydrogel produced the highest electrical energy output, exceeding the control panel by 0.065 Wh (approximately a 1.77% increase), indicating that plain PVA is the most effective coating among those tested in this study. However, this improvement is relatively small and may be influenced by experimental uncertainties, particularly because the battery charging current used in the experiment was only 1 A, making the calculated energy highly sensitive to small changes in voltage measurements. Minor measurement errors, fluctuations in light intensity, or variations in battery performance could therefore produce differences of this magnitude. Since no statistical significance test was conducted, it cannot be determined with certainty whether the observed increase reflects a true performance improvement or normal measurement variation. Thus, although plain PVA hydrogel appears to perform best, this conclusion should be interpreted with caution and confirmed through further experiments with more trials and formal statistical analysis.

The differences in performance can be explained based on the mechanism of light propagation at the air–hydrogel–glass interface of the solar panel. Air has a refractive index of approximately 1.00, while the glass on the surface of the solar panel has a refractive index of about 1.52. Pure PVA hydrogel, with a

refractive index of around 1.38, lies between these two values, forming a more gradual refractive index gradient. According to Fresnel's law, this gradient causes incoming light from air to be refracted gradually before entering the panel glass, thereby reducing light reflection at each interface.

In contrast, PVA hydrogels mixed with TiO_2 and ZnO have refractive indices of approximately 1.63 and 1.55, respectively. These values are higher than those of air and the panel glass. Based on Fresnel's law, this condition significantly increases light reflectance, causing part of the incident light to be reflected back before it can be transmitted into the panel glass. The increased reflectance in PVA– TiO_2 and PVA–ZnO hydrogels reduces the amount of light transmitted into the solar panel, resulting in lower electrical energy output compared to pure PVA hydrogel.

The average electrical energy produced by the control panel was 3.672 ± 0.0102 Wh. The solar panel coated with plain PVA hydrogel produced 3.737 ± 0.0087 Wh, while PVA– TiO_2 and PVA–ZnO coatings produced 3.663 ± 0.012 Wh and 3.668 ± 0.0084 Wh, respectively.

The relatively small standard deviation values indicate that the measurements were consistent across trials. However, because the difference between treatments is comparable in magnitude to the variability, further statistical testing

such as a t-test would be required to confirm whether the observed differences are statistically significant.

D. CONCLUSION AND SUGGESTIONS

Based on the research results, hydrogel coatings influence light reflection on the surface of solar panels. Pure PVA-based hydrogel shows the best performance in reducing light reflection compared to hydrogels mixed with nanoparticles; therefore, the first hypothesis is accepted. This result is consistent with Snell's law, in which the refractive index of pure PVA hydrogel, lying between that of air and the glass of the solar panel, forms a more gradual refractive index transition at the air-hydrogel-glass interface, thereby reducing light reflection.

Solar panels coated with pure PVA hydrogel generate the highest electrical energy compared to uncoated panels and panels coated with nanoparticle-mixed hydrogels; therefore, the second hypothesis is not fully supported. Theoretically, ZnO nanoparticles were expected to improve performance due to their transparency and high refractive index. However, their addition increased the hydrogel's refractive index beyond the optimal intermediate value between air and glass, creating a larger mismatch at the air-hydrogel interface. According to Fresnel's law, this increases light reflection and

reduces transmission into the panel. In addition, nanoparticles may aggregate within the hydrogel, forming clusters that scatter incident light and reduce optical clarity. These combined effects decrease the amount of light reaching the solar cells, so pure PVA hydrogel proved to be the most effective coating in this study.

For future researchers, it is recommended to explore hydrogel mixtures with nanoparticles other than ZnO and TiO₂ and to consider weather conditions, as measurements of solar panel effectiveness are highly dependent on the availability of sunlight.

E. BIBLIOGRAPHY

Abdullah, A., Putri, M., Syahrudin, M., Sitorus, N., Dharma, S., Jumaat, A. K., Ridzuan, A. R., Halomoan, D. M., & Husna, N. F. (2024). *Sistem penggerakan reflektor empat sisi untuk mendapatkan sudut ideal pantulan cahaya matahari pada panel surya*. RELE (Rekayasa Elektrikal dan Energi): Jurnal Teknik Elektro, 7(1), 161–168. <https://jurnal.umsu.ac.id/index.php/RELE/article/view/20583/1716>

Asnawi, A., Dinigsih, C., Khoiro, M., Firdaus, R. A., & Faiza, T. N. (2021). Efek lapisan ganda antireflektif untuk meningkatkan transmisi photovoltaics dari sel surya.

