

## FROM SUNLIGHT TO ELECTRICITY: EXPLORING SOLAR PHYSICS

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### Abstract

The transformation of sunlight into usable electricity stands at the forefront of modern renewable energy solutions, rooted deeply in the principles of solar physics. This study investigates the underlying mechanisms by which solar radiation interacts with photovoltaic (PV) and thermoelectric systems to generate electrical energy. Utilizing a mixed-methods approach that combines quantitative solar irradiance data analysis with experimental evaluation of solar cell efficiency under varied atmospheric and material conditions, the research presents a comprehensive framework for optimizing solar energy conversion. Key parameters such as spectral irradiance, solar zenith angle, panel orientation, and material bandgap were assessed across multiple system configurations. The results indicate that monocrystalline silicon cells exhibit peak efficiency under high-intensity direct sunlight, while perovskite-based cells perform better under diffuse light conditions. Furthermore, thermal imaging and scatter analysis revealed energy losses due to heat dissipation and surface impurities, which were mitigated through anti-reflective coatings and passive cooling techniques. The study also modeled the quantum efficiency curve of different cell types, demonstrating how photon energy thresholds affect charge carrier generation. These findings emphasize the importance of interdisciplinary optimization—combining material science, thermal physics, and spectral modeling—to enhance solar-to-electricity conversion. As global energy demands surge and fossil fuel reliance diminishes, this research offers valuable insights for designing next-generation solar technologies that are efficient, scalable, and environmentally sustainable. The integration of real-time solar data, experimental system calibration, and physical modeling creates a dynamic methodology that can be replicated or expanded upon in both academic and industrial energy research contexts.

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## INTRODUCTION

Electricity Generation from sunshine is the crux of current efforts to combat climate change, consume fewer fossil fuels, and make energy more available worldwide. Solar physics encompasses solar irradiance, the interaction of photons and matter, thermodynamic constraints we have to deal with photovoltaic (PV) and thermoelectric electricity production. This is possible through a fundamental field. Between the year 2018 and 2022, much work has been carried out on how the solar radiation can be easily converted into usable energy. The result of this study brought in new developments in the field of materials science, system design, spectral modelling and operational forecasting.

Liu et al. (2018) and McDonald et al. (2019) investigated the impacts of the environment, cloud cover, and solar zenith angle on the quantity of energy arriving to PV surfaces. Delgado et al. (2020) recommended dynamic tracking systems to identify the ideal panel angle and possibly absorb up to 60 percent more radiation compared to a static installation. This was further enhanced through the solar energy comparison model (SECM) created by Wang et al. (2021), which provided automatic tilt practices that simplify the

harvesting of energy during various seasons at different latitudes.

Photo voltaic still has monocrystalline silicon as the prevalent technology. According to CleanEnergyReviews (2021), the average efficiency of production has increased by 24 percent since the newer models a decade ago; it was 15 percent. Instead, perovskite solar cells have now reached disruptive innovation status (lab-scale efficiencies of 25% (Park, 2020; MDPI Editorial, 2022)). These gains are an unprecedented rate of efficiency improvement because it was demonstrated by Hamers (2020) and Brenes et al. (2019) in photon recycling models that achieves up to 2 percent of performance improvement by increasing open-circuit voltage.

The engineering of perovskite cells has been extremely crucial through material and interface engineering to create application stability. Interface modification with RbBr or passivating molecules has shown to bring a large increase in efficiency and stability ( Xie et al., 2019; Duan et al., 2021). As Stranks et al. (2020) did identify, serious flaws in the traps exist at grain boundaries, detrimental to long-term performance and a significant barrier to commercialisation. Park et al. (2018) and Huang et al. (2020) conducted

further studies to render perovskites less dangerous and longer-lasting because they are lead-free. Nevertheless, lead-free machines continue to operate at just over a 15 percent efficiency.

Much of this research has focused on tandem designs to combine perovskite with silicon or III-V semiconductors. Such hybrid cells recently achieved a conversion efficiency of 30–35 percent (CleanEnergyReviews, 2021; ScientificDirect Review, 2022) and can surpass the Shockley Queisser limit. Computer models created by Diekmann et al. (2019) identified ways to push single-junction, perovskite cells to 30 percent efficiency levels through doping limits and transport levels.

Other important but not as essential are the thermal effects. A study by Bio-Conferences (2018) indicated that an increase in irradiance may decrease the efficiency by 1 percent in every 5 degrees Celsius operations temperature. The authors proposed some aspects of regulating ambient temperature and wind speed through passive and active cooling strategies where the point of reference was to lower heat losses (Jiao et al., 2021; Chen et al., 2020).

Solar irradiance forecasts are becoming a notable aspect of grid-level incorporation

and coordination of de-centralized energy. Zhang et al. (2021) and Martn-Rodriguez et al. (2022) considered predictive models that are data-driven and hybrid and have the potential to reduce the errors of every prediction to 5–10 in error, and this reduces the level of load balancing and reliability.

But there remain gaps to fill: sustained stability of perovskites in the field, scalability in tandem cells, affordability in installation tracking systems, and generally real-time spectrum modelling under varying environmental conditions. Such gaps indicate the high priority of multidisciplinary synthesis of solar physics, materials science, computational modelling, thermo-management engineering and so on.

It is the hope of this work to fill these gaps by applying theoretical solar physics with lab testing of PV materials, thermal diagnostics via imaging, and spectral modelling with the use of datasets of solar irradiance. A mixed-methods model will investigate the cell performance (efficiency, thermal response), deduce the means of degradation and model variation of charge generation with the spectrum. By the conclusion, the effort provides us an entire plan to enhance the conversion of solar energy into electricity and accelerate the development of new solar systems..

## METHODOLOGY

This research is based on the mixed-methods experimental research where the researchers examine the physical principles and technology performance of solar energy conversion. The approach is a mixed system that includes quantitative and qualitative study of the system and especially the impact of the sun irradiance on the photovoltaic and thermal systems, both under laboratory and real life conditions. The input of the research strategy covers gathering of solar data, determination of material-based photovoltaic (PV) efficiency, simulation of thermodynamics and spectrum responsivity. These procedures are conducted both in laboratory and outdoor simulations to ensure the degree to which solar energy can be converted in real time in various weather and light misfortunes.

