ELEC2312: Solar Cell Research Exercise 2025

Name:	Emre Canogullari	**Email address:**	ec1u24@soton.ac.uk
Student ID:	36278734		

Task 1

(a) The I-V characteristic curve created by the data measured [1] from the solar cell in baseline measurement conditions, where distance $d = 10cm$, angle of incidence $\theta = 0°$, and the temperature $T = 20°C$, with only $1cm^2$ of the cell is revealed to be illuminated due to the external mask present on the cell, can be found in the graph Figure 1 below.

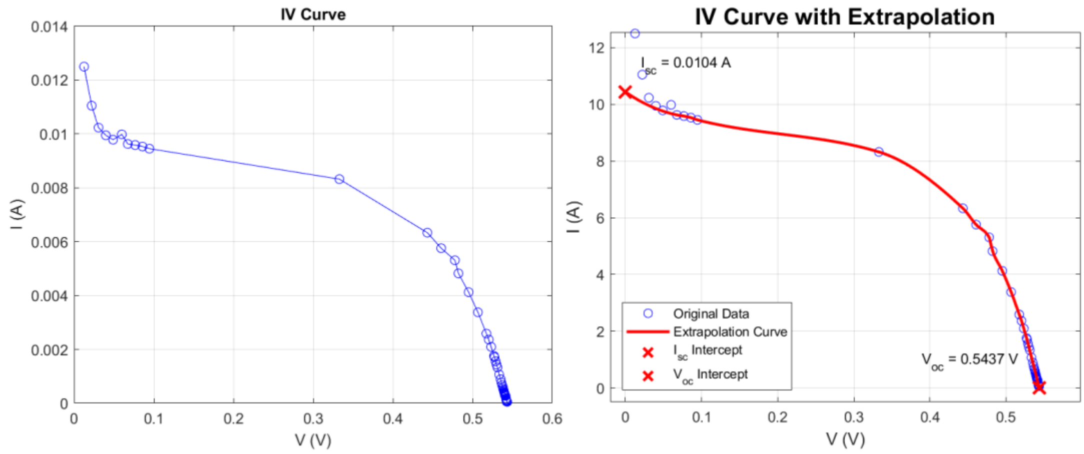

Figure 1: IV Curve for baseline measurements of the solar cell distance $d = 10cm$, angle of incidence $\theta = 0°$, temperature $T = 20°$ (left) vs the extrapolated IV curve for the same data points (right)

(b) The open circuit voltage V_{oc} occurs when the cell is not connected to any load, where the voltage across the cell is at its maximum value and the current across the cell is at its minimum value [2]. Opposite to the open circuit voltage, the short circuit current I_{sc} occurs when the voltage across the cell is at its minimum, therefore the current leaving the cell is at its maximum value. In the I-V curve created by the data gathered, these two points could not have been measured, as the variable resistance box only allowed resistances between 1Ω and 9999Ω, with the minimum allowed change being 1Ω. This does not allow to take the voltage and current values where resistance R approaches zero or infinity. To add onto this, the experiment instructions state that the data gathered where resistance R approaches zero gets inaccurate due to the method used to extract these measurements, which requires an extrapolation to be used from the linear section near the y-intercept.

The extrapolated data can be observed from Figure 1, which looking at the x-intercept, gives the voltage reading $V = V_{oc} = 0.5437V$ which is the open circuit voltage V_{oc}. Looking at the y-intercept gives the I_{sc} value to be $I = I_{sc} = 0.0104A = 10.4mA$. The maximum power point of the graph can be calculated by graphing the result of the multiplication of the voltage and the current at each point, and taking the point where the graph's maximum point occurs [2]. This value can be extracted from the power curve in Figure 2, which gives the max power point occurring at voltage $V_{mp} = 0.3907V$ and current $I_{mp} = 7.52mA$, which gives the max power output to be $P_{max} = 2.94mW$.

The fill factor FF can be calculated using the values V_{oc}, I_{sc}, V_{mp} and I_{mp} by using the formula $FF = \frac{V_{mp} * I_{mp}}{V_{oc} * I_{sc}}$, giving a fill factor of $FF = \frac{0.3907*7.52*10^{-3}}{0.5437*10.4*10^{-3}} = 0.5196$, which is equivalent to 51.96%.