- Jurnal Komunikasi Fisika Indonesia*, 18(3), 230–237.
- Fuhaid, N., Ismail, N., & Nurhadi, E. (2016). Pengaruh jenis kaca penutup dengan variasi laju aliran terhadap efisiensi solar *water heater* sederhana. https://www.academia.edu/143722733/Pengaruh_Jenis_Kaca_Penutup_Dengan_Variasi_Laju_Aliran_Terhadap_Efisiensi_Solar_Water_Heater_Sederhana
- Hadi, V., Notonegoro, H., Soegijono, B. (2025). Peningkatan efisiensi solar sel, melalui pelapisan komposit hydrogel-nano silika amorph pada permukaan solar panel. https://www.researchgate.net/publication/399678471_Peningkatan_Efisiensi_Solar_Sel_Melalui_Pelapisan_Komposit_Hydrogel-Nano_Silika_Amorph_Pada_Permukaan_Solar_Panel
- Fitriana. (2022). Analisis efek panjang gelombang cahaya terhadap karakteristik arus-tegangan sel surya menggunakan simulasi berbasis finite element method. *Jurnal Teknik Elektro Uniba*, 6(2), 228–234. <https://jurnal.fte.uniba-bpn.ac.id/index.php/JTE/article/view/123/90>
- Hiendro, A., Alamsyah, T., & Abidin, Z. (2021). Analisis potensi energi matahari sebagai pembangkit listrik tenaga surya menggunakan panel mono-crystalline dan poly-crystalline di Kota Pontianak dan sekitarnya. *Jurnal Untan*, 9(2), 1-10. <https://jurnal.untan.ac.id/index.php/j3eituntan/article/download/48425/75676590121>
- Law, A. M., Jones, L. O., & Walls, J. M. (2023). *The performance and durability of anti-reflection coatings for solar module cover glass – a review*. *Solar Energy*, 261, 85–95. <https://doi.org/10.1016/j.solener.2023.06.009>
- Loosdrecht, M., El-Naas, M., Zouari, N., Surkatti, R., Onwusogh, U., & Al Disi, Z. A. (2021). Isolation and identification of organics-degrading bacteria from gas-to-liquid process water. *Journal of Environmental Chemical Engineering*, 8(1), Article 603305. <https://www.researchgate.net/publication/348500839>
- Pitaloka, A. B., Barleany, D. R., Jayanudin, Yulvianti, M., Lumbantobing, P. I., Lestari, R. S. D., & Prasetyo, Z. E. (2024). Synthesis of polyvinyl alcohol-based polymer hydrogel as water holding in sandy soil using gamma radiation technique and its application for urea loading. *Results in Materials*, 21, Article



100402.

<https://www.sciencedirect.com/science/article/pii/S2666016424000288>

Rusdiana, D., Prima, E. C., & Ekarani, P. (2023). Pengaruh ketebalan lapisan tipis ZnO terhadap kinerja sel surya perovskit fleksibel. *Jurnal Inovasi Pendidikan Fisika dan Riset Ilmiah*, 7(2), 46–55. <https://journal.unuha.ac.id/index.php/JIPFRI/article/download/2692/823/6871>

Setiawan, W. (2024). Pengaruh nanotitania/nanosengoksida (TiO₂/ZnO) pada bahan polietilena untuk memblokir sinar ultraviolet. [http://digilib.unila.ac.id/80894/3/TEISIS%20FULL%20TANPA%](http://digilib.unila.ac.id/80894/3/TEISIS%20FULL%20TANPA%20BAB%20PEMBAHASAN.pdf)

[20BAB%20PEMBAHASAN.pdf](#)

Siroj, R. A., Afgani, W., Fatimah, F., Septaria, D., & Salsabila, G. Z. (2024). Metode penelitian kuantitatif pendekatan ilmiah untuk analisis data. *Jurnal Pendidikan, Ilmu Sosial, dan Pengabdian Kepada Masyarakat*, 5(3), 191-199. <https://journal.universitaspahlawan.ac.id/index.php/jrpp/article/view/32467>

Sudarti, Dwisari, V., & Yushardi. (2023). Pemanfaatan energi matahari: Masa depan energi terbarukan. *Jurnal Optika*, 7(2), 85–92. <https://doi.org/10.37478/optika.v7i2.3322>