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Solar PV Recycling Waste Management using Graphene-Based Solar Cells

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Abstract — In the rapidly growing usage of solar energy, traditional silicon-based cells present challenges such as limited recycling methods and significant End-of-Life (EOL) waste. In contrast, Graphene-based solar cells, emerge as a promising alternative, offering higher efficiency, durability, and improved recycling prospects. The recycling process incorporates collection, disassembly, material recovery, and component repurposing. This method requires less energy and fewer chemicals, as graphene can be reclaimed with minimal environmental impact and synthesized from bio-waste. Graphene's robust mechanical properties also contribute to longer operational lifespans, delaying EOL waste. This sustainable approach not only addresses waste challenges but also offers scalable, eco-friendly recycling methods that lower the ecological footprint of solar energy.

Keywords — *Graphene-based solar cells; Silicon-based PV cells; Life Cycle of a PV module*

1. Introduction

The demand for renewable energy solutions has grown dramatically in recent decades, driven by the need to reduce reliance on fossil fuels, decrease greenhouse gas emissions, and address the ongoing climate crisis. Solar power stands at the forefront of this movement. However, with the global expansion of solar technology, managing the waste generated by ageing and decommissioned solar panels has become a major challenge. Without efficient waste management strategies, solar energy, despite its sustainability during operation, could contribute to significant environmental pollution, negating some of the environmental benefits it provides [1-3].

Silicon-based PV cells have a limited lifespan, typically between 25 and 30 years, after which they degrade and require disposal. Unfortunately, the disposal and recycling of silicon-based panels are complex and energy-intensive, often involving hazardous materials like lead, cadmium, and other toxic elements. These panels require specialized processes to separate reusable materials, and the current recycling infrastructure struggles to manage the rising volume of PV waste. As a result, finding alternative, more easily recyclable materials is critical to the long-term sustainability of solar power systems.

Graphene-based solar cells have emerged as a promising solution to this issue. Graphene, a single layer of carbon atoms arranged in a hexagonal lattice, offers remarkable mechanical, electrical, and thermal properties, making it an attractive material for next-generation solar cells [4-6]. Unlike silicon, graphene is lightweight, flexible, and can be derived from abundant carbon sources, offering significant advantages in both performance and sustainability. Graphene-based solar cells have the potential to deliver high energy conversion efficiencies with fewer resource-intensive manufacturing processes, which, in turn, reduces the overall environmental impact.

Apart from improving the efficiency and durability of PV systems, it also aids in the development of sustainable recycling infrastructures. This shift could significantly reduce the ecological footprint associated with solar energy, as older panels can be more easily broken down and their materials reused.

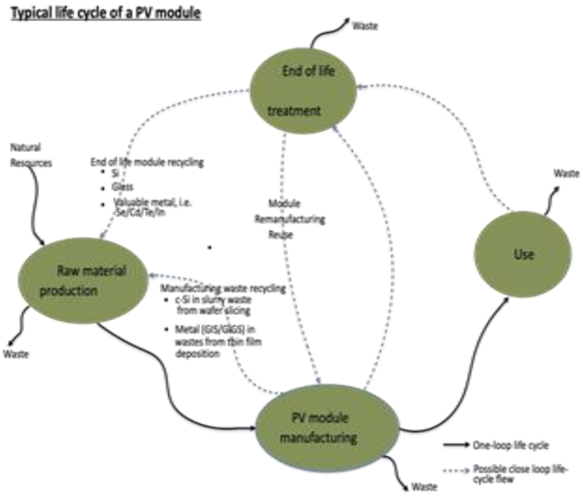

Fig. 1: Typical Life Cycle of a PV module

Furthermore, graphene's durability and resistance to environmental degradation may extend the lifespan of these solar cells, reducing the volume of PV waste over time. Relating to this work focuses on, *(i) Research and Analysis*

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of existing solar cell recycling methods, (ii) *Design and Development* of graphene-based solar cells, (iii) *Create efficient recycling methods* for graphene-based solar cells, and (iv) *Evaluate* the potential reduction in waste and toxic materials by implementing graphene-based alternatives.