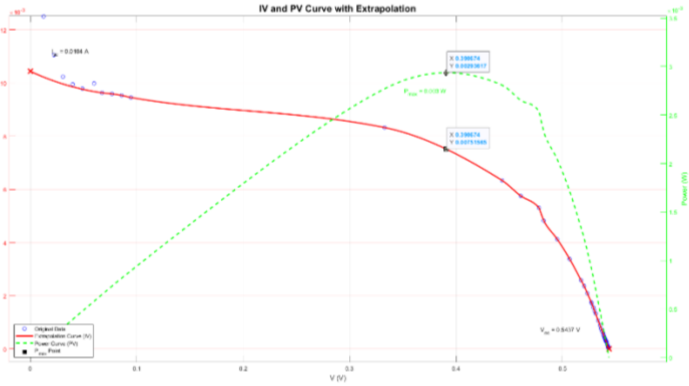

Figure 2: The power curve for the solar cell in baseline measurement conditions

(c) As stated in part (a), the solar cell is masked precisely so that only $1cm^2$ of the solar cell is illuminated. The distance between the solar cell and the light source was set up so that a distance $d = 10cm$ exists between the cell and the light source. The power density of the light from the source was given to be $0.35kW/m^2$ at a distance of 10cm. As the illuminated area is $1cm^2$, with $1cm^2 = 1 * 10^{-4}m^2$, the power input to the system equals $P_{in} = 350 * 10^{-4} = 35mW$. The power conversion efficiency η can be calculated by dividing the maximum power output P_{max} by the input power P_{in}, which gives a power conversion efficiency of $\eta = \frac{2.94*10^{-3}}{35*10^{-3}} = 0.084$, which is equivalent to an efficiency of 8.4%.

(d) The datasheet of the solar cell used in this experiment, given in the experiment instructions, states the values present in Table 1. As observed from the table, there exists a significant difference between the datasheet values and the measured values, especially with the measured values being almost 1/1000 of the datasheet values for the current values.

One reason for these differences could be because different operating conditions were used between the standard measurements and the experiment. The Standard Test Conditions (STC) are used when testing the efficiency of the solar cells, where the standard test condition being defined as: $1000W/m^2$ of solar irradiance at an ambient temperature of $25°C$ with a sea level air mass [4]. Comparing these to the baseline measurement conditions that were used for the data gathered, we can see that there is a significant difference between the solar irradiance and the ambient temperature, which could have altered the collected data. Firstly, the solar irradiance of $1000W/m^2$ is almost 3 times the value of the power density of the light source, which was $350W/m^2$, which could be one of the major reasons of the difference in the datasheet and calculated values for the current value data. The ambient temperature given in STC is $25°C$, when compared to the solar cell temperature of $20°C$, there is a difference of $5°C$ in temperature. This could be the reason behind the difference between the voltage readings, as V_{oc} decreases approximately 0.3% to 0.5% for every $1°C$ increase in temperature [5].

Another reason could be because of the mask present on top of the solar cell. The mask is placed so that only a $1cm^2$ area of the cell is illuminated. The datasheet gives the cell dimensions to be $156mm \times 156mm$, which gives an area of $243.36cm^2$. The solar cell was limited to be illuminated from only 1/243 of its surface area, which could explain the huge differences between the circuit readings.

Table 1: Datasheet values vs calculated values for the solar cell used in experiment

	Short Circuit Current I_{sc}	Open Circuit Voltage V_{oc}	Maximum Power Current I_{mp}	Maximum Power Voltage V_{mp}	Fill Factor FF
Datasheet	8.46A	613mV	7.94A	516mV	78.93%
Calculated	10.4mA	543.7mV	7.52mA	390.7mV	51.96%

Task 2

(a) The IV characteristic curves corresponding to the different distances $d = 10cm, d = 20cm$, and $d = 30cm$ with angle of incidence $\theta = 0°$ and temperature $T = 20°C$ can be found in Figure 3 below. It should be noted that looking at plot (iv), as the distance between the solar cell and the light source increase, V_{oc} and I_{sc} decrease as a response.