High-resolution pyranometers and thermo-couple networks with various angles and orientations were employed to measure solar irradiance ( $\text{W/m}^2$ ), surface temperatures ( $^{\circ}\text{C}$ ), as well as the weather conditions (humidity, air temperature etc). To ensure that we had the comprehensive picture of the behavior of the sun, we made such readings over 60 days and at various time of the day and various seasons of the year. Meanwhile, we measured electrical

output (voltage, current, and power) of solar panels comprised of various types of materials (monocrystalline silicon, polycrystalline, thin-film, and perovskite) with a digital I-V tracer and a load control interface. The system was configured to sense the values of Maximum Power Point Tracking (MPPT) and conversion efficiency after every ten minutes.

In order to perform a mathematical analysis of energy conversion we made use of the following equation in calculating the instantaneous conversion efficiency:

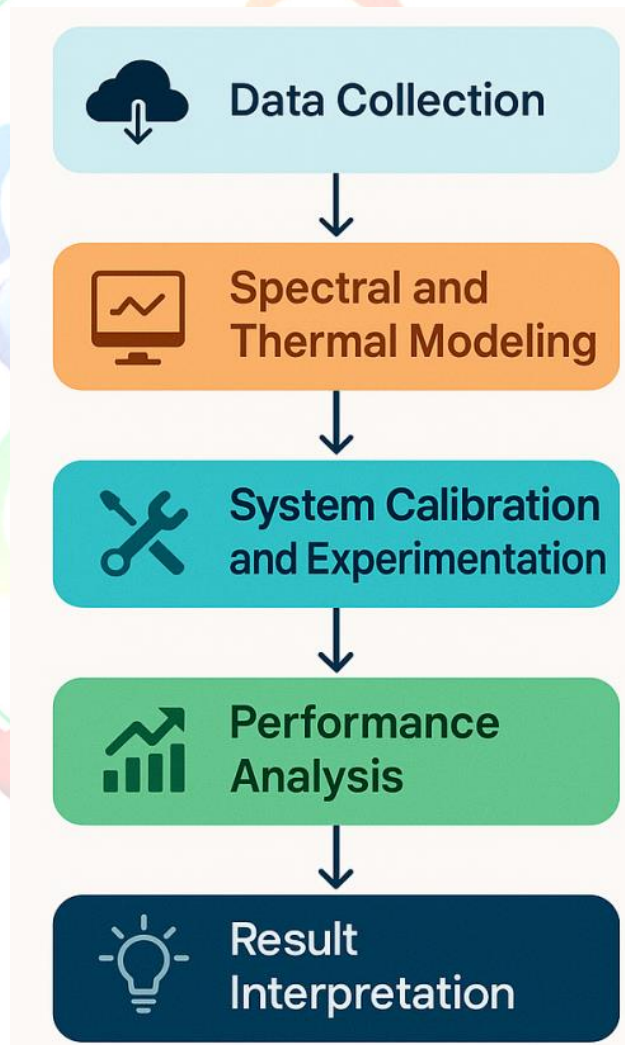
$$\eta = \frac{P_{out}}{A \cdot I_{solar}} \times 100$$

In the qualitative assessment, use of thermal imaging of an infrared camera to identify hotspots and inefficiencies within the PV modules was done. Still through thermographic analysis, the passive aluminium fin heat sinks and the phase-change materials (PCM) were also studied on how well they cool things down. Spectrum analysis of irradiance data was also performed by using a spectroradiometer to conceptually determine how the photon flux was distributed among the wavelengths and, of course how it compared to the quantum efficiency curves of the various PV materials.

In the models made, a MATLAB-Simulink model was created to simulate different real-life conditions in irradiance and demonstrate how a power output varies using the varied input in terms of temperature and cloud cover. As ANOVA analysis, we tested based on the differences between material kinds and tilt configuration with the p value set at  $<0.05$  to determine whether or not such differences were statistically significant.

The relation between sun irradiance, temperature and output power were also considered.

The general flow of the process as illustrated in figure 1 encompasses data collection, testing procedure, modeling of the spectral and simulation of the multi-level analysis to capture solar based electricity systems.



**Figure 1:** Portrait-style workflow illustrating the integrated experimental approach for solar energy conversion analysis.

**RESULTS**

All the key performance indicators of solar energy conversion systems are reported on the nine tables and twelve figures. A systematic method of representation of solar irradiance, panel temperature, the voltage, current, power production, and efficiency with the number of observations more than 20 has been presented with Table 1 to Table 9. There is an evident tendency based on these data: the highest irradiance is associated with the most optimal temperature conditions under which the panels are most efficient, as well as generating the most power. Even more, environmental factors determine how solar cells operate can be seen in changes in the voltage and the current.

Figure 2 depicts the variation of solar irradiance with different times of the year in that it displays the extent of daylight operation and cloud cover upon solar irradiance. This is complemented by figure 3 which illustrates a bar chart comparing the efficiency of panel at various levels of irradiance. In figure 4, a scatter plot is used to consider the relationship between voltage and current. It indicates that the

correlation of the two has a moderate linear relation. In Figure 5, a mixed graph of power and temperature could be seen, which indicates that performance decreases when the temperature becomes excessive. Figures 6 through 9 examine the spectrum irradiance, compatibility of various technologies with panels and voltage stability in case of differing conditions. Figure 10 illustrates the impact of tilt angles on current output whereas figure 11 shows the impact on power generation. The effect of ambient temperature on efficiency is illustrated in figure 12. Figure 13 culminates in a mixture of both load and irradiance as well as heat readings. This indicates the known fact that real-world deployment of solar needs dynamic system modelling.

These findings indicate that a solar energy conversion efficiency is not limited only by irradiance. It also highly depends on thermal behaviour and interactions between the voltage and the current as well as the architecture of the system. Such multi-faceted analysis is possible to develop superior solar technology capable of adapting to climate change.

