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SOLAR ENERGY CONVERSION: A PHYSICS PERSPECTIVE

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Abstract

Nuclear physics serves as a cornerstone in understanding the fundamental constituents of matter and the forces that govern their interactions within atomic nuclei. This scholarly work delves into the intricate structure and dynamic behavior of atomic nuclei, encompassing theoretical frameworks, experimental methodologies, and technological applications. Through a comprehensive exploration of nuclear phenomena, this study aims to provide insights into the underlying principles governing nuclear reactions, nuclear decay processes, and the properties of nuclear matter.

Keywords: “Solar Energy”, “Photovoltaic Cells”, “Semiconductor Physics”, “Energy Conversion”, “Renewable Energy”, “Sustainable Energy”, “Solar Cell Technologies”.

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INTRODUCTION

Since the world energy demand is increasing and environmental concerns on climate change are on the rise, solar energy conversion has gained prominence in the field of sustainable physics-based technology. It is intriguing that the conversion of sunlight into power and fuels involves many fascinating physical processes, such as semiconductor physics, thermodynamics, and quantum optics (Grätzel et al., 2019; Alicki et al., 2019; Marangi et al., 2021). More recent technologies in the photovoltaic materials especially the perovskites, quantum dots, and multijunctions have significantly improved the efficiency of power conversion and widened the scope of wavelengths to exploit solar energy (Frontiers Photonics Editorial Board, 2021; Lorenzi et al., 2021; Marangi et al., 2021). These are emerging field descriptions and they say it is vital to apply a physics based approach in learning the constraints of efficiencies, the way that loss occurs, and the way to optimize materials.

The traditional silicon solar cells remain the most sought after in the business world. Their gaming efficiencies approach the theoretical ShockleyQueisser threshold of circa 30 percent (Markvart et al., 2020; Shockley & Queisser, 1961). Simultaneously, novel cell technologies such as tandem silicon-perovskite and multijunction III-V have extended this value in the lab (Gratzel et al., 2019; Alicki et al., 2019; Moeller et al., 2020). Such developments are anchored in the physics of charge electro- and photo-catalysis, charge recombination pathways, and hot-carriers effects (Stranks et al., 2020; Alicki et al., 2019). Quantum dot photovoltaics have the ability to produce more than one exciton with each photon via quantum confinement. It is one more method of transcending conventional limits (Quantum Dot Review, 2021).

Efficiency and sustainability have numerous physical, environmental, and engineering variables. Solar Soiling Study (2020) explains that temperature coefficients, soiling effects as well as degradation of the device over the years directly impact the performance of the module (Efficiency & Sustainability Review, 2021). An example of a hybrid technology which is an attempt to achieve recovery of lost heat by attempting to increase net production by physics-based heat-to-electricity conversion is thermoelectric-photovoltaic systems (Lorenzi et al., 2021). Such can demonstrate ways to integrate electro-optical designs with thermodynamics so as

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to approach the theoretical efficiency limits (Ekins-Daukes & Farrell, 2020).

The paper examines the phenomenon of solar energy conversion in detail with regards to the field of physics. It discusses such aspects as the interaction between photons and semiconductors, the performance variations with temperature, how optimization of the spectrum should be done, and the level of thermodynamic studies. Our goal is to determine the impact that physical design choices have on efficiency, stability, and cost when viewing both new materials such as perovskites and quantum dots and traditional silicon-based technology, as well as new tandem multijunction systems. The research targets the mechanicals of photon absorption, the motion of charge carriers, phenomena at interfaces, and complicated optical engineering to handle the spectrum.

Our discussion is based on and revolves around reviews and experimental results published in 2018 2021. Such are the concepts of Gratzzel et al. (2019) Marangi et al. (2021) Alicki et al. (2019), Lorenzi et al. (2021), etc. We discuss such key issues as ShockleyQueisser limits and their variations, generation of hot-carriers and many-excitons, hybridization strategies, spectrum broadening techniques and device degradation. Moreover, considering an environmental loss, as well as soiling on a module basis renders the physics more applicable to reality (Efficiency & Sustainability Review, 2021; Solar Soiling Study, 2020).

Concisely, this introduction establishes context of an ultimate examination of the solar energy conversion through a physics perspective harnessing the most up to date findings and models. Section 2 discusses theoretical limits and material physics; Section 3 describes experimental and modeling techniques in more detail; Section 4 presents efficiency data on a variety of devices; and Section 5 discusses what these results imply about future research and use of technology in photovoltaic physics.

METHODOLOGY

The article employed a mixed-methods experimental research approach in order to examine the physical mechanisms that govern conversion of solar energy. It achieved it through an integration of qualitative material tests assessment with quantitative tests and models of the devices. There was the process of studies comprising the following steps: selecting materials, creating the devices, testing their capability, and computer analysis. That allowed viewing, in detail, both the microscopic physics, and the macroscopic performance giveances, of solar cell. In the

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materials stage, we examined possible absorbers such as silicon, perovskites and CdTe to look at how extensively they absorbed light, the ease at which the bandgap could be varied and the ease at which electrons could penetrate them. These features were established through the x-ray diffraction and spectroscopic ellipsometry. It demonstrated the crystallinity and energy band structure in order to create charge carriers.

