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Novel Materials for Effective Harvesting of Solar Energy

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Modernization and the increasing population worldwide have resulted in a growing demand for energy to meet their needs. Non-renewable sources of energy are widely used to meet this growing demand has led to increased carbon emissions, pollution, and the expounded effects of global warming. As a mitigation measure, renewable energy sources, such as solar energy, have received great interest due to their abundance. However, harnessing the full potential of solar to provide abundant energy requires the use of novel technologies and definite materials to harvest it. These materials and technologies will enhance power conversion efficiencies, maximizing the potential of solar cells to generate adequate power. Currently, there is scant or limited research in this domain, particularly on the best materials that can be used to effectively harvest solar power.

Therefore, the purpose of this study is to explore the innovative materials used to harvest solar power. The findings reveal that the optimum conversion of sunlight to generate energy can be achieved using prober definite materials with exceptional physical, chemical, thermal conversion, and optical properties. Some of these materials include graphene, nanomaterials, and nanofluids. Using materials like CIGS/Cds improves the efficiencies of thinner film PVs for a greater harvest of solar power by reducing the optical losses, reflection loss, and absorption losses of light photons. The high absorption rates of solar radiation, decreased optical loss, and improved efficiency of PVs are achieved using plasmonic nanostructures. Although it is evident that emerging materials have advanced the harvesting of solar, these materials have myriad challenges, which impede their maximum applications. Therefore, this paper recommends future studies should focus on addressing these challenges and provide innovative solutions, that will enhance the scalability, stability, and durability of these materials for optimum solar harvesting.

Keywords: Solar energy, Materials, Photovoltaics, Nanomaterials, Nanostructures, Nanofluids, Solar Thermal Absorbers, thin film solar cells, Quantum dots, Developments.

1. Introduction

Rapid industrialization and the increasing population worldwide have resulted in growing demand for energy to meet their needs. Non-renewable sources of energy are widely used as the main supply of energy. However, the rise in global warming and climate change associated with these sources poses critical environmental and health concerns; hence, calling for measures, particularly in the production of energy to mitigate this threat. These measures include using alternative sources of energy like renewable sources while minimizing the use of fossil fuels to reduce carbon footprint while meeting the constantly growing demand for power by the population (Zabihi and Saafi, 2018). Some of these alternative uses include geothermal generation and solar power. Most people or organizations have shifted to the latter because of its abundance, cleanliness, and cost-effective production.

Nevertheless, proper generation of power from the sun requires using specific materials or technologies to improve overall efficiency in power generation to meet the increasing energy uses (Pastuszak and Węgierek, 2022). Conversely, there is a literature gap on the material selection for the ideal harvesting of solar or trapping of light photons for an effective supply of energy. Therefore, this journal explores and discusses innovative materials used to harvest solar power while fulfilling the literature gap. The current novel technologies used to harness energy from the sun for solar power/energy generation are shown in Fig. 1.0 below

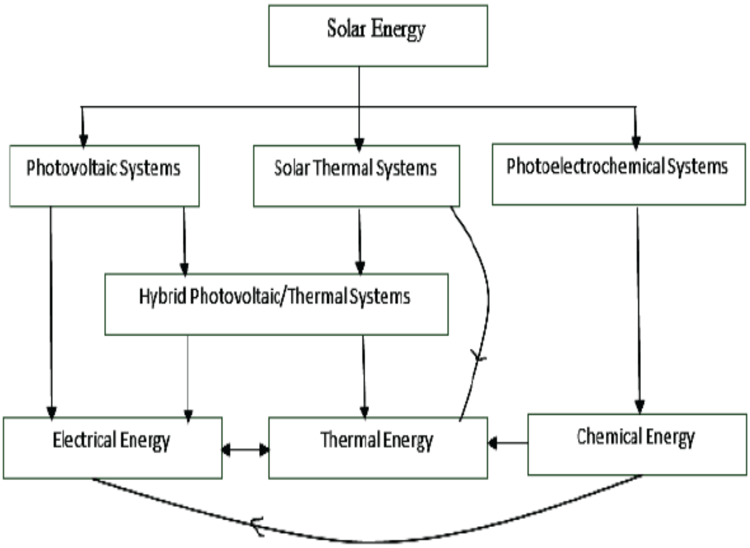


Figure 1. Existing technologies used to harvest/harness energy from the Sun

Source: Adapted from Koech et al. (2019; pg. 627)

Converting solar radiation to power is significantly challenging due to issues associated with it, which include power conversion efficiencies, absorption rates, performances (i.e., optical), electro-thermal problems, and degradation of materials used in the solar cells (Almosni et al., 2018). The optimum conversion of sunlight to generate energy can be achieved using prober absorbers, and definite materials that address these issues, such as nanomaterials and nanofluids (Kant and Singh, 2022). In this regard, this paper provides insights into the advanced use of nanomaterials and nanofluids in photovoltaics or solar harvesters to convert solar radiation, which would result in improved generation of energy.