2. Proposed Solution For Improved Solar Panel Recycling

2.1 Graphene

Graphene is a hexagonally arranged single layer of carbon atoms, known for its extraordinary properties and versatility in various fields, from electronics and energy storage to composites and solar cells [7]. Notably, graphene exhibits remarkable electrical conductivity, transparency, and mechanical strength, alongside flexibility and high thermal conductivity. These qualities make it a leading candidate for solar cell technologies, particularly as researchers seek materials that can provide both high efficiency and adaptability. One of graphene's most impressive attributes is its electron mobility, which is higher than that of traditional materials like silicon. This allows electrons to move through it with very little resistance, leading to faster charge transport and reduced energy loss during conversion. In addition to this, its structure allows it to be an effective transparent electrode, a component crucial in solar cells.

Graphene's flexibility and lightness also differentiate it from traditional solar cell materials. Conventional solar cells, typically made of silicon, are heavy and rigid, which restricts their use to fixed installations like rooftops or large solar farms. Graphene-based solar cells, however, could enable lightweight and flexible solar panels that could be integrated into wearable devices, portable electronics, or even curved surfaces like vehicles. In addition to its practical benefits, graphene presents several environmental advantages. The methods for graphene production from available graphite, such as chemical vapor deposition (CVD) are advancing. In contrast to some materials, graphene offers a greener alternative with a smaller environmental footprint. Graphene does not possess a natural band gap, which is necessary for effective control of electron flow in solar cells and other semiconducting devices. Relating to this continuous research on introducing a band gap in graphene through chemical doping or hybridizing it with other materials is being carried out.

Another challenge is the cost-effective, large-scale production of high-quality graphene. While substantial progress has been made, the production of graphene at a scale suitable for widespread use in solar technology remains costly and complex. Addressing this challenge is critical for integrating graphene fully into the renewable energy industry.

2.2 Properties and Characteristics of Graphene

This section explores the major advantages of graphene according to the properties it exhibits [8]. The overall block diagram involved in recycling PV panels is given in Figure 2.

(a) Atomic Thickness: Graphene is just one atom thick, making it an exceptionally thin material. This atomic-scale thickness enables its use in applications where minimal bulk and high precision are required.

(b) High Carrier Mobility: Graphene exhibits exceptional electrical conductivity, with electrons able to move at incredibly high speeds across its surface, promoting electronic devices that require fast charge transport, such as transistors and sensors.

(c) Transparency: Nearly transparent, graphene allows light to pass through it, making it suitable for optoelectronic applications, including solar cells and transparent displays.

(d) Mechanical Strength: Despite its atomic thickness, graphene is extremely strong and flexible, with a tensile strength above steel. This combination of strength and flexibility opens opportunities in fields requiring durable, lightweight materials.

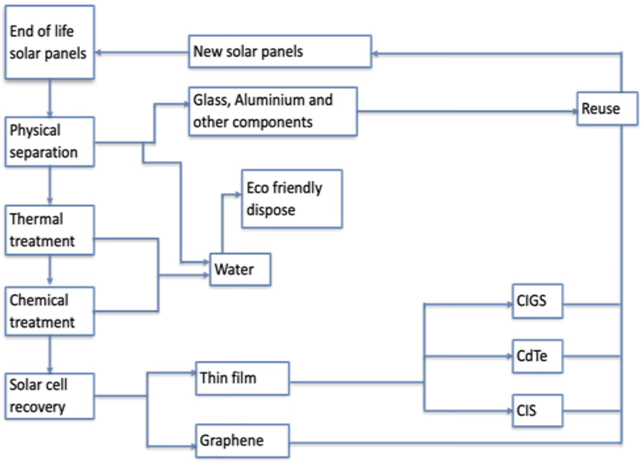

Fig.2: The block diagram represents the end-of-life solar panel recycling process

(e) Electrical Conductivity: Graphene is an outstanding conductor of electricity, making it suitable for various electronic and optoelectronic devices, including high-speed transistors, flexible circuits, and conductive inks.

(f) Thermal Conductivity: With high thermal conductivity, graphene effectively dissipates heat, which is beneficial for electronic devices where efficient thermal management is essential.