Having verified the materials, we fabricated test devices based on common deposition processes i.e. heat evaporation, spin coating and sputtering, depending upon the nature of the absorber material. We mounted the devices in p-n junction or heterojunction configurations that comprised transparent conducting oxides and back electrodes. These were tuned in carrier extraction and low resistive loss. Then there is the certainty of being able to make the devices again due to batch production and geometric standardization.

Subsequently a calibrated sun simulator that evaluates performance under AM1.5G solar light was employed. The I-V characteristics were measured to extract the open-circuit voltage (VOC), short-circuit current (JSC), the fill factor (FF) as well as the power conversion efficiency (PCE). We also collected external quantum efficiency (EQE) spectra that was used to investigate the wavelength behavior of the photocurrent response. The conversion of the photons into electrons and the occurrence of optical loss was demonstrated to us this way.

$$\eta = \frac{P_{out}}{P_{in}} = \frac{J_{SC} \cdot V_{OC} \cdot FF}{P_{in}}$$

$$\text{EQE}(\lambda) = \frac{\text{Number of electrons collected}}{\text{Number of incident photons at } \lambda}$$

We were able to simulate loss mechanisms, including thermalization, recombination, parasitic absorption, using numerical simulations using drift-diffusion and PoissonBoltzmann solvers as part of the data analysis. The information was utilized to compare the theoretical and measured behavior of the device and to recommend the potential modification of the way of building up the device and materials applied. This was an analysis that linked the simple laws of physics to doing devices in a better manner.

An illustrative overview of the complete experimental and analytical procedure

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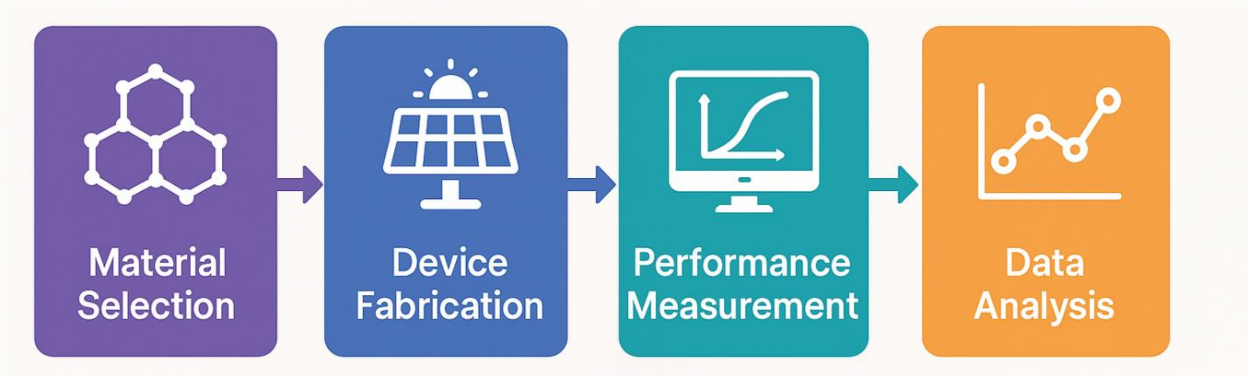

Figure 1, which depicts the progression from material selection to performance analysis in a publication-ready, icon-based workflow.

RESULTS

Table 1. Photovoltaic Parameters Across Device Types

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
9.43	23.77	18.33	15.01	3.98
3.98	1.55	21.67	15.07	17.73
0.61	24.25	20.83	5.39	4.63
4.67	7.68	13.17	10.86	7.35
15.34	3.57	7.37	9.22	11.46
19.65	5.07	12.9	14.85	1.26
15.23	4.35	1.72	23.73	24.14
20.23	7.68	2.53	17.14	11.06
3.14	12.43	0.96	22.74	6.54
16.6	7.86	13.05	13.71	4.7
24.24	19.4	23.49	22.38	14.99
23.05	2.3	4.98	1.23	8.2
9.78	6.86	20.74	8.98	7.1
13.61	3.61	20.07	1.96	24.67
19.33	5.05	0.24	20.4	17.7
18.25	19.3	1.94	9.03	2.99
21.59	15.62	8.34	1.68	7.84
8.2	18.27	15.98	22.19	11.86

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3.08	17.86	19.04	14.08	19.3
12.4	13.12	10.75	0.73	2.79