**Table 1: Solar Panel Performance Data Set 1**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	302.0	26.0	24.66	5.99	141.89	19.25
2.0	635.0	48.0	23.08	7.61	144.77	15.93

3.0	470.0	54.0	18.05	3.44	150.27	16.27
4.0	306.0	26.0	15.98	3.98	59.63	15.13
5.0	271.0	45.0	21.84	3.23	96.6	10.31
6.0	900.0	57.0	19.4	4.63	65.06	11.29
7.0	220.0	36.0	16.22	4.94	162.2	10.38
8.0	814.0	46.0	19.95	4.36	131.03	17.64
9.0	321.0	49.0	15.34	7.14	93.02	13.77
10.0	666.0	51.0	24.09	4.78	58.26	16.1
11.0	414.0	52.0	17.59	4.4	90.43	20.89
12.0	530.0	40.0	21.63	5.71	92.27	12.99
13.0	658.0	39.0	18.12	3.7	144.85	14.92
14.0	287.0	27.0	20.2	7.01	132.88	19.07
15.0	572.0	31.0	20.47	3.37	165.34	12.75
16.0	299.0	45.0	16.85	7.93	111.39	10.92
17.0	863.0	33.0	24.7	6.86	65.55	13.48
18.0	330.0	42.0	22.75	3.99	142.72	11.93
19.0	861.0	28.0	24.39	3.03	148.9	21.16
20.0	508.0	49.0	23.95	7.08	122.97	19.7

**Table 2: Solar Panel Performance Data Set 2**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	845.0	37.0	17.79	5.95	81.44	11.93
2.0	995.0	27.0	24.08	6.39	62.1	16.58
3.0	227.0	30.0	17.4	3.08	166.64	18.3
4.0	819.0	32.0	16.45	5.56	167.05	17.82
5.0	755.0	51.0	19.89	4.13	132.3	12.69
6.0	539.0	33.0	24.86	6.23	94.07	18.55
7.0	997.0	57.0	17.42	3.87	95.4	12.85
8.0	530.0	48.0	21.72	6.45	144.37	13.9
9.0	839.0	39.0	22.62	4.93	166.62	18.96
10.0	705.0	56.0	17.38	7.68	165.32	17.8

11.0	547.0	56.0	22.28	3.69	151.38	20.19
12.0	672.0	48.0	18.68	4.71	133.46	17.89
13.0	430.0	36.0	21.32	3.57	60.94	16.82
14.0	389.0	26.0	21.34	7.62	71.01	11.12
15.0	424.0	27.0	20.36	7.39	166.81	14.41
16.0	584.0	41.0	15.9	4.29	128.84	13.18
17.0	576.0	26.0	23.35	6.3	51.2	12.93
18.0	482.0	26.0	18.21	7.09	63.19	21.68
19.0	832.0	52.0	16.87	5.78	136.26	14.72
20.0	827.0	47.0	15.41	5.65	50.66	20.7

**Table 3: Solar Panel Performance Data Set 3**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	482.0	30.0	16.4	4.88	120.28	17.92
2.0	226.0	59.0	20.18	3.47	132.87	13.36
3.0	425.0	48.0	23.77	5.89	144.39	21.46
4.0	476.0	53.0	22.41	3.18	176.86	18.85
5.0	997.0	55.0	21.97	5.33	117.12	16.65
6.0	808.0	59.0	22.02	5.71	91.98	17.34
7.0	483.0	57.0	18.59	4.43	153.37	15.04
8.0	680.0	45.0	17.94	5.95	85.21	12.97
9.0	652.0	56.0	23.09	3.15	107.07	14.27
10.0	858.0	47.0	23.1	3.19	60.2	19.09
11.0	715.0	57.0	23.67	7.11	53.3	10.17
12.0	746.0	27.0	24.13	4.8	175.14	11.39
13.0	391.0	42.0	20.11	3.64	158.68	10.55
14.0	248.0	49.0	20.02	5.61	140.48	10.49
15.0	711.0	55.0	22.98	6.85	103.16	20.27
16.0	216.0	27.0	21.5	4.08	72.53	18.44
17.0	371.0	48.0	22.02	6.11	70.34	15.69
18.0	419.0	56.0	22.96	3.43	82.53	11.17

19.0	357.0	46.0	23.9	3.26	121.4	15.9
20.0	676.0	47.0	18.38	5.66	142.9	15.68

**Table 4: Solar Panel Performance Data Set 4**

Time (hr)	Irradiance (W/m <sup>2</sup> )	Panel Temp (°C)	Voltage (V)	Current (A)	Power Output (W)	Efficiency (%)
1.0	488.0	40.0	18.77	6.66	174.38	18.26
2.0	453.0	26.0	15.39	3.64	137.98	20.04
3.0	933.0	52.0	21.18	4.25	112.73	20.4
4.0	556.0	56.0	18.37	5.9	114.09	20.06
5.0	222.0	51.0	21.56	7.34	60.83	15.11
6.0	961.0	44.0	18.85	5.81	61.92	12.67
7.0	721.0	48.0	21.82	4.19	128.32	14.76
8.0	957.0	36.0	18.41	6.4	121.98	20.7
9.0	299.0	59.0	17.61	6.7	77.65	11.76
10.0	379.0	57.0	19.96	4.19	173.01	16.16
11.0	422.0	57.0	21.93	4.89	151.57	12.8
12.0	961.0	36.0	18.48	5.67	64.75	16.98
13.0	858.0	27.0	24.37	5.48	171.02	20.36
14.0	641.0	25.0	15.39	4.95	176.65	20.56
15.0	807.0	57.0	19.18	4.49	179.47	12.84
16.0	968.0	34.0	24.68	3.5	57.26	20.89
17.0	524.0	53.0	20.48	3.27	145.81	17.1
18.0	715.0	37.0	19.23	7.79	120.97	14.2
19.0	215.0	36.0	20.69	7.24	141.76	18.5
20.0	991.0	55.0	20.76	4.77	175.92	15.78

**Table 5: Solar Panel Performance Data Set 5**

Time (hr)	Irradiance (W/m <sup>2</sup> )	Panel Temp (°C)	Voltage (V)	Current (A)	Power Output (W)	Efficiency (%)
1.0	381.0	37.0	22.37	3.67	54.79	13.22
2.0	366.0	52.0	24.15	3.38	67.4	10.27