The study also provides a detailed discussion of the materials or technologies used to achieve effective charge transfer and usage, as well as maximize absorption of solar radiation. It also discusses the challenges associated with materials, technologies, or fluids used to harvest solar energy, and offers future directions or solutions, which would result in improved solar harvesting. Based on the findings, the author will offer conclusions, future outlook as well as proposals for better harvesting of solar power, and further research. Generally, this study has five themes developed based on the analytical and comprehensive appraisal of the existing studies pertinent to this journal’s topic. The themes include photovoltaic materials, definite absorbers for solar harvesting/conversion, technological and material advancements, innovative strategies for enhancing the absorption of light, and challenges associated with material or technological uses in this domain. These themes are discussed in subsequent sections.

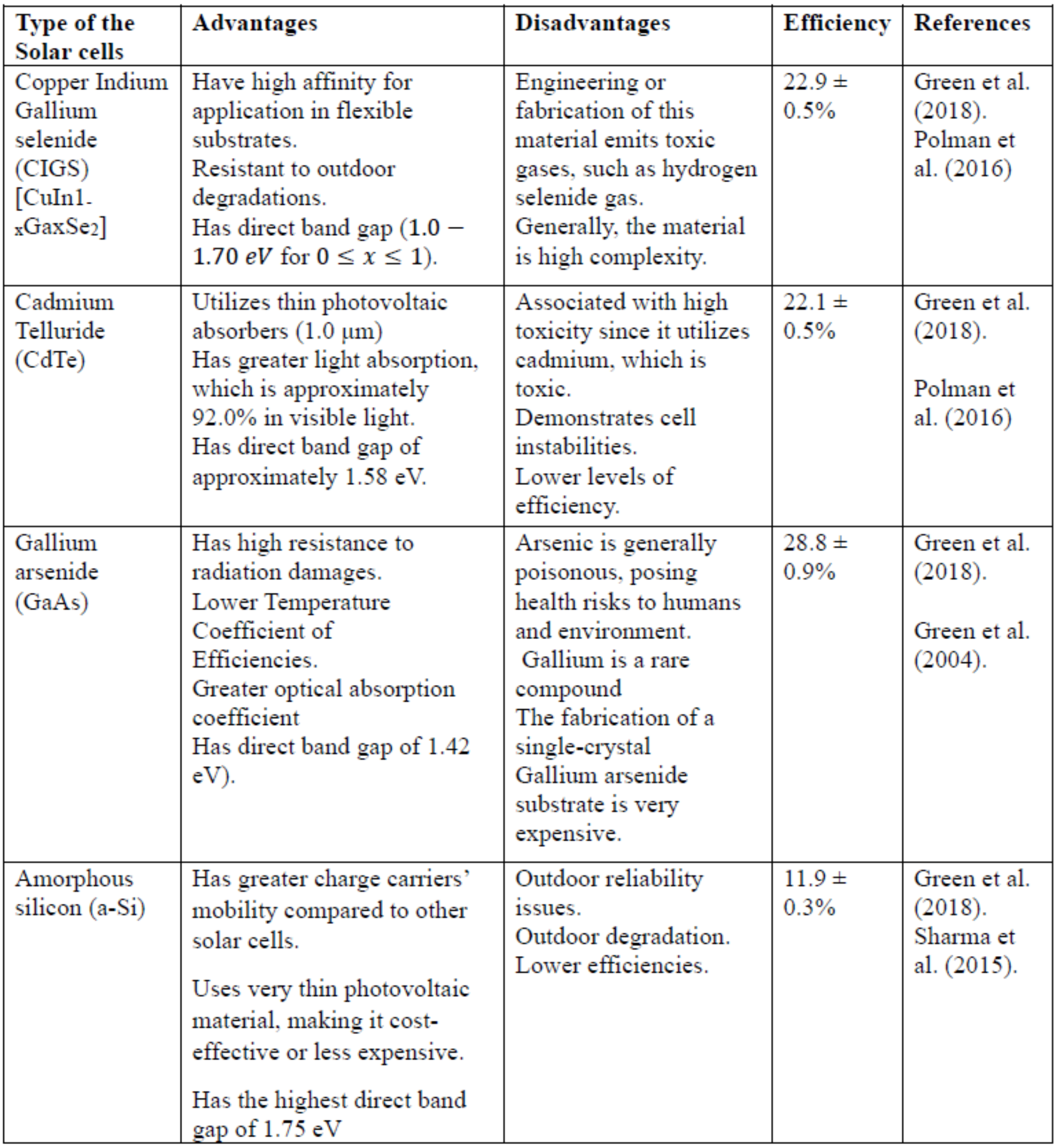
2. Photovoltaic materials used to harvest solar radiation

Advances in the use of silicon to fabricate photovoltaics have decreased costs, enhanced lifespan, improved durability, and increased efficiencies of Si-PVs. The reduced cost is associated with the easy availability of Si material, which is plentiful in nature. The material is also strong, robust, and lower - volume-weight ratio. These materials also depict exceptional electrical as well as optical attributes. The enhancement of the internal reflection and decrease of the cell surface reflections is achieved using surface grates. Adding a layer of Si-oxide with high transparency and conduction to the Si-PVs will decrease the loss of absorbed sunlight while increasing the trapping of light and absorption of photons from the sun for conversion. Si tends to have greater power conversion efficiency and stability. For example, the use of multi-crystalline in PV achieves more than 21% efficiency while the utilization of Si-crystalline achieves 25.9% efficiency of power conversion on Silicon-PVs. This implies that these solar harvesters fabricated using Si will be durable, stable, efficient, and will serve for a longer time.