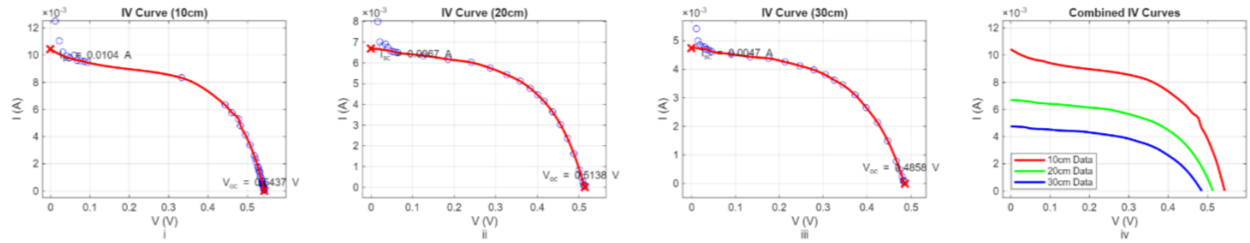

Figure 3: The extrapolated IV curves for the solar cell at distances d=10cm (i), d=20cm (ii), and d=30cm (iii) for angle of incidence $\theta = 0°$ and temperature $T = 20°C$, with plot (iv) where all IV curves are plotted on the same plane

(b) The solar cell can be expresses using its equivalent circuit formula shown in Equation 1 below [6], where I_L is the light generated current, I_0 is the dark saturation current, R_s and R_{sh} are series and shunt resistances respectively, n is the ideality factor, and V_T is the thermal voltage. The formula for the thermal voltage is $V_T = \frac{kT}{q}$, where k is the Boltzmann's constant $1.381 \times 10^{-23} J/K$, q is the elementary charge $1.602 \times 10^{-19} C$, and T is the temperature in kelvin.

$$I = I_L - I_0\left(e^{\frac{V+IR_S}{nV_T}} - 1\right) - \frac{V+IR_S}{R_{sh}} \qquad (1)$$

Assuming an ideal solar cell for the calculations in this section, the series resistance value R_s will approach 0, whereas the shunt resistance value R_{sh} approaches infinity [7]. This allows Equation 1 to be simplified down to $I = I_L - I_0(e^{\frac{V}{nV_T}} - 1)$. Evaluating the equation in the two extremes I_{sc} and V_{oc} gives the following expressions. When the current equals I_{sc}, the voltage is 0, which gives the expression to $I_{sc} = I_L - I_0\left(e^{\frac{0}{nV_T}} - 1\right) = I_L$. When the voltage equals V_{oc}, the current is 0, therefore the expression becomes $0 = I_L - I_0(e^{\frac{V_{oc}}{nV_T}} - 1)$, which gives $I_L = I_0(e^{\frac{V_{oc}}{nV_T}} - 1)$. Setting the two expressions equal to each other gives $I_{sc} = I_L = I_0(e^{\frac{V_{oc}}{nV_T}} - 1)$, therefore the equality $I_{sc} = I_0(e^{\frac{V_{oc}}{nV_T}} - 1)$ is achieved. As the exponential $e^{\frac{V_{oc}}{nV_T}}$ will be much greater than 1, the -1 in the parenthesis can be safely ignored, leaving the equation to be $I_{sc} = I_0 e^{\frac{V_{oc}}{nV_T}}$.

Taking the natural log of both sides of the equation $I_{sc} = I_0 e^{\frac{V_{oc}}{nV_T}}$ gives the expression $\ln(I_{sc}) = \ln(I_0 e^{\frac{V_{oc}}{nV_T}})$. This expression can be simplified to $\ln(I_{sc}) = \ln(I_0) + \ln(e^{\frac{V_{oc}}{nV_T}})$ due to log rules, which gives a final expression of $\ln(I_{sc}) = \frac{V_{oc}}{nV_T} + \ln(I_0)$. This expression gives a linear relationship between the $\ln(I_{sc})$ and V_{oc} values, as the equation is in the form $y = mx + c$.

The short circuit current I_{sc} and the open circuit voltage V_{oc} values for each IV curve at different distances can be extracted from Figure 3. Using these values, a plot for $\ln(I_{sc})$ vs V_{oc} can be formed, as it can be observed in Figure 4. Using the equation for the best fit line, the unknown values in the equation $\ln(I_{sc}) = \frac{V_{oc}}{nV_T} + \ln(I_0)$ can be solved for.