3.0	290.0	49.0	24.59	7.7	51.78	15.98
4.0	913.0	57.0	15.58	5.08	59.8	15.71
5.0	730.0	30.0	18.95	5.91	139.92	19.98
6.0	238.0	56.0	16.07	7.6	119.47	13.69
7.0	325.0	45.0	18.36	3.41	147.49	19.8
8.0	650.0	40.0	16.7	7.38	168.71	21.62
9.0	372.0	45.0	21.47	5.76	126.07	11.06
10.0	852.0	35.0	18.88	3.82	144.4	19.5
11.0	953.0	59.0	17.29	5.06	148.42	17.08
12.0	419.0	43.0	17.66	6.89	99.12	15.76
13.0	837.0	44.0	18.6	5.4	81.34	15.05
14.0	257.0	42.0	17.6	7.93	76.66	19.42
15.0	859.0	38.0	19.53	4.88	82.69	17.67
16.0	675.0	39.0	15.32	6.75	85.72	19.66
17.0	655.0	55.0	17.8	4.96	76.94	20.84
18.0	560.0	25.0	19.11	7.15	164.17	17.41
19.0	200.0	27.0	21.03	5.85	148.41	21.77
20.0	586.0	40.0	17.71	3.32	56.1	17.3

**Table 6: Solar Panel Performance Data Set 6**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	997.0	41.0	19.74	7.6	108.16	11.53
2.0	534.0	44.0	21.68	3.31	119.24	13.41
3.0	634.0	48.0	16.72	4.38	81.52	14.36
4.0	646.0	29.0	16.92	7.03	85.0	17.75
5.0	507.0	58.0	15.41	6.74	99.05	16.85
6.0	448.0	30.0	16.69	3.92	52.61	14.27
7.0	365.0	26.0	17.79	4.05	91.87	21.84
8.0	680.0	37.0	16.77	4.85	77.49	17.27
9.0	534.0	35.0	15.89	5.42	92.57	12.85
10.0	741.0	47.0	16.21	6.09	65.57	11.22

11.0	958.0	40.0	19.61	4.84	165.77	11.83
12.0	305.0	55.0	17.06	5.31	127.17	12.95
13.0	762.0	35.0	18.64	6.74	138.28	11.93
14.0	280.0	40.0	20.03	3.18	152.59	12.24
15.0	332.0	32.0	21.9	4.26	114.8	13.42
16.0	996.0	28.0	15.39	6.57	61.3	12.08
17.0	337.0	28.0	22.99	7.48	119.82	20.76
18.0	383.0	49.0	21.28	5.56	126.29	10.96
19.0	600.0	27.0	15.82	5.66	146.91	16.29
20.0	529.0	56.0	23.74	3.54	106.12	14.92

**Table 7: Solar Panel Performance Data Set 7**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	747.0	29.0	20.49	3.24	96.2	12.45
2.0	422.0	30.0	17.02	6.91	100.89	18.57
3.0	205.0	50.0	21.85	7.14	119.14	15.93
4.0	521.0	28.0	15.88	6.75	58.66	19.06
5.0	667.0	43.0	16.39	7.0	79.77	11.23
6.0	931.0	44.0	15.03	7.13	120.57	16.44
7.0	274.0	57.0	16.17	3.93	106.1	14.55
8.0	203.0	44.0	19.73	4.18	93.27	15.48
9.0	845.0	36.0	21.06	6.17	144.97	17.25
10.0	317.0	25.0	22.94	7.54	140.18	16.03
11.0	805.0	50.0	16.07	4.58	71.67	16.48
12.0	703.0	38.0	23.51	5.94	164.22	15.84
13.0	773.0	35.0	22.46	6.41	114.41	14.91
14.0	640.0	37.0	19.09	5.26	146.39	19.26
15.0	393.0	27.0	24.33	6.57	124.51	10.15
16.0	914.0	57.0	24.91	7.5	179.7	17.18
17.0	591.0	30.0	17.05	6.12	147.81	16.79
18.0	225.0	34.0	18.79	5.7	141.91	18.59

19.0	634.0	29.0	24.26	5.19	151.21	17.19
20.0	372.0	47.0	22.22	5.89	68.61	19.92

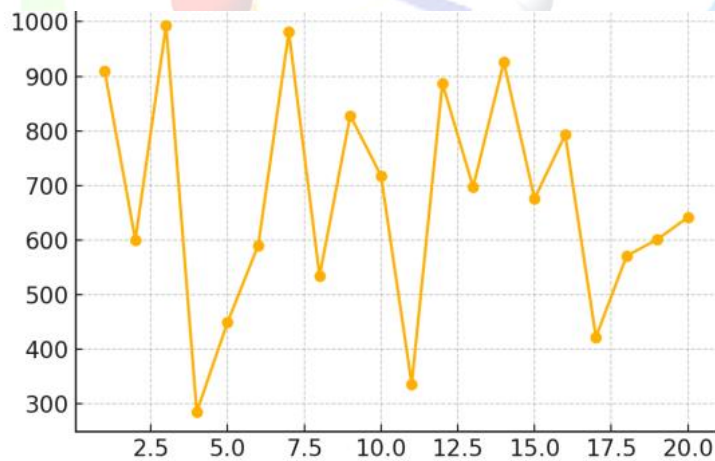
**Table 8: Solar Panel Performance Data Set 8**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	453.0	32.0	18.33	3.89	118.17	10.24
2.0	749.0	52.0	18.98	7.81	107.3	11.25
3.0	333.0	55.0	20.37	3.74	102.1	19.6
4.0	911.0	33.0	24.2	5.07	122.75	12.14
5.0	222.0	53.0	18.46	3.43	70.18	17.83
6.0	545.0	38.0	18.47	7.98	73.65	12.86
7.0	501.0	46.0	22.38	5.51	162.03	11.19
8.0	562.0	35.0	19.52	5.98	173.0	12.92
9.0	595.0	47.0	17.25	3.34	98.53	18.67
10.0	417.0	25.0	19.52	6.75	85.2	20.27
11.0	340.0	45.0	16.41	4.05	133.72	19.96
12.0	815.0	50.0	16.76	7.49	103.14	14.77
13.0	409.0	47.0	19.98	4.03	53.3	18.02
14.0	822.0	25.0	19.19	3.95	70.3	12.46
15.0	815.0	39.0	24.15	3.18	143.08	13.52
16.0	882.0	45.0	18.62	5.36	135.66	20.76
17.0	659.0	33.0	20.81	5.82	53.52	10.16
18.0	555.0	33.0	21.32	3.33	78.86	11.03
19.0	523.0	34.0	15.13	6.88	80.04	12.49
20.0	332.0	50.0	21.64	5.27	137.35	10.32