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(g) Flexibility: Its flexibility allows it to be integrated into flexible and wearable electronic applications, where both durability and adaptability are crucial.

While considering recyclability, the separation of useful components after PV lifetime is important, which will be discussed in the following section

2.3 Overview of the working process

The recycling process for end-of-life (EOL) solar panels begins with collection and initial processing, where panels are gathered, sorted by type, and dismantled to separate components like frames and junction boxes. Following this, heat treatment is applied to remove organic compounds such as encapsulants and back sheet materials using controlled thermal processes. This leaves the glass and metal layers intact for further processing. Next, chemical processing is employed to isolate valuable materials through methods like acid leaching, effectively extracting metals and purifying solar cells.

The final step is the thin Film and Graphene Recovery. In cases where thin-film solar cells are used, materials specific to thin-film technology are recovered. CIGS (Copper Indium Gallium Selenide): A material used in thin-film solar cells. CIGS is valued for its efficiency in absorbing sunlight and converting it into electricity. CdTe (Cadmium Telluride) is cost-effective and highly efficient and CIS (Copper Indium Selenide) offers favourable photovoltaic properties for thin-film solar cells [9].

3. Comparative Analysis With Alternative Solar Cell Materials

To comprehensively evaluate graphene's performance, we also simulated the IV (current- voltage) and PV (power-voltage) characteristics of other well-known solar cell materials, including Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), Amorphous Silicon (a- Si), and Perovskite. Each material was selected for its unique properties, providing a diverse range of photovoltaic behaviors for comparison with graphene.

4. Simulation of VI And PV Characteristics Using Matlab

The simulation of the PV module using various solar cell materials was carried out and the results are presented in this section. Figure 3 shows the overall simulation circuit.

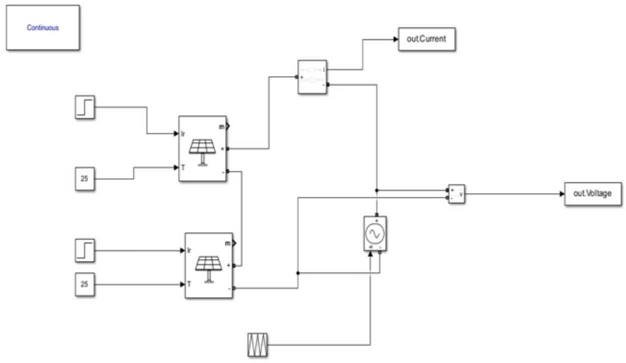

Fig. 3: Simulation of solar panel in Matlab

5. Results and Discussion

The following figures from fig. to fig. shows the various characteristics output obtained for the various materials in the solar module.

5.1 Crystalline silicon solar cell

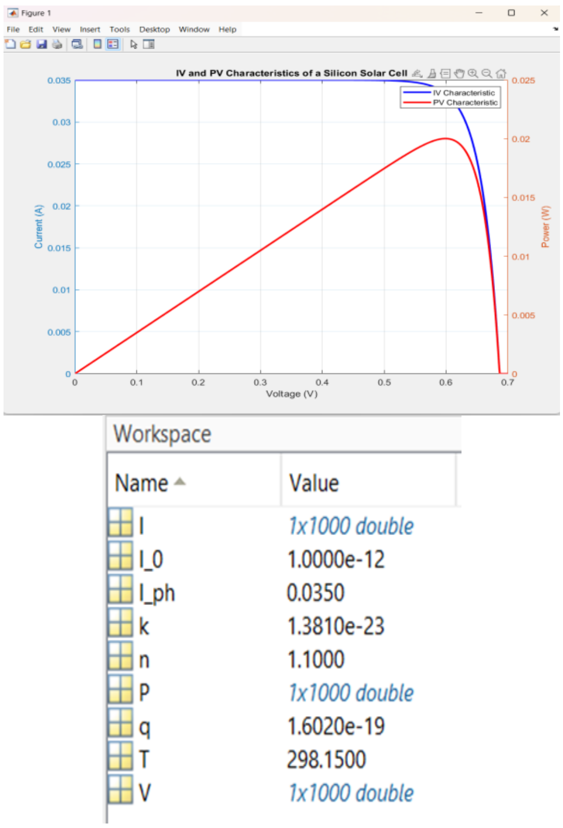

Fig. 4: IV Characteristics and PV Characteristics of Crystalline Silicon Solar Cell

y-y axis left and y-y axis right allow you to plot the IV and PV characteristics with different y-axes. The legend function labels each curve for clarity. Adjusting set