Thin-film materials are used in second-generation solar cells and play a crucial role in harvesting or generating solar energy. The thinner film materials utilize minute/thinner layers of materials for sunlight absorption, which have a greater capacity for light absorption (Meillaud et al. 2015). A comparison of the thin film photovoltaic materials, which includes their disadvantages, advantages, as well as efficiencies was made and the results are shown in Table 1.

Currently, there is an increasing use of thin film photovoltaics or solar cells to harvest solar energy. The efficiency of thin-film solar cells is negatively impacted by the optical losses, reflection loss, and absorption losses, undermining the potential application of thin films in solar harvesting. Therefore, these losses can be minimized or prevented by using CIGS and Cds with recommended thickness. The higher the wavelength, the higher the absorption losses on CIGS/Cds-based solar cells. Additionally, the thicker the CIGs/Cds, the higher the absorption in the layers, leading decreased T(ʎ) [transmission spectrum] and more optical losses. Adding an antireflection coating to the layer results in increased T(ʎ) values, as illustrated in figure 1.1b. The function of CdS thickness, which is the T(ʎ) when the layers are 100.0nm thick, is illustrated in figure 1.1a. These values were computed using Equation 1. Increased T(ʎ) values to around 90.0% is achieved by increasing the antireflection coat’s thickness, which is consistent the solar radiation’s maximum at the 1.50AM, as seen in figure 1.1a.

Table 1. Comparison of the thin film photovoltaic materials



Type of the Solar cells	**Advantages**	**Disadvantages**	**Efficiency**	**References**
Copper Indium Gallium selenide (CIGS) [$\text{CuIn}_{1-x}\text{Ga}_x\text{Se}_2$]	Have high affinity for application in flexible substrates. Resistant to outdoor degradations. Has direct band gap ($1.0 - 1.70\ eV$ for $0 \le x \le 1$).	Engineering or fabrication of this material emits toxic gases, such as hydrogen selenide gas. Generally, the material is high complexity.	22.9 ± 0.5%	Green et al. (2018). Polman et al. (2016)
Cadmium Telluride (CdTe)	Utilizes thin photovoltaic absorbers (1.0 µm) Has greater light absorption, which is approximately 92.0% in visible light. Has direct band gap of approximately 1.58 eV.	Associated with high toxicity since it utilizes cadmium, which is toxic. Demonstrates cell instabilities. Lower levels of efficiency.	22.1 ± 0.5%	Green et al. (2018). Polman et al. (2016)
Gallium arsenide (GaAs)	Has high resistance to radiation damages. Lower Temperature Coefficient of Efficiencies. Greater optical absorption coefficient Has direct band gap of 1.42 eV).	Arsenic is generally poisonous, posing health risks to humans and environment. Gallium is a rare compound The fabrication of a single-crystal Gallium arsenide substrate is very expensive.	28.8 ± 0.9%	Green et al. (2018). Green et al. (2004).
Amorphous silicon (a-Si)	Has greater charge carriers' mobility compared to other solar cells. Uses very thin photovoltaic material, making it cost-effective or less expensive. Has the highest direct band gap of 1.75 eV	Outdoor reliability issues. Outdoor degradation. Lower efficiencies.	11.9 ± 0.3%	Green et al. (2018). Sharma et al. (2015).

$$T(\lambda) = (1 - R_{\text{arc}})(1 - R_{23})(1 - R_{34})e^{-\alpha_2 d_2}e^{-\alpha_3 d_3} \quad \text{(Eq.1)}$$