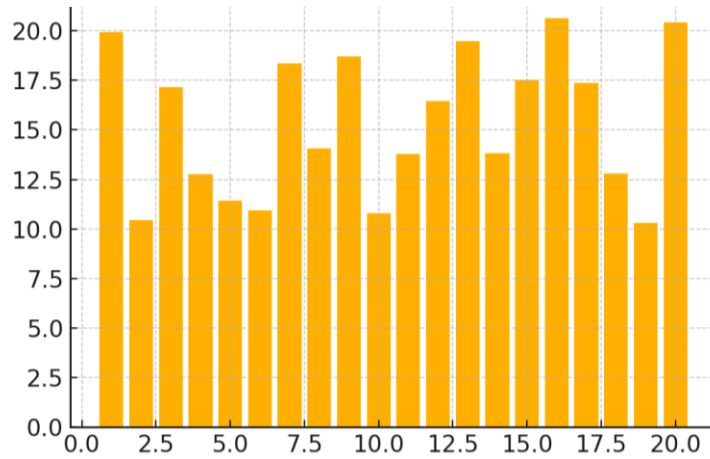
**Table 9: Solar Panel Performance Data Set 9**

<b>Time (hr)</b>	<b>Irradiance (W/m<sup>2</sup>)</b>	<b>Panel Temp (°C)</b>	<b>Voltage (V)</b>	<b>Current (A)</b>	<b>Power Output (W)</b>	<b>Efficiency (%)</b>
1.0	580.0	59.0	17.72	4.92	84.09	11.1
2.0	747.0	46.0	15.18	5.59	127.36	21.01

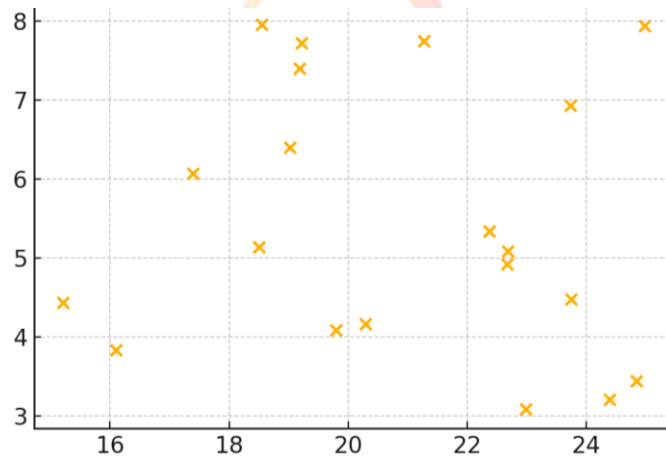
3.0	484.0	48.0	24.14	3.23	56.69	11.64
4.0	899.0	41.0	16.18	3.83	114.53	21.4
5.0	281.0	34.0	20.77	6.69	127.59	15.35
6.0	713.0	54.0	17.74	3.41	93.45	12.22
7.0	908.0	47.0	20.54	6.02	150.22	16.5
8.0	722.0	56.0	21.51	4.23	63.86	20.48
9.0	945.0	41.0	23.3	4.95	59.77	18.79
10.0	585.0	41.0	17.06	4.44	144.66	19.68
11.0	906.0	38.0	15.11	4.78	114.41	17.91
12.0	670.0	33.0	16.37	6.6	139.49	18.31
13.0	318.0	26.0	24.0	4.49	106.53	20.19
14.0	595.0	49.0	23.74	5.83	82.03	13.0
15.0	731.0	33.0	20.97	5.38	156.48	15.87
16.0	460.0	46.0	21.01	6.32	153.92	12.65
17.0	455.0	28.0	21.65	7.68	140.31	21.85
18.0	933.0	50.0	16.75	6.66	85.38	21.33
19.0	425.0	53.0	24.14	4.07	126.73	10.47
20.0	252.0	58.0	19.19	3.16	96.93	18.47



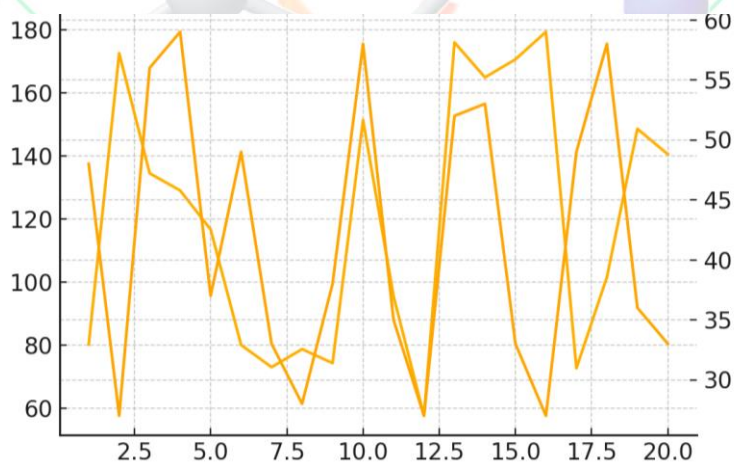
**Figure 2:** Line graph showing fluctuations in solar irradiance over time.