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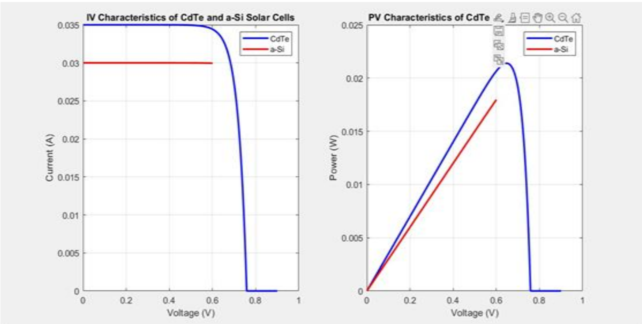
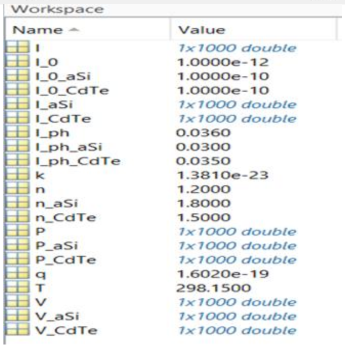
(gcf, 'Position', [100, 100, 800, 600]) changes the figure window size to make the plot easier to view.

5.2 CdTe and a-Si Solar Cells



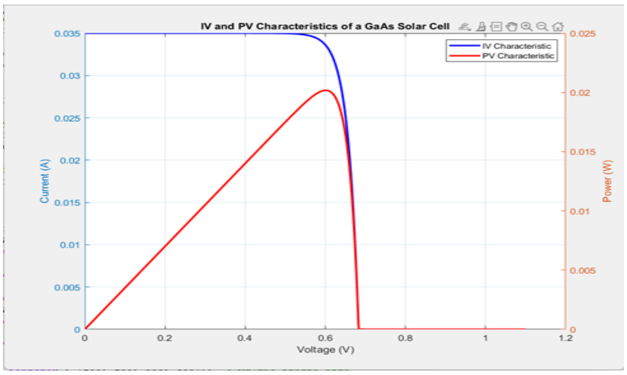


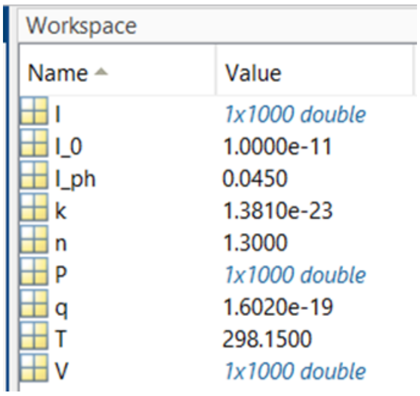
Name	Value
I	1x1000 double
I_0	1.0000e-12
I_0_aSi	1.0000e-10
I_0_CdTe	1.0000e-10
I_aSi	1x1000 double
I_CdTe	1x1000 double
I_ph	0.0360
I_ph_aSi	0.0300
I_ph_CdTe	0.0350
k	1.3810e-23
n	1.2000
n_aSi	1.8000
n_CdTe	1.5000
P	1x1000 double
P_aSi	1x1000 double
P_CdTe	1x1000 double
q	1.6020e-19
T	298.1500
V	1x1000 double
V_aSi	1x1000 double
V_CdTe	1x1000 double

Fig.5: A IV Characteristics of CdTe Solar Cell and PV Characteristics of CdTe Solar Cell

The IV characteristics of CdTe and a-Si solar cells are represented in the first subplot, where the current-voltage (IV) curves are plotted. The CdTe solar cell is depicted with a blue curve, while the a-Si solar cell is shown in red, with a legend clearly indicating the material corresponding to each curve. The second subplot illustrates the power-voltage (PV) characteristics for both solar cells, maintaining the same color scheme: blue for CdTe and red for a-Si. These plots provide a comparative analysis of the electrical and power output behaviors of the two solar cell technologies.