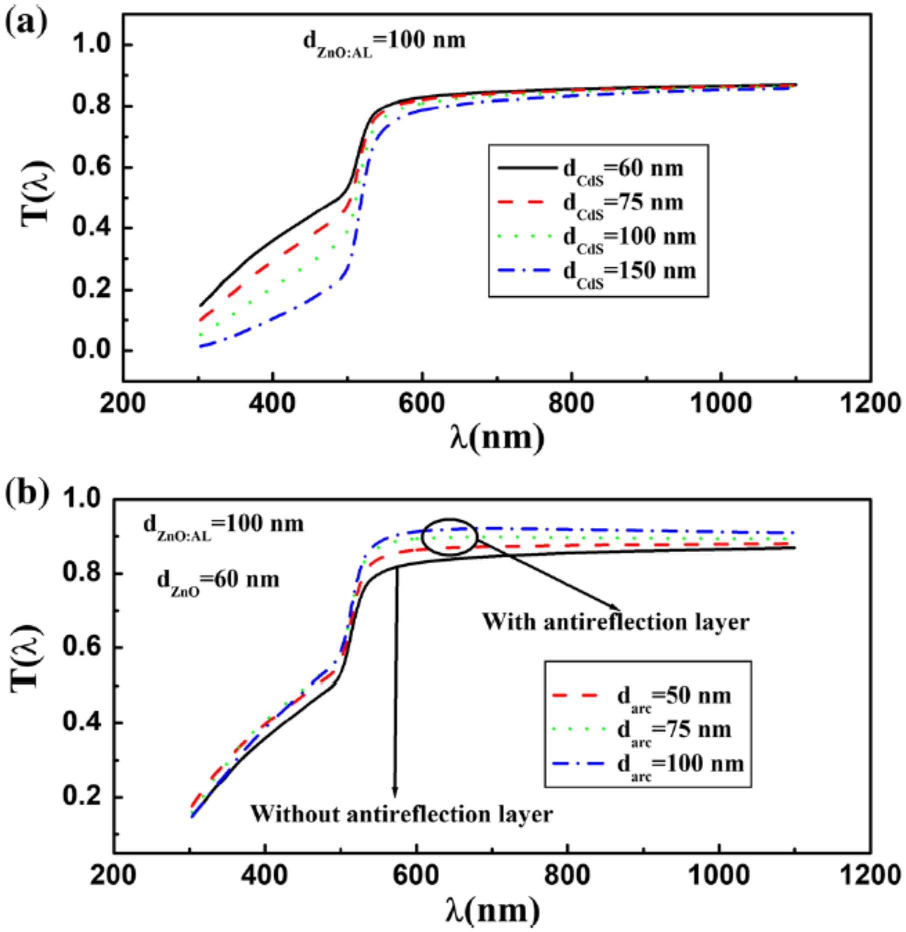


Figure 1.1. Effects of the coatings and size of cds/CIGs on solar harvesting

Source: Adapted from Mohamed and Mohamed (2019)

At different Nonaluminum thickness, size of CdS differs, which further impacts the short-circuit current density as illustrated in fig.1.2a. Equation 2 was used to determine the short-circuit current density $[J_{sc}]$ where $\eta_{int}\ (\Lambda) = 1.0$. Increased thickness of ZnO: Aluminum and CdS, results in reduced J_{sc} values, as seen in figure 1.2a. Thus, implying that the thinner the Cds/ZnO:Aluminum the higher the absorption rate, resulting in higher solar harvesting. On the other hand, the thicker the antireflection layer in coated on the Cds, the higher reduced J_{sc} values (See fig. 1.2b). This implies that thicker the antireflection layer in coated solar cells, the higher absorption rate and reduced absorption losses, leading in maximum trapping of light photons for efficient harvesting of energy.

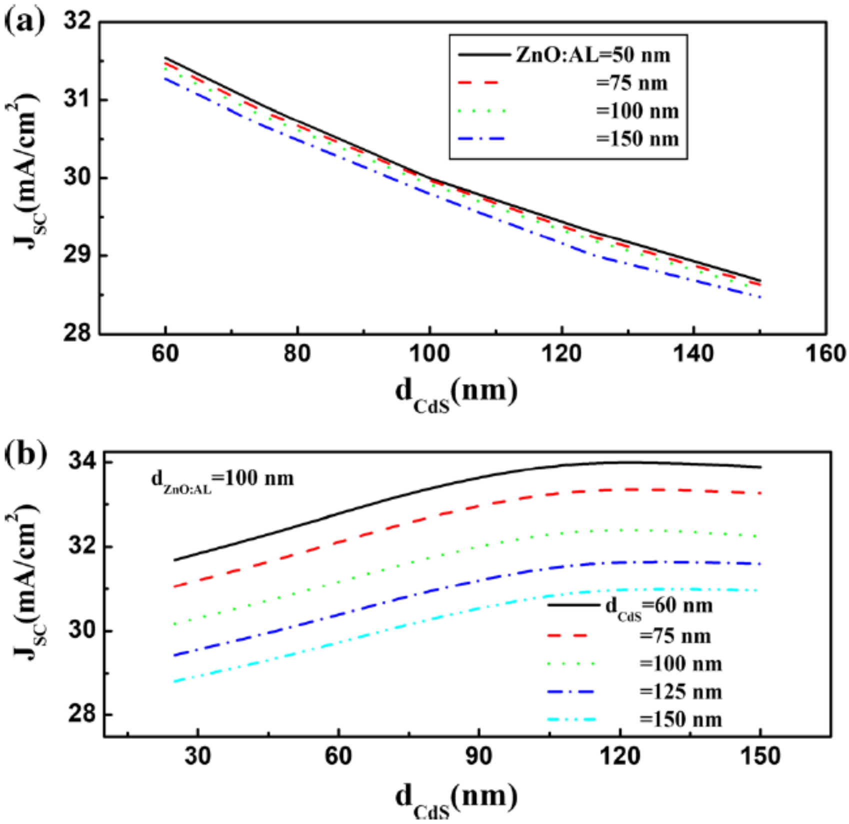


Figure 1.2. Impacts of size of materials and antireflection layers on absorption rates/losses.