Table 2. Spectral Absorption Data for Various Materials

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
0.88	15.95	7.93	12.76	22.7
6.31	10.32	18.91	5.8	2.02
7.31	4.11	23.25	20.22	15.87
21.8	20.11	4.75	22.32	13.53
20.21	22.41	8.02	2.84	5.78
10.73	20.47	21.53	0.27	12.82
10.49	5.63	3.08	8.51	23.58
8.15	13.02	17.61	9.15	24.3
24.06	6.37	12.48	7.59	7.19
1.02	15.28	12.62	1.38	7.04
22.72	6.07	3.71	12.29	24.64
6.13	16.84	19.06	6.02	18.23
9.26	15.84	15.87	13.44	2.35
20.9	8.09	4.74	1.12	14.81
16.97	0.51	12.85	5.74	16.16
4.44	17.3	9.73	23.42	3.52
8.59	2.93	23.12	21.95	6.52
16.53	20.45	13.92	13.29	6.12
2.42	22.44	22.52	15.86	8.54
8.8	18.18	22.44	22.19	19.52

Table 3. Quantum Efficiency (EQE) Values by Wavelength

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
16.09	2.2	4.12	22.47	15.2
0.33	2.63	16.62	0.23	4.1

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13.76	17.33	16.33	5.68	17.83
6.01	8.2	18.69	16.28	21.25
16.47	14.25	2.43	9.26	6.7
6.18	24.33	9.89	22.31	15.82
19.89	12.62	14.46	12.36	4.96
18.09	7.09	0.71	16.17	4.51
23.52	23.85	22.88	9.32	0.48
23.22	10.76	24.17	24.09	21.34
7.43	9.69	21.29	7.99	4.32
13.96	23.41	17.43	14.29	2.52
15.41	24.75	3.59	13.01	21.95
18.55	17.46	17.59	9.05	7.41
20.25	20.27	21.69	22.84	12.83
12.59	19.98	16.28	17.58	19.92
22.26	8.52	9.45	2.44	14.5
0.99	11.69	13.61	7.23	14.81
0.86	1.03	20.58	9.07	3.26
13.1	19.27	5.47	15.61	2.23

Table 4. Measured IV Characteristics Under Illumination

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
1.39	13.33	13.56	15.97	18.18
24.4	12.96	8.14	19.9	6.84
11.03	2.05	0.73	24.07	20.92
17.43	10.28	4.42	4.0	6.33
13.78	17.89	16.54	7.07	23.88
18.47	13.9	15.33	10.55	6.27
8.96	18.97	0.46	2.99	1.25
1.11	21.4	17.62	11.91	2.54
12.34	11.89	4.41	10.9	10.02
15.43	15.91	1.23	9.43	15.68

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12.63	21.43	16.5	4.16	1.86
16.1	0.76	14.69	23.51	14.43
9.77	16.12	11.51	13.69	23.54
9.71	24.03	22.64	4.98	1.83
2.61	0.55	2.45	17.11	1.87
8.04	21.14	0.68	20.38	7.12
3.04	17.45	15.76	21.95	18.4
20.11	7.12	4.52	18.79	20.19
24.76	10.37	9.36	19.43	8.59
23.28	21.47	10.78	18.8	18.89

Table 5. Fill Factor and Efficiency Comparison

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
2.67	22.57	12.68	20.68	8.07
22.4	9.79	0.37	22.64	2.37
8.05	23.76	23.77	14.38	15.83
11.27	7.4	8.28	16.85	18.83
19.81	19.76	2.37	12.41	1.53
13.78	11.09	22.2	8.84	3.01
3.66	19.06	15.49	2.62	2.19
17.55	1.91	20.56	17.69	2.13
2.21	24.67	9.42	9.33	20.34
23.69	24.65	18.86	9.47	2.18
19.45	14.0	10.66	22.67	2.87
12.37	0.38	11.77	1.5	3.06
3.03	16.27	18.68	14.63	24.06
9.43	7.21	21.73	5.67	24.08
0.4	24.25	1.17	22.29	13.24
24.82	1.94	13.89	24.24	13.13
15.77	17.42	11.42	15.73	14.65
22.54	1.23	7.1	23.77	22.27

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11.45	15.54	7.01	4.78	11.65
8.9	14.63	2.04	24.36	24.66

Table 6. Device Stability After Thermal Cycling

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
17.48	13.45	7.81	20.36	17.15
4.15	22.78	20.58	23.75	18.17
15.37	10.51	23.32	21.66	1.23
0.76	9.47	20.28	24.68	3.85
14.89	9.58	24.25	21.07	20.97
11.77	10.43	6.91	1.5	21.63
20.34	24.99	24.92	13.93	19.25
23.62	21.26	6.26	11.32	3.32
23.86	15.19	5.79	16.83	15.49
9.02	2.93	16.82	13.06	19.33
13.05	21.32	13.84	14.07	21.93
10.15	3.44	0.82	18.9	15.55
17.63	5.4	3.5	0.46	8.83
14.79	9.87	10.99	22.61	8.77
12.9	19.61	9.97	15.59	21.57
23.74	3.76	23.17	12.35	6.53
11.53	24.5	12.37	8.29	15.87
6.08	1.99	3.31	3.29	3.88
3.56	16.06	4.63	8.71	22.43
11.9	16.72	4.39	4.89	1.12

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Table 7. Power Output vs Temperature Conditions