5.3 GaAs Solar Cells



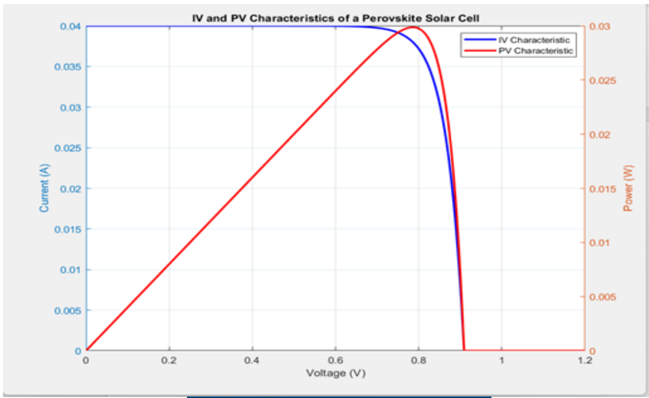


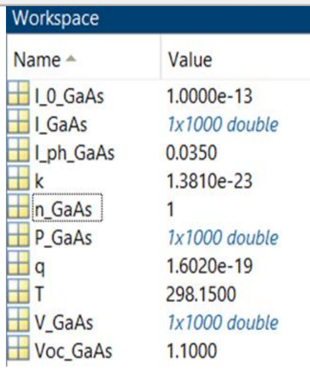
Name	Value
I	1x1000 double
I_0	1.0000e-11
I_ph	0.0450
k	1.3810e-23
n	1.3000
P	1x1000 double
q	1.6020e-19
T	298.1500
V	1x1000 double

Fig.6: IV Characteristics of GaAs Solar Cell and PV Characteristics of GaAs Solar Cell

y-y axis left and y-y axis right create dual y-axes, allowing one y-axis for current (A) and the other for power (W). The legend function helps identify each characteristic and set (gcf, 'Position', [100, 100, 800, 600]) adjusts the figure size for better visualization.

5.4 Perovskite solar cell





Name	Value
I_0_GaAs	1.0000e-13
I_GaAs	1x1000 double
I_ph_GaAs	0.0350
k	1.3810e-23
n_GaAs	1
P_GaAs	1x1000 double
q	1.6020e-19
T	298.1500
V_GaAs	1x1000 double
Voc_GaAs	1.1000

Fig. 7: IV Characteristics of Perovskite Solar Cell and PV Characteristics of Perovskite Solar Cell

Dual y-axes: The y-y-axis commands allow for separate y-axes to plot both current and power characteristics. This provides clarity on how current and power change with voltage [10].

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Higher Voc: Perovskite cells typically exhibit a high open-circuit voltage due to their efficient photon absorption and low recombination rates.

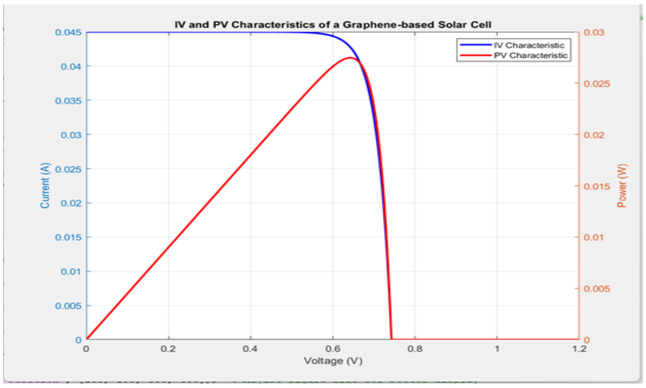
Clear Legend: With both IV and PV characteristics on a single plot, this setup aids in analyzing performance metrics like maximum power point (P_max) and open-circuit voltage (Voc), which are useful for comparing cell efficiency.

5.5 Graphene solar cell

Dual y-axes: The y-y-axis left is used for plotting the IV curve with current (A) as the y-axis, while y-y-axis right is used for the PV curve with power (W) as the y-axis.