Source: Adapted from Mohamed and Mohamed (2019)

$$J_{SC} = q \sum_{i} T(\lambda) \frac{\Phi_i(\lambda_i)}{h\nu_i} \eta_{\text{int}}(\lambda_i) \Delta\lambda_i \qquad (2)$$

In which:

η_{int} = Aggregate internal quantum harvest

Δʎ = T(ʎ) value intervals as provided in Eq.1

Equation 2 was used to determine the J_{sc}Max. where η_{int} (ʎ) = 1.0 while Tʎ ≤1. The computed values were used to determine the optical loss values. The findings show that the increased thickness results in higher optical losses. For example, 22.0% optical loss is achieved with 60. nm thick Cds and 50.01nm thick ZnO:Al at 31.5mA/cm^2 J_{sc}. The thicker the material to around 150.01nm, the higher the optical losses to 30.0%, as illustrated in figure 1.2. Thus, reducing the size (i.e., using thinner material) will reduce losses of photons and increase the amount of absorbed sunlight for greater power supply. Therefore, this implies that reduction of the absorption coefficient prevents loss of absorption while reducing the refractive indices' variations minimizes losses related to reflection, resulting in improved optical attributes of CIGs/CdS/zinc oxide for improved efficiency of thin-film PVs. On the other hand, applying correct size of anti-reflection coating (i.e., ≤100.nm) will result in increased J_{sc} to 7.9% while reducing optical losses to ≤16.01% (see figure 1.2b), leading to improved efficiency of the thin-film solar cells-thin-film PVs/solar cells manufactured with CIGs/CdS/ materials. Eq. 3 shows an expression of this efficiency.

$$\eta = \frac{\mathrm{FF} \times J_{\mathrm{SC}} \times V_0}{P_{\mathrm{in}}} \qquad (3)$$

P_{in}=1.50AM solar energy power's aggregate density.

V_0= Voltage of the open-circuit

η= refers to the efficiency

FF = refers to the fill factor, as articulated in eq.4 below

$$\mathrm{FF} = \frac{J_{\mathrm{m}} \times V_{\mathrm{m}}}{J_{\mathrm{SC}} \times V_0} \qquad (4)$$

V_m= maximum density of voltage

J_m= maximum density the current

3. Solar Thermal Absorbers

Nanomaterials and absorbers trap sunlight, which is converted to solar energy; hence, they have significantly contributed to the harvesting of solar power. Utilizing materials with higher rates of absorption and minimum reflection loss rates will result in improved efficiencies of diverse PVs, such as power conversion efficiencies, and increased amount of solar power harvested or produced (Abbas et al., 2019). Some of these materials include carbon-based materials and plasmonic nanoparticles. Nanofluids significantly contribute to the improvement of the efficacy of harvesters. The utilization of different nanofluids to harvest solar energy is illustrated in Table 1.

The heat volume, thermal conductivity as well as absorption effectiveness of solar cells is improved using nanofluids, such as nanofluids that have graphene oxides, carbon nanotube-based nanofluids, and those that have black carbon and collagens. Using carbon nanohorn also increases the capacity of solar harvesters to absorb greater light, leading to greater energy production (Hossain et al., 2020; Kosinska et al., 2021

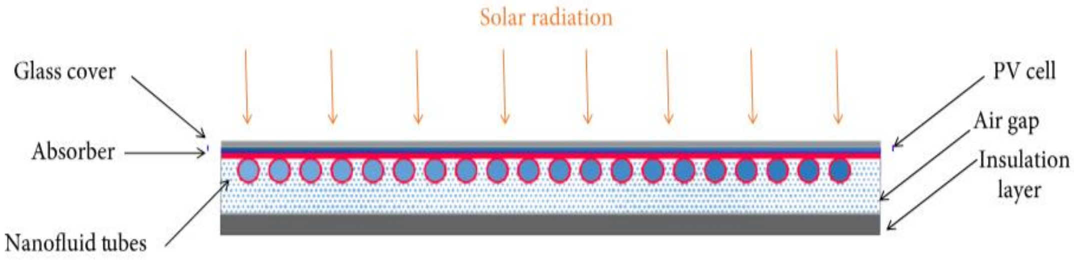


Figure 2. shows how nanofluids are combined with absorbers as seen in Ahmeds work (2019)

The diagram presented in Figure 2.0 above demonstrates how nanofluids and absorbers are commonly used to collect energy, from sunlight. Nanofluids serve as absorbers that enhance the efficiency of harnessing power from sunlight through harvesting methods. They are preferred for their ability to conduct heat well absorb radiation quickly and facilitate heat transfer resulting in light absorption and increased energy capture, from the sun. These fluids exhibit efficiencies, excellent thermal properties and optical characteristics that contribute to better utilization of solar power and heat retention. By incorporating these fluids improved photothermal conversions, increased energy yields and enhanced harvester efficiency can be achieved as supported by studies (Fu et al., 2019; Kumar et al., 2022; Moghaieb et al., 2023; Suresh et al., 2018; Smaisim et al., 2022). Nanofluids that contain water and silver, as well as those that have copper and water, have greater impacts on improving the efficiency of solar harvesters (see Fig. 2.1 below).