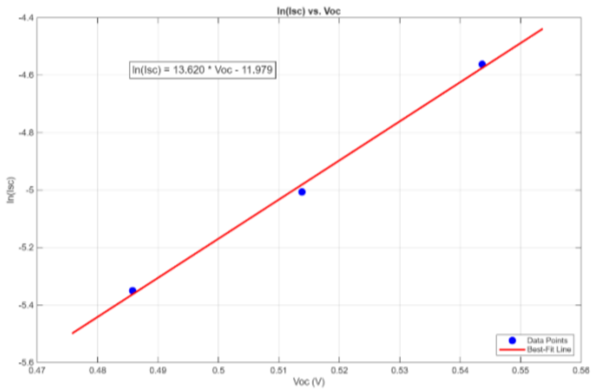

Figure 4: $\ln(I_{sc})$ *vs* V_{oc} plot generated with I_{sc} and V_{oc} values extracted from Figure 3

Comparing $\ln(I_{sc}) = \frac{V_{oc}}{nV_T} + \ln(I_0)$ with the equation for the best fit line for the plot in Figure 4 $\ln(I_{sc}) = 13.620V_{oc} - 11.979$ gives $\frac{1}{nV_T} = 13.620$ and $\ln(I_0) = -11.979$. As the temperature for the cell was set to $20°C$, it is equivalent to $T = 293.15K$, which can be used to find the value of the thermal voltage in these conditions to be equal to $V_T = 0.0253$. Rearranging the equality $\frac{1}{nV_T} = 13.620$ gives $\frac{1}{13.620} = nV_T$, which can be solved to find an estimate value for the ideality factor, which equates to $n = 2.90$, which is higher than the typical range of 1-2. To solve for the dark saturation current I_0, the expression $\ln(I_0) = -11.979$ can be used. If both sides are used as an exponential, the result $I_0 = 6.27\mu A$ is achieved, which is the estimate value for the dark saturation current for this cell.

(c) Even though an assumption of an ideal cell being used was made in part (b) to simplify equations, this isn't the case in reality, as R_s and R_{sh} will contribute to the values extracted from the solar cell. To extract the resistance values, the slope at the two extremes I_{sc} and V_{oc} of one of the plots in Figure 3 can be used. The shunt resistance R_{sh} can be obtained with the expression $R_{sh} = -\frac{1}{m_{sc}}$, where m_{sc} is the slope around the point where I_{sc} occurs [8]. Likewise, the series resistance R_s can be obtained with the expression $R_s = -\frac{1}{m_{oc}}$, where m_{oc} is the slope around the point where V_{oc} occurs. This method can produce inaccurate results due to the difference of the slopes between the different IV curves around those two points.

Task 3

(a) For this task, the effect of the angle of incidence on the IV curve of the solar cell was chosen to be investigated. The IV characteristic curves generated by the different angle of incidences $\theta = 0°$, $\theta = 30°$ and $\theta = 75°$, at a distance of $d = 10cm$ and a temperature of $T = 20°C$ can be observed from Figure 5.

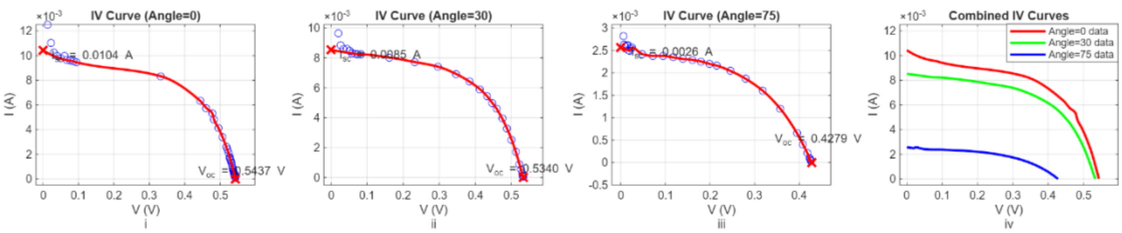

Figure 5: The extrapolated IV Curves for the solar cell for different angle of incidences $\theta = 0°$ (i), $\theta = 30°$ (ii) and $\theta = 75°$ (iii) at a distance of $d = 10cm$ and a temperature of $T = 20°C$, with plot (iv) having all the IV curves on the same plane