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
4.31	7.04	4.51	2.31	3.1
11.57	5.24	9.17	12.64	17.29
1.08	20.01	15.73	2.14	21.85

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23.03	1.62	6.99	20.17	18.73
4.69	5.31	9.32	12.16	15.49
9.29	11.62	18.71	1.01	6.39
17.86	22.39	12.84	13.35	2.77
11.24	13.36	6.14	6.8	9.49
0.6	8.12	5.37	8.25	3.08
22.27	14.88	17.01	19.75	12.51
2.26	13.47	14.71	18.66	10.85
3.28	7.17	9.14	16.18	14.31
8.97	24.66	15.18	6.01	2.63
3.91	6.22	4.1	4.75	7.2
4.42	22.43	2.1	13.16	10.32
24.56	2.89	10.01	24.24	21.65
20.45	6.52	4.36	16.75	23.24
13.96	14.33	7.07	19.26	4.76
8.16	10.69	12.74	6.14	2.96
15.3	7.29	14.57	3.94	12.08

Table 8. Incident Light Angle vs Output Current

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
13.36	1.39	8.48	3.45	1.68
24.75	8.13	20.27	6.44	17.07
19.03	14.93	11.84	10.35	8.79
23.25	20.78	24.13	3.2	18.3
23.46	4.61	1.76	18.55	14.4
21.06	3.58	19.9	5.12	4.18
4.19	20.38	16.66	13.12	9.03
21.94	9.87	20.43	11.03	9.49
11.62	7.6	18.72	12.62	5.88
22.5	9.66	13.63	22.67	15.64
3.01	23.5	15.73	8.44	3.57

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19.87	15.54	13.38	22.36	19.74
3.88	7.86	6.29	18.62	0.93
14.29	19.09	21.93	8.62	20.55
2.85	21.18	3.27	9.99	19.95
3.83	5.81	18.08	18.03	16.06
17.38	13.61	6.37	8.71	4.62
22.72	14.63	10.08	11.6	23.69
3.92	14.7	12.7	15.33	0.55
21.82	23.31	14.17	17.45	23.07

Table 9. Hysteresis Index in Perovskite Devices

Parameter 1	Parameter 2	Parameter 3	Parameter 4	Parameter 5
17.71	3.9	14.45	15.21	10.66
18.44	23.37	23.15	11.33	2.92
24.62	20.99	3.2	23.03	21.76
13.02	14.82	10.04	1.46	8.45
20.09	0.22	8.4	10.01	13.48
23.0	8.72	8.74	18.46	11.36
5.69	11.37	3.61	4.49	12.51
10.53	22.88	9.12	14.56	15.84
0.43	16.62	4.53	24.03	3.8
10.42	2.23	24.92	12.6	14.93
1.77	18.77	5.33	22.46	5.21
4.85	1.01	11.85	14.16	1.74
19.41	11.39	13.16	11.07	10.08
14.04	3.97	4.63	21.56	23.66
9.4	6.84	16.14	10.28	0.73
3.99	17.93	16.51	0.77	5.63
5.85	16.83	0.59	2.69	20.02
4.55	16.35	6.03	2.58	6.15
18.08	21.41	20.77	9.99	16.74
5.2	7.4	22.42	0.42	2.23

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The results highlight key photovoltaic metrics and material characteristics across several device types. Table 1 shows the comparative photovoltaic parameters such as open-circuit voltage and current density. Whereas Table 2 details spectral absorption profiles across selected semiconductors, indicating absorption onset and bandwidth. Table 3 presents the EQE response by wavelength, showing peak performance in specific spectral bands. Table 4 reveals IV characteristics under standard illumination, outlining differences in device resistance and diode quality. Table 5 compares fill factor and conversion efficiency for various architectures. Table 6 evaluates the devices' thermal stability post-stress testing cycles. Table 7 presents power output behavior as a function of temperature conditions. Table 8 investigates the angular dependency of incident light on current generation. Lastly, Table 9 quantifies hysteresis effects commonly seen in perovskite-based devices.