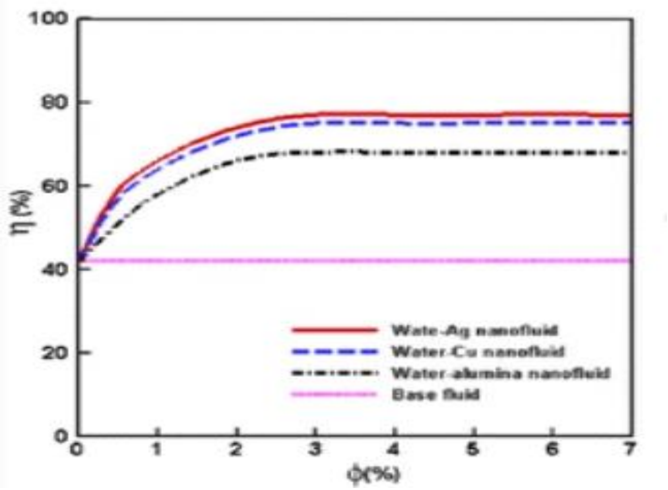


Figure 2.1. Increasing efficiency of harvesters using fluids like copper-water, as well as water-silver.

(ϕ is volume fraction of the particles in the fluids and η-is the efficiency of the harvester)

Source. Adapted from (Parvin, Nasrin, and Alim, 2014)

4. Material and Technological Advancements

The advanced research studies on eco-friendly, effective, and cheaper photovoltaic technologies that have lower energy payback time have led to numerous solar cell generations, as shown in Fig. 2.2 below. The main light-absorbing materials are used to classify the solar cell's generations, as illustrated in Fig. 2.2.

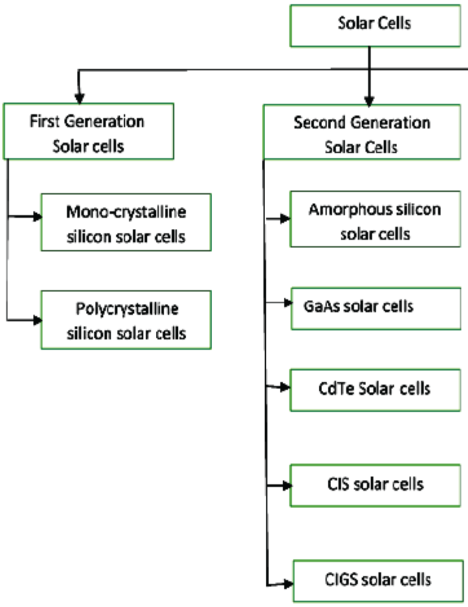


Figure 2.2. Solar Cell technologies used in solar generation or harvesting

New advancements in materials used to harvest solar energy show that graphene has great potential since it has intrinsic properties. Current developments have enhanced the efficiency of power conversion of graphene. These developments include solving the passivation problems at the graphene's interfaces or surface, enhancing overall reflectivity, and improving the work function of graphene, as well as its conductivity. Fig. 3.0a shows the overall structure of graphene/Silicon solar cells (Song et al., 2015).