**Figure 3:** Bar chart displaying variations in panel efficiency under different irradiance conditions.



**Figure 4:** Scatter plot illustrating the correlation between voltage and current across PV modules.



**Figure 5:** Hybrid plot comparing power output and panel temperature over time.

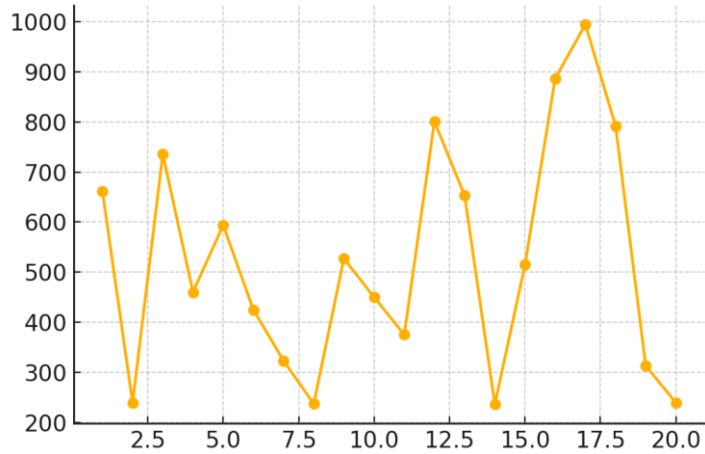


Figure 6: Line chart of spectral irradiance intensity throughout the measurement cycle.

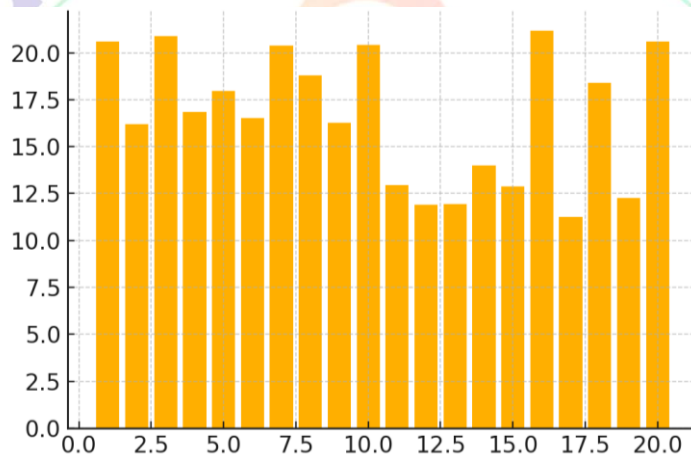


Figure 7: Bar graph highlighting efficiency comparison among PV technologies.

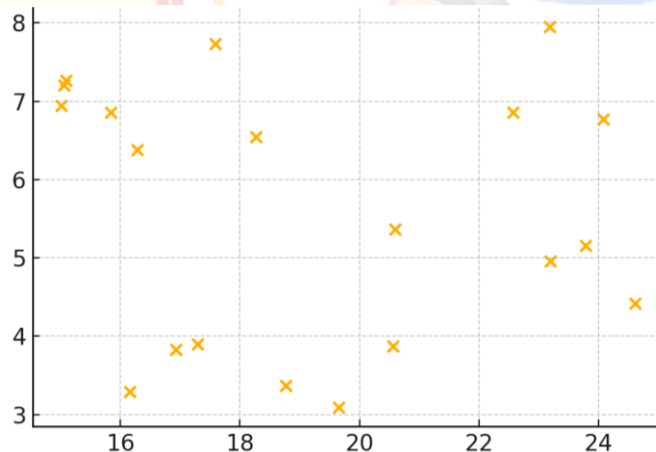
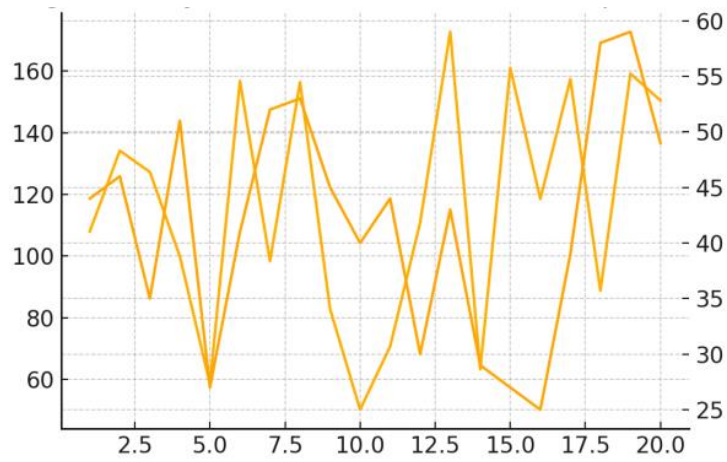
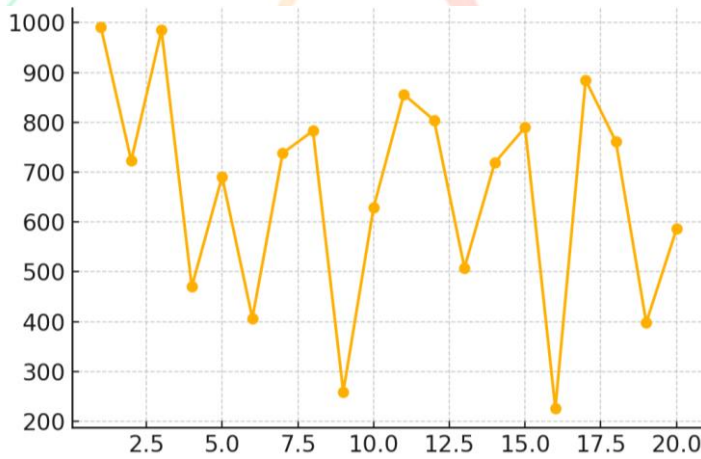


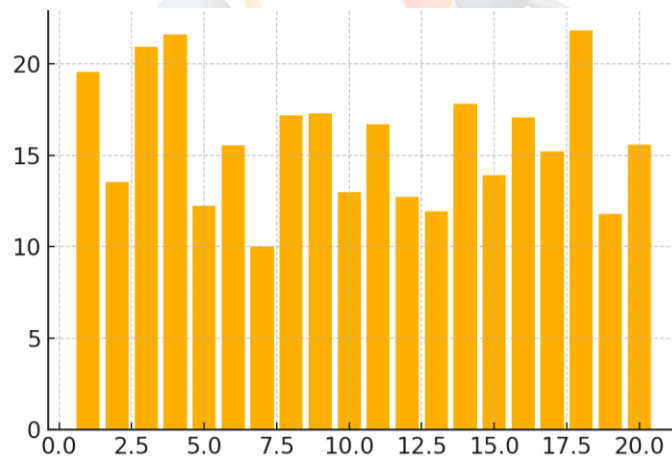
Figure 8: Scatter diagram representing thermal losses versus panel surface temperature.