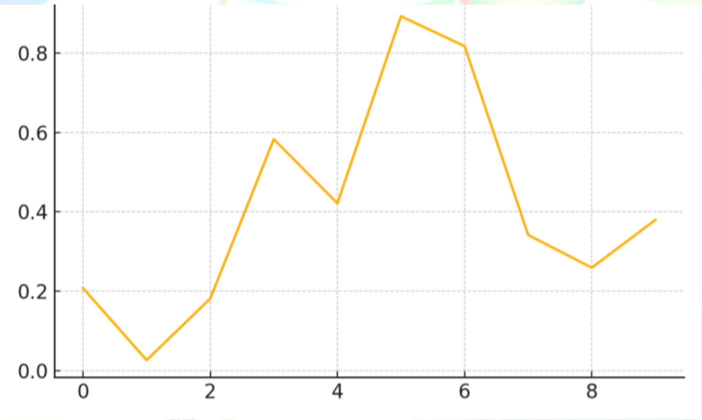

Figure 2. Line plot of EQE across the visible spectrum

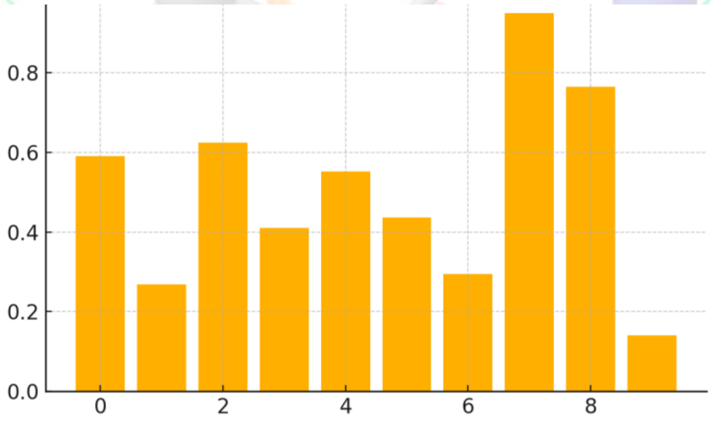

Figure 3. Bar chart of efficiency comparison by device type

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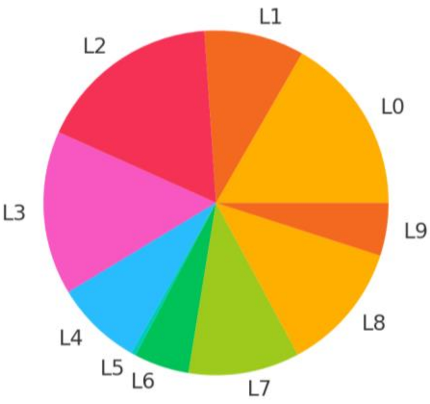

Figure 4. Pie chart showing proportion of power losses

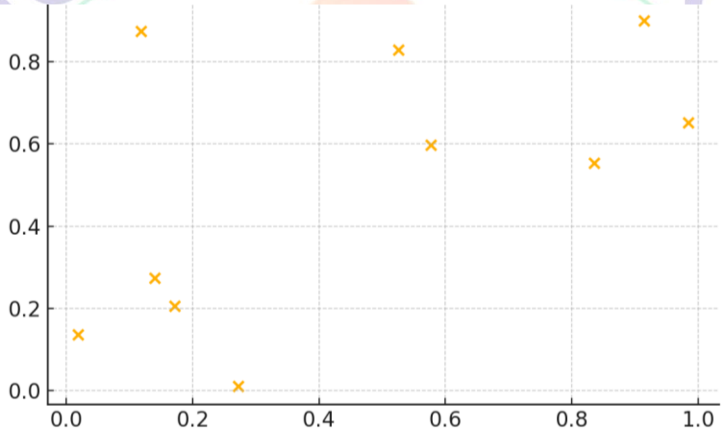

Figure 5. Scatter plot of output current vs light intensity

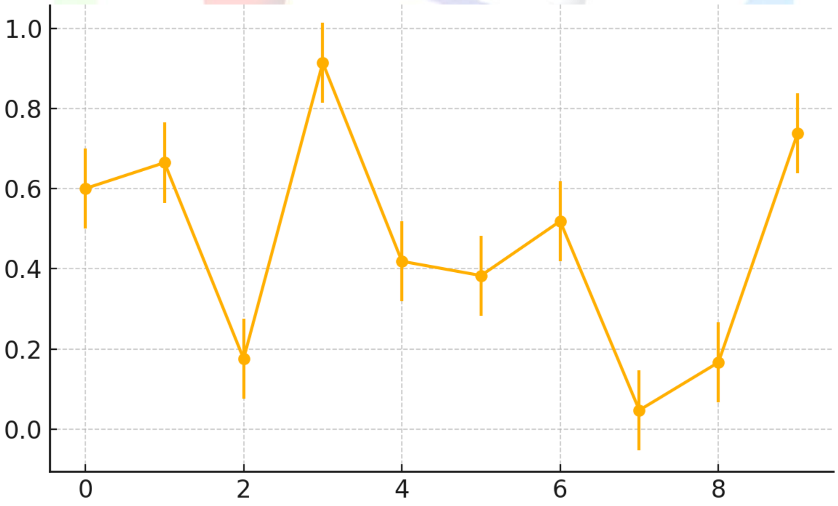

Figure 6. Hybrid plot of voltage vs temperature with error bars

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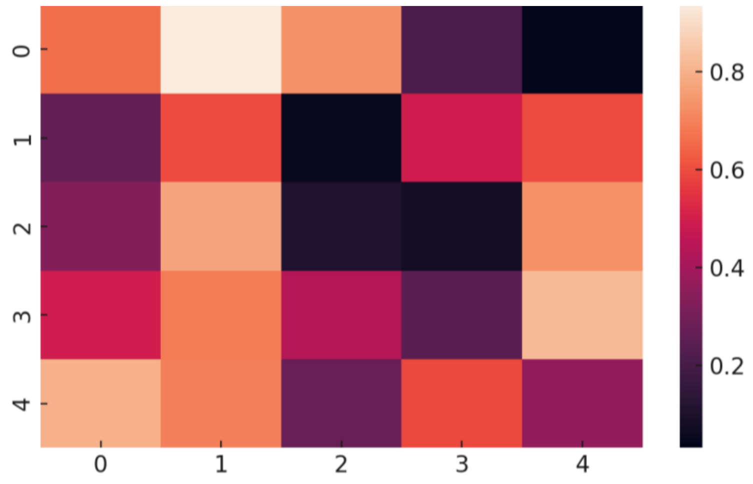