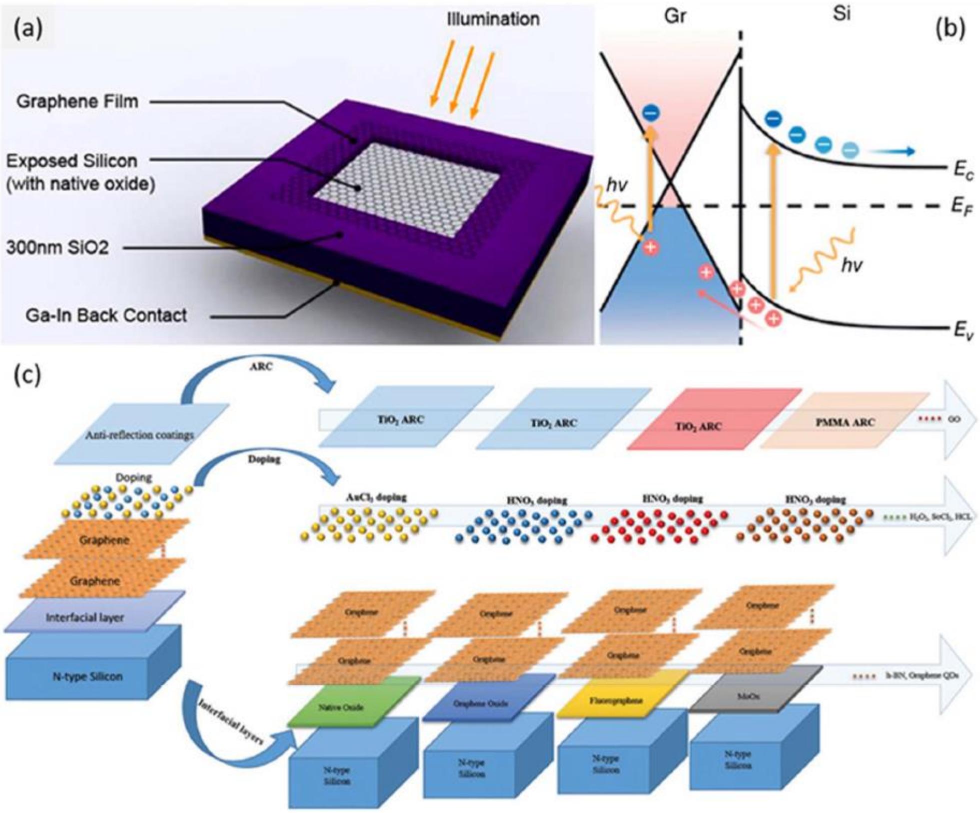


Fig. 2.3. Graphene/Silicon solar cell structure

Source: Adapted from Song et al. (2015)

Graphene/Si solar cell is fabricated following various processes, including the use of wet transfer for moving chemical vapor deposited graphene and placing it on the uncovered n-Si/ SiO2. Next, it is also deposited on the rear/front electrode, forming an n-silicon/graphene heterojunction shown in Figure 2.3b (Huang et al., 2018). The graphic illustration of Silicon/graphene SB-Solar cells built on heterojunction structures, which use different anti-reflection coatings, doping, as well as interfacial layers, is shown in Figure 2.3c (Bhopal et al., 2017).

The efficiency of the carrier collection of graphene-based solar cells has been enhanced by fabricating and using grid electrodes with high efficiencies, as well as expanding the functional areas of these solar cells. In spite of these advancements, the efficiency of Si/graphene-based PV cells further requires enhancement to achieve or surpass the Si p–n junction solar cell’s efficiency. Nevertheless, the use of van der Waals graphene heterojunctions has the potential to advance the harvesting of solar energy over the recent past (see Fig. 2.4).