Voc and current improvements: This visualization shows the impact of graphene's transparency and conductivity on photovoltaic performance, demonstrated by a higher photocurrent (I_{ph}) and open-circuit voltage (V_{oc}) compared to conventional materials.

Color coding and legend: The IV and PV curves are colored differently, making it easier to distinguish between them



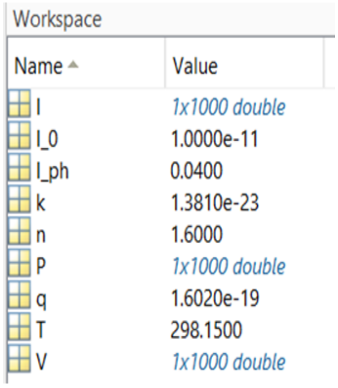


Fig. 8: IV Characteristics of Graphene Solar Cell and PV Characteristics of Graphene Solar Cell

6. Comparative Analysis of Solar Panel Materials

Graphene-based solar cells, with high transparency and conductivity, achieve the highest open-circuit voltage (Voc ~1.2V) and strong short-circuit current (Isc ~0.045A), offering exceptional power output and sustainability for advanced applications. Perovskite cells, with Voc ~1.1V and Isc ~0.04A, combine high efficiency and cost-effectiveness but face stability challenges [11]. Gallium arsenide (GaAs) excels in efficiency (Voc ~1.1V, ideality factor ~1.0) and spectral response, making it ideal for specialized high-cost uses. CdTe cells strike a balance between efficiency (Voc ~0.85V, Isc ~0.03A) and cost, suitable for commercial use, while amorphous silicon (a-Si) cells, with lower Voc (~0.7V) and Isc (~0.025A), are economical and flexible but limited in output. Dye-sensitized solar cells (DSSCs), with Voc ~0.6V and Isc ~0.02A, are cost-effective for small-scale applications but lack efficiency [15-18].

Table 1. Comparative Review Solar Panel Materials

Solar Cell Type	**IdealIty Factor (n)**	**Photocurrent (I_{ph}, A)**	**Saturation Current (I_0, A)**	**Open-Circuit Voltage (V_{oc}, V)**	**Short-Circuit Current (Isc, A)**	**Max Power (W)**	**Comments**
Graphene -Based	1.3	0.045	1e-11	~1.2	0.045	~0.02 5	High transparency cy and conductivity y.
Perovskite	1.6	0.040	1e-11	~1.1	0.040	~0.02 2	High efficiency, moderate stability issues.
Gallium Arsenide	1.0	0.035	1e-13	~1.1	0.035	~0.02 0	High efficiency but costly and complex to make.
CdTe	1.5	0.030	1e-10	~0.85	0.030	~0.01 8	Good efficiency, toxic materials involved.
Amorphous Silicon	1.8	0.025	1e-9	~0.7	0.025	~0.01 5	Cost-effective but lower efficiency.
Dye- Sensitized	2.0	0.020	1e-8	~0.6	0.020	~0.01 2	Economical but limited in efficiency and stability.

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7. Conclusion

Through this work, it can be observed that graphene's characteristics distinguish it as a superior material in solar cell technology compared to conventional materials, including Gallium Arsenide (GaAs), Cadmium Telluride (CdTe), and the potential perovskite solar cells. Its characteristics like high electrical conductivity, exceptional transparency, mechanical strength, and flexibility give it a unique advantage in solar applications. In contrast to other materials that are costly and complex to manufacture, graphene-based cells can be manufactured using cost-effective methods. This also enables the potential for lightweight, flexible solar cells that are ideal for a wide range of applications, from wearable devices to space technology.

While Perovskite solar cells are competitive in efficiency and cheaper to manufacture but have stability and scalability challenges. In comparison, graphene-based solar cells provide a more balanced solution by offering high efficiency along with flexibility and environmental safety. Furthermore, graphene's adaptability for hybrid applications, including perovskite-graphene composites, promises advancements that could push solar cell efficiency and durability even further. This makes graphene a stronger contender for the next generation of sustainable, high-performance solar cells.

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