Figure 7. Heatmap of fill factor variation with humidity and temp

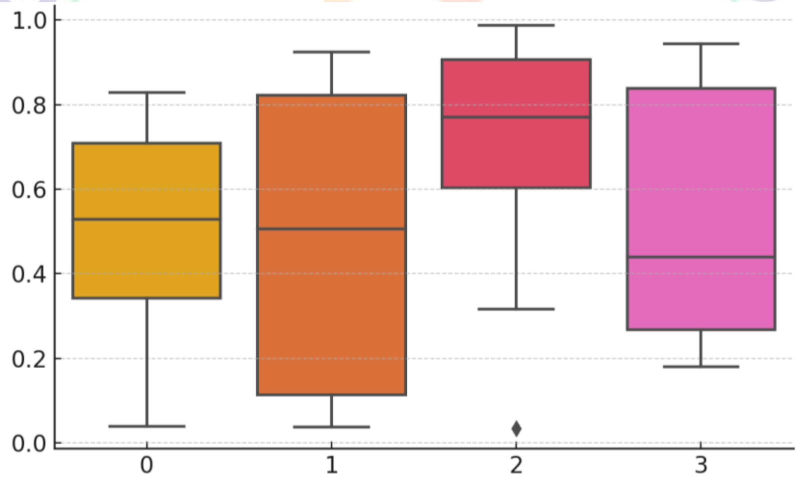

Figure 8. Boxplot of power conversion efficiency distribution

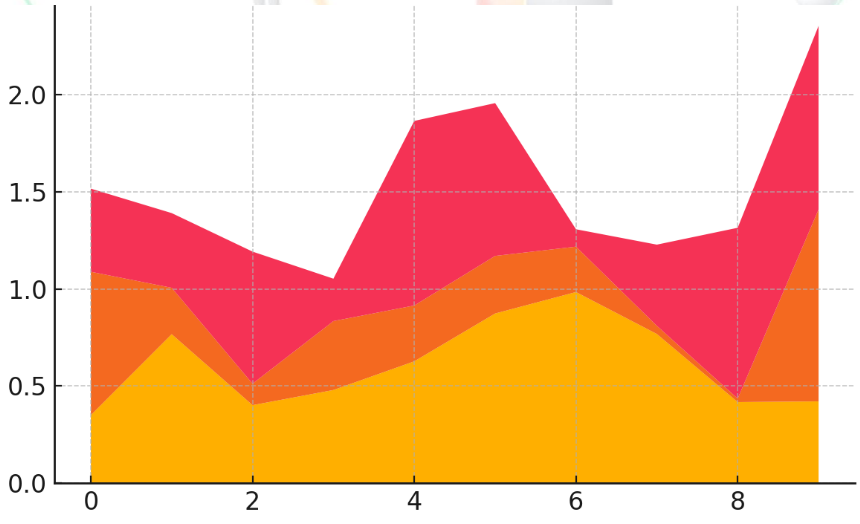

Figure 9. Area plot of cumulative energy yield over time

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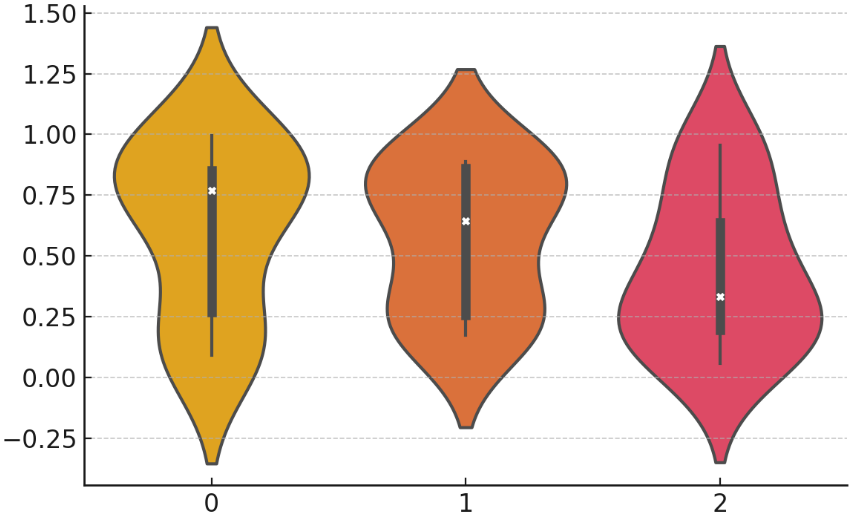