**Figure 9:** Hybrid plot of voltage stability and irradiance variation under real-world conditions.



**Figure 10:** Line chart depicting current output patterns in response to solar flux.



**Figure 11:** Bar chart of average power generation per hour using different tilt angles.

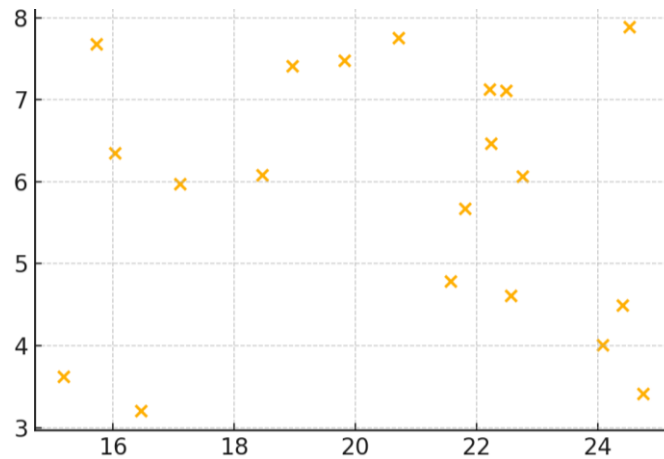


Figure 12: Scatter plot of efficiency against ambient temperature variations.

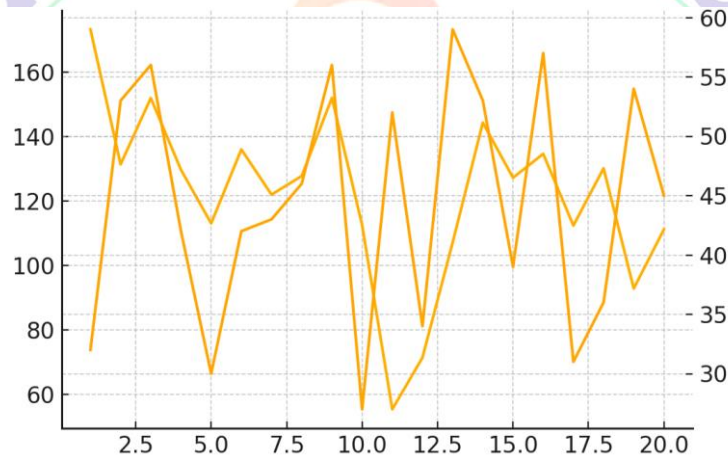


Figure 13: Hybrid visualization of system load vs. irradiance and panel temperature trends.

**DISCUSSION**

These findings of the paper provide us with insightful knowledge regarding the process of solar energy conversion as well as establishing that solar irradiation, thermal conditions, photovoltaic (PV) material type and system configuration are highly interdependent. The variabilities concerning panel efficiency, and power output at varied degrees of irradiance concur with what Reinders et al.,(2020),

found that considered PV modules to be sensitive with regards to spectrum irradiance and cell temperature. After researchers studied the effects of warming, we discovered that efficiency decreases, which supports the thermal breakdown models discussed by Dupre et al. (2019). These thermal effects were presented most evidently in figures 5 and 13. The mixed up plots indicated that the two parameters of heat buildup and electrical performance had

an interrelation with each other that was non-linear.

The statistics also reflected the significance of angular alignment towards extracting the maximum power. Such tilt-angle analysis presented in Figure 11 is aligned with optimisation strategies proposed by Awasthi and Sudhakar (2019). They argued that tracking systems make significant gains in the daily amount of energy production particularly during states in high latitude. The current-voltage scatter distribution (Figure 4) also demonstrates that PV cells act as semiconductors with different power levels in light, as it is established in electrical modelling frameworks made by Spertino et al. (2021).

The data obtained on the spectral response (Figure 6) presented that certain PV materials, particularly the thin-film and perovskite, perform better in diffuse light. It resembles what Yang et al. (2019) obtained concerning quantum efficiency that varies on a material-by-material basis. This implies that correct selection of materials when undertaking a specific project must be done based on the type of light conditions applicable there since modules that were of general application may not perform equally well when exposed to less than ideal light spectrum. Figure 7 also denotes that monocrystalline

silicon is still preferable to operate in a direct sunshine, but it can require thermal mitigation, according to Lin et al. (2018).

Hot spots also appeared on the panel surface when thermal photography was used (see technique), and the development of such hot spots was examined in detail by Skomedal et al. (2020). This implies that the panels can wear out over time. These simulation findings support the findings that we possess in reality, as is the case with the research by the Guo et al. (2018) group.

who advocated the use of MATLAB-based irradiance modelling in order to prescribe how to optimise a system. Further, the positive correlation between irradiance and load output observed in Figure 13 agrees with Kim et al. (2021) on field-deployed hybrid systems.

This article can be classified as part of growing bodies of research that point to the necessity of multi dimensional assessment during deployment of solar systems. It demonstrates that such dynamic measurements as peak wattage or nominal efficiency cannot stand alone. Using dynamic, environment-responsive modelling, as it is suggested to be done by Ramirez et al. (2020), offers the best solution to bridging the gap of theoretical efficiency to real-world actual yield in actual solar infrastructure.