(b) As it can be observed from Figure 5, as the angle of incidence increases, both I_{sc} and V_{oc} values tend to decrease, as well as the overall power output of the solar cell. This phenomenon can be explained with Lambert's Cosine Law, which states that the radiant intensity being reflected from an ideal diffusing surface is directly proportional to the cosine of the angle between the direction of light and the normal vector from the surface of that surface [9]. If the I_{sc} values are observed from Figure 5, it is visible that there is a similar correlation between the values. If I_{sc-i} is defined to be the short circuit current of plot (i) in Figure 5 (with an angle of incidence $\theta = 0°$), then the following short circuit currents can be defined as $I_{sc} = I_{sc-i}\cos(\theta)$, where θ is the angle of incidence for that data set. Using $\theta = 30°$ for plot (ii), the value of I_{sc} for plot (ii) can be calculated as $I_{sc} = 0.0104 \times \cos(30°) = 0.0090A$, which is close to the measured value $I_{sc} = 0.0085A$. Doing the same procedure for $\theta = 75°$ for plot (iii) gives $I_{sc} = 0.0027A$, which is almost the same value measured $I_{sc} = 0.0026A$.

It can be realized from looking at Figure 5 that unlike I_{sc}, V_{oc} doesn't tend to decrease in the same proportions. This due to the expression $\ln(I_{sc}) = \frac{V_{oc}}{nV_T} + \ln(I_0)$ derived in Task 2 (b). Rearranging the expression gives $V_{oc} = nV_T \ln(\frac{I_{sc}}{I_0})$. This shows that while the short circuit current has a linear relationship with the angle of incidence, due to the radiant intensity affecting the light generated current directly, the open circuit voltage has a logarithmic relationship, due to being dependent on the light generated current rather than the angle of incidence. Hence, Lambert's Cosine Law doesn't directly hold for the open circuit voltage V_{oc}, but instead affects it logarithmically.

(c) Even though the solar cell datasheets express high output values due to being tested in Standard Test Conditions (STC) to allow evaluation under reproducible conditions, the real-world power outputs received from solar cells tend to be less than the stated values due to environmental effects [10]. These effects can add up to each other to significantly decrease the output power of the solar cell. As the power output of the solar cell is directly dependent on how much light has been absorbed by the module, any factors affecting how much light is present to be absorbed have a direct effect on the generated power.

Irradiance, which is the quantity of how much power comes from the solar source per unit area, can fluctuate daily due to the weather and the time of day, as the sun's altitude, the angle between the sun's rays and the horizontal plane, tends to change depending on what time it is [10]. Due to Lambert's Cosine Law, the maximum solar irradiation occurs when the solar cell modules are perpendicular to the incoming solar radiation. This causes the point where the most energy is absorbed by the solar cell to be at noon, where the sunlight is perpendicular to the solar cell. Any deviation from this angle reduces the electricity output. The time of year contributes to these deviations due to the amount of time the sun stays close to being perpendicular to the solar cell. Especially during summer, higher sun positions and longer daylight hours causes more power to be generated due to the greater solar irradiance, whereas during winter, the power output from the solar cell tends to be less, especially in higher latitudes. To combat the loss due to latitude, the idea of installing the solar cells with a tilt angle was formed, with the rule of thumb being the angle of tilt to be equal to the latitude of the installation location [11]. It was later found out that this rule of thumb didn't work well at latitudes over 45°, and that changing the tilt angle multiple times each year yielded a higher output power than keeping the latitude angle.

One other solution to this problem was to use a tracking system, that would position the cell to get the most power output possible. The two types of tracking systems were 1-axis and 2-axis solar tracking systems [11]. It was found in a study that a 2-axis tracking system produced 25-45% more power than fixed angle solar cells. However, another study shows that under cloudy conditions, this situation was quite the opposite, as 50% more power was received by the fixed-angle solar cells. One other study shows that a north-south axes tracking system achieved 30-45% more power than fixed angle. Comparing these results, it can be said that the choice of using a tracing system or a fixed angle approach comes down to the location where the solar cell will be positioned, weather conditions (as well as heat, due to the possibility of the tracking system introducing extra heat can reduce the power output in places where the sun itself is abundant), and the available investment on the system, as a tracking system will cost more to deploy than a fixed system.