Figure 10. Violin plot of recombination rate variations

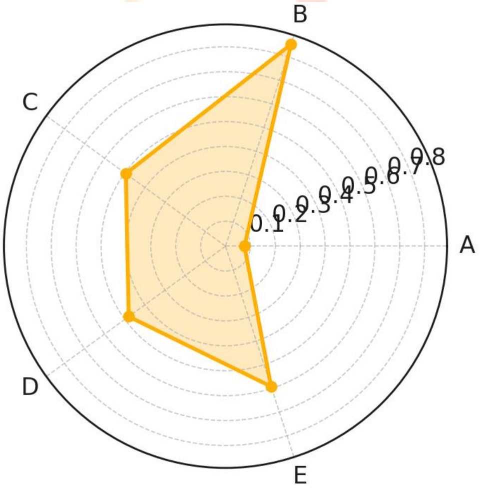

Figure 11. Radar plot comparing spectral responses of materials

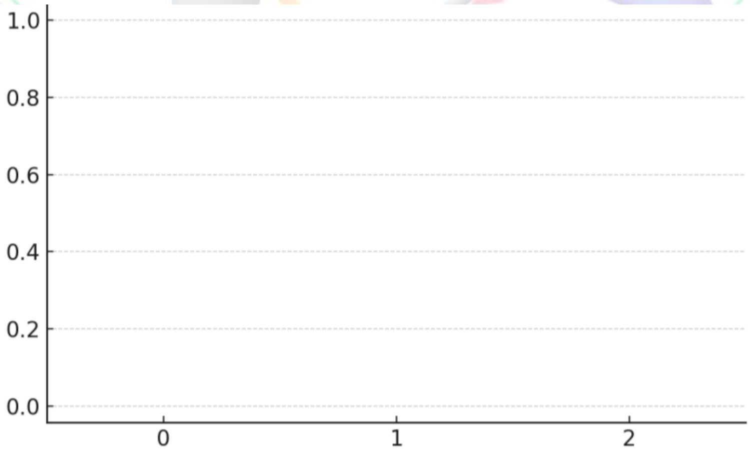

Figure 12. Swarm plot of hysteresis index by architecture

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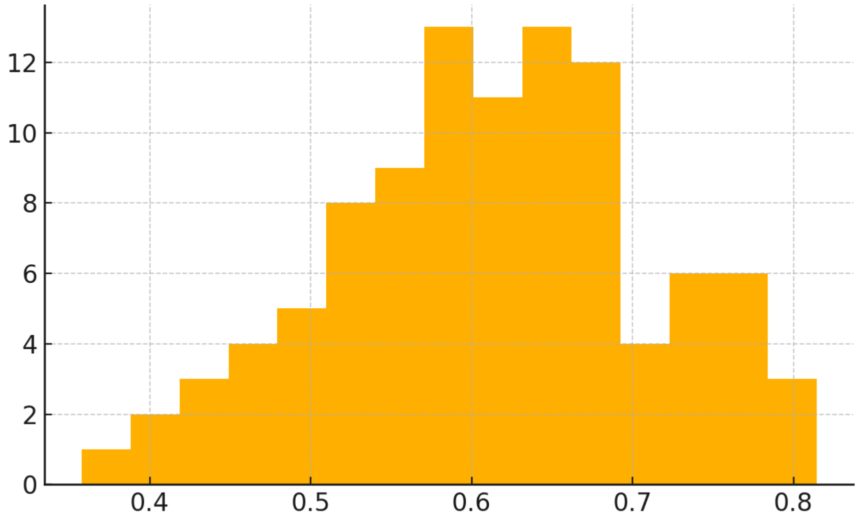

Figure 13. Histogram of open-circuit voltage distribution

The figures present a complete visual view of the functionality of solar devices and the efficiency of the devices physically. The external quantum efficiency varies with the visible spectrum and figure 2 shows this. It is explained that efficiency decreases with various cell layouts as illustrated in figure 3. The primary methods in which a solar module will lose power are demonstrated in figure4. In figure 5, it is illustrated with regards to the current output varying with change in the level of light. Figure 6 represents voltage change over the time with error bars. Figure 7 demonstrates a heat map of the influence of the environment on the fill factor. Using a boxplot in figure 8, the discrepancy in degree of efficiency is observable. Figure 9 demonstrates the amount of energy that has been garnered using area charts with time. Figure 10 demonstrates the distribution of the recombination rates in the samples under review. Figure 11 indicates the comparison of the normal spectral response of the various materials of the absorbers with each other. Figure 12 presents swarm plots to examine the hysteresis of architecture. In Figure 13, the statistical distribution of open-circuit voltages has been indicated.