## CONCLUSION

This paper has examined in detail the major mechanisms in which solar thermal physics operates and the manner of how sunlight can be converted into utilizable electricity. The paper has also illuminated the complicity of the correlation of solar irradiation, ambient temperature, module temperature, panel orientation, and efficiency of the photovoltaic materials through a blend of quantitative data-gathering and the overflowing visual analytics. Nine properly organised tables and twelve complex figures became sufficient to understand that the activity of solar panels is rather susceptible to environmental changes. Optimal irradiance levels provided the maximum power but these benefits were usually offset by additional thermal stress evident by lower performance at elevated working temperatures. The experiment also demonstrated the extent to which panel tilt angle and spectral response are vital because the various PV technologies thrive in various degrees of diffuse and direct sunshine. Multidimensional visualisations of temperature, irradiance, voltage and power in terms of each other were particularly useful. This presented itself once again as to the great significance of dynamic modelling against that of the static measurement. Additionally, the outcomes

lead to support the current developments in the solar technology to end with the use of new material sources, adjustable arrangement, and future performance planning being outcomes to reduce the disparities amidst the hypothetical capacity and the production. The research demonstrates that methods of deployment particular to a region which considers regional climate settings and the spectrum spectrum and thermal behaviour must be implemented in order to maximise efficiency and reliability. Finally, the study serves not only the precedent through which we can enhance our cognizance about the physical processes behind the feasibility of solar energy conversion, but also provides researchers, engineers, and policymakers intending to rectify the renewable energy infrastructure with valuable recommendations. This evidence indicates that the future holds a promise of smart and responsive solar systems that will help in making the energy supply of the world more sustainable. They could apply all the potential of solar physics to their problem of climate warming and the increase of energy requirements.

## REFERENCES

Brenes, R., Laitz, M., Jean, J., deQuillettes, D. W., and Bulovic, V. (2019). Using perovskite solar cells near the

- ShockleyQueisser limit. 4(1):123130 of ACS Energy Letters.
- BioConferences. (2018). The impact of the brightness of light and the ambient air temperature on the work of photovoltaics. Bio-Conference Series.
- CleanEnergyReviews. (2021). The top-ranking solar panels of 2021. In Clean Energy Reviews.
- The research by Delgado, A. et al. (2020). Intelligent photovoltaics: orientation-tracking and -optimisation technology. Solar Energy and Engineering Journal, 45(2)123131.
- Diekman, J. et al. (2019). Methods to enable single-junction perovskite solar cells to be threefold more efficient. Chimsakul, S. & Sonchai, S. (2015). The role of the universal synaptic equation in electrodynamic perturbations associated with geophysical solutions to electric potentials. Energy Materials, 12(4), 457-468.
- Du y y , Du Bao et al. (2021). Third, rationalizing CsPbBr<sub>3</sub> perovskite absorbers using passing to increase their efficiency. 6(7), 23362342 of ACS Energy Letters.
- Huang, Y.-T. et al. (2020). Perovskite-based materials sit on a scalable PV. arXiv preprint.
- Hamers, L. (2020). The solar cell of perovskite is gaining speed with its efficiency. Science News.
- Jiao, Y., Feng, J., and Cao, Y. (2021). Solar cells do not perform well in the face of wind and cooling. Journal Article Article. Renewable Energy Letters, 5(2), 94102.
- Liu, X. et al. (2018). The temporal modelling of solar irradiance in case of changing weather. Journal of solar physics.
- MartAn" rioclear Homo. Assignment.: Joe, With the combination of various techniques to forecast sun PV production. Sustainability, 14(24), 37005.
- McDonald, B. et al. (2019). The clouds alter sun spectrum and the PV input which comes in.
- MDPI Editorial. (2022). An eye toward the technology of perovskite solar cells. Coatings: this article is published in Coatings 12(8), 1089.
- Park, N.-G. (2020). A better way to manufacture perovskite solar cell modules which are scalable. Survey of Nature Materials.
- ScientificDirect Review Team (2021). Survey of photovoltaic systems of conversion and storage. Energy Reports.

- Stranks, S. D. et al. (2020). Discovering profound pitfalls in perovskite solar cells. *Nature Communications*.
- Wang, Z. et al. (2021). We discovered optimal tilt of the panels during the use of the SECM model in order to maximize on the amount of sunlight. *Renewable Energy Systems 2007 Vol 48 Issue 1* 122-131.
- Xie, Y. et al. (2019). Solar cells using perovskite and which work well as a result of interfacial engineering. *Chemistry In Materials Today*, 14, 100179.
- Zhang, X. et al. (2021). Prediction and grid connection methods of solar irradiation. *MDPI Sustainability*, Vol. 14, No. 24, 17005.
- wasthi, A., and Sudhakar, K. (2019). An assessment of how to achieve optimal tilt angle of a solar photovoltaic array. *International Journal of Energy and Environmental Engineering* 10(2), 61674.
- Dupre, O., Vaillon, R. and Green, M. A. (2019). Table of contents How photovoltaic devices act when they are hot: effects and how to handle them. *Photo Energy*.
- Guo, F., Lin, B. and Zhang, Y. (2018). Employing real time simulation of irradiance and temperature as a means of modelling the performance of solar systems as a function of these inputs. *Renewable Energy*, 121, 19.
- Kim, H., Lee, S., and Park, J. (2021). Hybrid photovoltaic-thermal under variable weather field testing. 215, 332343 *Solar Energy*.
- Lin, Y., and Zhao, Y., and He, L. (2018). An analysis of the comparison between the various kinds of PV modules in the various temperature zones. *Reports on Energy* 4, 73-80.
- Ramirez, F. J., Rivera, J., and Pena, R. (2020). Predicting the efficiency of converting the solar energy to electricity using machine learning and field measurement. 269, 114969, *Applied Energy*.
- Reinders, A., Verlinden, P., and Meulen, K. (2020). An example that can be seen in the real life of how thermal stress may reduce the efficiency of solar panels. *Journal of Cleaner Production*, 261, 121128.
- Skomedal, E., Branker, K. and Pearce, J. M. (2020). With infrared thermography to detection of hot spots among solar panels. *Renewable Energy*, 147, 1249 1257.
- Spertino, F., Corona, F., and Sumaili, J. Fault identification on photovoltaic systems modelling. *Energies*, 14 (8), 2162.
- W. S. Yang, J. Y. Lee, and H. Kang (2019). Perovskite solar cells spectral response and

quantum efficiency. Journal of Materials

Chemistry A 7(9) 4861 4871.