One would think that having the solar cell being deployed in a location where it gets excessive sunlight might be the best case to get the most power output. However, it should be noted that there are multiple different factors that affect the power output that should be taken into consideration as well. One of them is the temperature of the location. A typical solar cell converts 6-20% of incident light into electricity, whereas the rest that doesn't get converted generates heat [10]. This heating effect causes the cell temperature to correlate more with the irradiation than ambient air temperature. However, the ambient air temperature can affect the heat dissipation of the cell, which overall decreases the cell's output efficiency. To add onto this, solar modules experience more rapid degradation as well as lower lifetimes due to high temperature environments. Another factor to keep in mind is the possibility of dust and debris building up on the cell. Dust built up on the cell can cause hot spots, as well as block the absorption of the incoming light. The dust layer can also accelerate the corrosion and degradation of the cell if they aren't regularly cleaned. It should be noted that glass surfaces tend to attract dust less than epoxy or plastics, though encapsulating the cell protects the cell from debris to build up right on the cell, as well as prevent the oxidation of the cell [12]. The encapsulation of the cell can also improve the long-term performance of the cell by protecting the unit from the environmental effects such as ambient moisture, heat, UV radiation and debris. Although it should be noted that specific properties such as reflectivity and transparency of the encapsulation should be ensured to prevent new inefficiencies from causing a drop in the output power.

Overall, there isn't one correct way to deploy solar cells in practice, and multiple factors should be taken into consideration before choosing to proceed with a specific option to ensure the power output of the cell is maximized.

References

[1] https://sotonac-my.sharepoint.com/:x:/g/personal/ec1u24_soton_ac_uk/EVum4YRS5ydCvNTi9EEqe4QBttuWdoZfz528eCCnxUEV_g?e=0UFRky

[2] Alternative Energy Tutorials, "Solar Cell I-V Characteristic and the Solar Cell I-V Curve," *Alternative Energy Tutorials*. https://www.alternative-energy-tutorials.com/photovoltaics/solar-cell-i-v-characteristic.html (accessed Nov. 19, 2025).

[3] TeachEngineering.org, "Photovoltaic Efficiency: Maximum Power Point." Accessed: Nov. 19, 2025. [Online]. Available: https://www.teachengineering.org/content/cub_/lessons/cub_pveff/Attachments/cub_pveff_lesson03_fundamentalsarticle_v11_tedl_dwc.pdf

[4] Alternative Energy Tutuorials, "Standard Test Conditions (STC) of a Photovoltaic Panel," *Alternative Energy Tutorials*. https://www.alternative-energy-tutorials.com/photovoltaics/standard-test-conditions.html (accessed Nov. 19, 2025).

[5] Solar N Plus, "How Temperature Impacts Solar Cell Efficiency," *Solar N Plus*, Jun. 02, 2024. https://www.solarnplus.com/how-temperature-impacts-solar-cell-efficiency/ (accessed Nov. 19, 2025).

[6] M. Boyd and C. Hansen, "Single Diode Equivalent Circuit Models," *PV Performance Modeling Collaborative (PVPMC)*. https://pvpmc.sandia.gov/modeling-guide/2-dc-module-iv/single-diode-equivalent-circuit-models/ (accessed Nov. 19, 2025).

[7] E. L. Meyer, "Extraction of Saturation Current and Ideality Factor from Measuring V_{oc} and I_{sc} of Photovoltaic Modules," *International Journal of Photoenergy*, vol. 2017, no. 1, pp. 1–9, Dec. 2017, doi: https://doi.org/10.1155/2017/8479487.

[8] X. Ma and W.-H. Huang, "Introduction to I−V Curves," *Cran R-Project*, Apr. 14, 2021. https://cran.r-project.org/web/packages/ddiv/vignettes/IVcurve.html (accessed Nov. 19, 2025).

[9] "Lambert's Cosine Law: concept, significance and applications.," *Testbook*. https://testbook.com/physics/lambert-cosine-law (accessed Nov. 19, 2025).

[10] O. Bamisile, C. Acen, D. Cai, Q. Huang, and I. Staffell, "The environmental factors affecting solar photovoltaic output," *Renewable and Sustainable Energy Reviews*, vol. 208, no. 115073, Feb. 2025, doi: https://doi.org/10.1016/j.rser.2024.115073.

[11] M. M. Fouad, L. A. Shihata, and E. I. Morgan, "An integrated review of factors influencing the perfomance of photovoltaic panels," *Renewable and Sustainable Energy Reviews*, vol. 80, pp. 1499–1511, Dec. 2017, doi: https://doi.org/10.1016/j.rser.2017.05.141.

[12] K. Aitola *et al.*, "Encapsulation of commercial and emerging solar cells with focus on perovskite solar cells," *Solar Energy*, vol. 237, pp. 264–283, May 2022, doi: https://doi.org/10.1016/j.solener.2022.03.060.