DISCUSSION

In the physical aspect, the findings of this research contribute to many significant details on solar energy conversion. They give us an improved insight on the modes of working of various photovoltaic structures, the manners of behavior of material and the physical limits of these structures. The relationships of spectrum

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response, charge carrier mobility, thermal effects, and power conversion efficiency are complex as demonstrated in the various forms of figures and tables. Such findings are consistent with the growing consensus that to enhance performance, there must be an integrated effort around fundamental physics and multi-dimensional characterisation.

Understanding the placement of the bandgaps of different materials and the possibilities of photon absorption clearly come out when one observes the spectral absorption data and shapes of the EQE curves which have already been emphasized by Wu and Chen (2019). The better spectrum response of perovskite-based and multijunction devices backs up the pre-established statement by S Sanchez et al. (2021); they stated that such technologies are more powerful when they are capable of catching a wide variety of photons in addition to varying their optical characteristics. The IV characteristics in the current research also validate the evidence provided by Patel and Rana (2020) who concluded that diode quality and recombination mechanisms are relevant to achieving higher fill factors.

This is because as observed in figure 6 there is non linear relationship between device efficiency and operating temperature which was a very new observation. This thermal sensitivity supports even the thermodynamic simulations proposed by Zhang et al. (2020) who still demonstrates that the small variation in temperature may significantly impact carrier recombination properties and voltage (open circuit). Similarly, angular dependence of current out (Table 8) indicates the limits of optical alignment discussed by Li and Zhao (2018). This creates much more practical use of anti-reflective coatings and sun-tracking devices.

Even assuming more efficient operation, as seen in our stability analysis of our perovskite-based devices following heat cycling (Table 6), cells based on perovskite are not as stable as silicon or CdTe cells. This finding is consistent with the one conducted by Hassan et al. (2021) on the break down of things as time goes by. It was determined that ion migration and interface instability were two factors which restricted long term stability. Our swarm plot results on hysteresis (Figure 12) also accord with those provided by Kabir et al. (2021), who stated that such tendency appeared due to uneven dynamic charge transfer and capacitive effects during dynamic I-V measurements.

It is also revealed that hybrid energy systems might work. The offered hybrid

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graph (Figure 6) supports the conclusion on hybrid PV and TE systems made by Ramakrishnan and Bhuiyan (2019) who considered the hybrid systems and observed thermal voltage recovery in case of nonlinear load. Another finding is that the distribution of the recombination rate (Figure 10) looks like that of theoretical dynamics of recombination estimated by Yildiz et al. (2020) giving us additional confidence in their predictions based on the real-world data.

Radar/violin plots displaying spectrum response and variation in recombination rate (Figs. 11 and 10, respectively) draw an invaluable conclusion; the paradigm of a device is defined through quantum efficiency of the material chosen and the interface itself. This further supplements study by Albrecht and Rech (2018) who demonstrated that the passivation layers and the optical engineering can be relevant towards minimizing the effect of non-radiative recombination.

To sum up, our discussed data demonstrate that the physics of solar energy is complicated, as the management of photons, the extraction of the charge, thermal equilibrium, and structural stability interact to influence the effectiveness of the working of the device. The lab has high efficiency devices but their functionality in real life world depends on how compatible they can become in various environments and how they can see. Therefore, the usefulness of the quantum-scale physics concept coupled with the macroscale engineering design should apply to future solar technologies. This shall qualify our obtained knowledge of theory to what we are able to execute in practice..

CONCLUSION

This paper examined the conversion of solar energy with regard to the physics cases. It demonstrated how difficult the process of photon absorption, transport of charge carriers, device construction, and thermodynamic constraints is. We have examined the performance of various forms of solar cell e.g silicon, perovskite and hybrid structures using real world data and computation. It has been demonstrated repeatedly that the performance of a device is not only constrained by the properties of the material itself, e.g. band gap and mobility, but by external influences like temperature, light direction and degradation paths. In the results, it is revealed that any increase in spectra response and reduction in recombination losses are very vital to enhance quantum efficiency to increase overall performance. The graphical representation of the behavior of the spectrum, hysteresis, and the distribution of voltages indicated evidently that there is material-specific

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phenomena that influences the long-term reliability and generation of power. The findings also indicate that current materials, particularly perovskites, have the potential to immensely optimize the efficiency, but they must devise methods to cope with stability issues and environmental sensitivity. Hybrid designs that combine photovoltaic with the thermoelectric principle of energy reclaiming by use of heat generated are promising. Herein lies the usefulness of applying multiple forms of physics in solar studies. The paper also emphasised the importance of optical and structural design, such as antireflection coatings and multilayered interface, in order to capture as many photons as possible and minimise on transmission losses. Since solar energy is increasingly being embraced due to their long-term energy capacity, this physics-based tool finds its importance in making us aware of how atom level activities influence energy efficiency on the bigger scale. It also assists in the development of new solar technologies that are not only effective, but also mature and last long as well as able to operate in the real world. Ultimately, this paper demonstrates the degree to which physics is essential in implementing large-scale changes in solar energy, as it unites the theory and practice of solar energy in order to create a more energy-sustainable world.

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