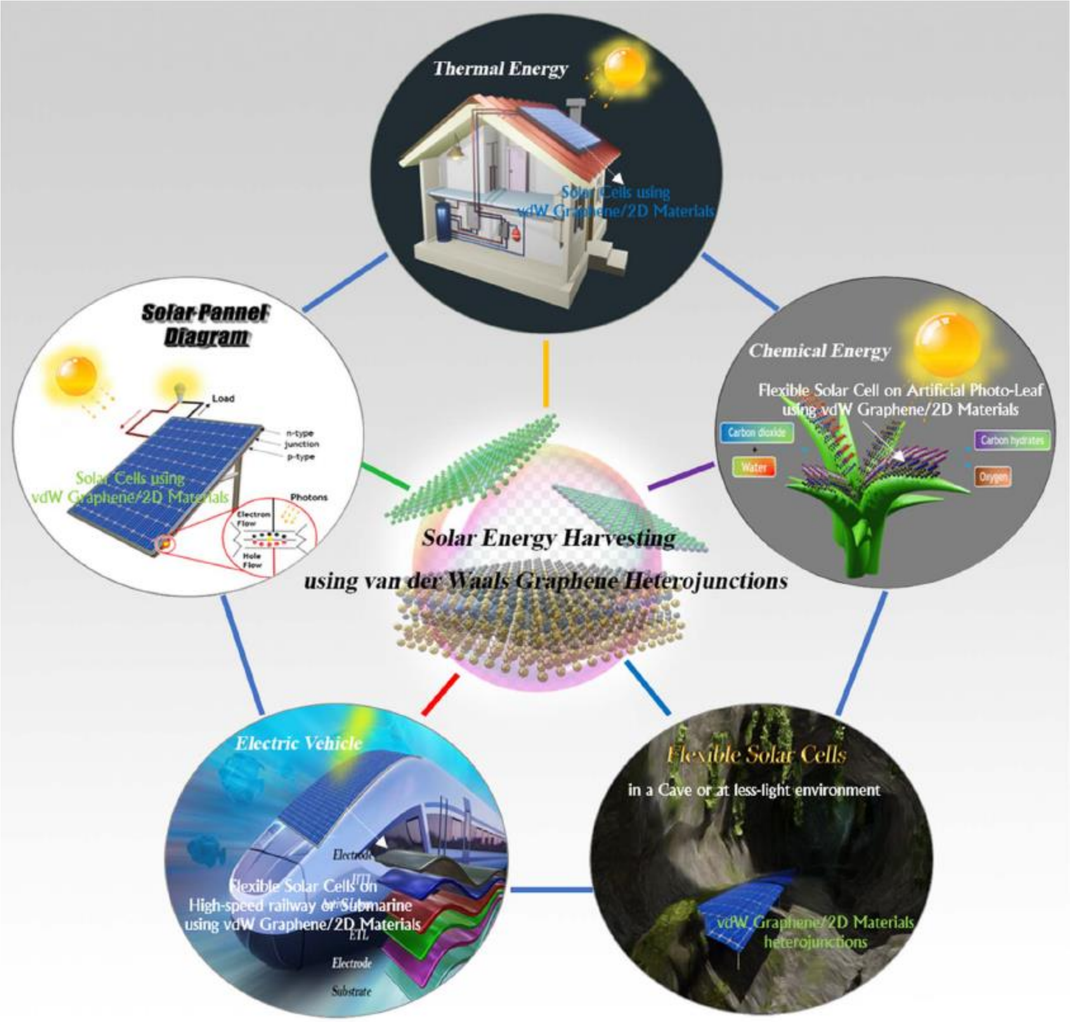


Fig. 2.4. Future potentials of integrating van der Waals graphene heterojunction(s) to harvest solar energy.

Source: Adapted from Leet al., (2023; pg. 31286).

Heterojunction on PVs is usually created using graphene (see Fig. 3.0a), which results in over 2.0% power conversion efficacy and increased open-circuit voltage (Li et al., 2018). The efficiency of OPVs is also enhanced using 2d materials as shown in figure 3.0b. These materials enable OPVs to attain open circuit voltage above 0.5 and more than 15% power conversion efficiency (Zhao et al., 2021). For example, forming PV’s Schottky junctions in harvesters of light photons using Molybdenum disulfide increases by over 5% (Tsai et al., 2014).

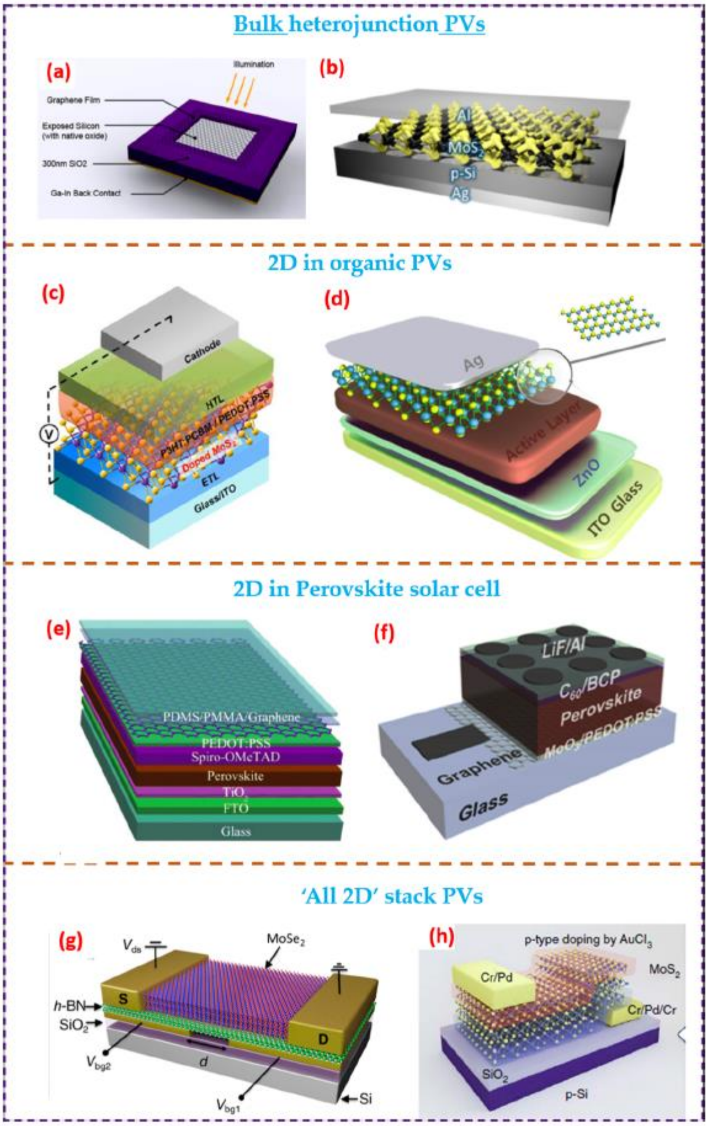


Figure 3.0. How diverse solar cells uses two-D materials to enhance efficiency and performances.

Organic photovoltaics (OPVs) are favored for their flexibility, efficiency, lightweight design and cost effectiveness when it comes to harnessing energy. The cell structure of OPVs is illustrated in Figures 3.0c and 3.0d showcasing layers of OPVs electrodes hole extraction layers and distinct electrons. To boost efficiencies and ensure stability, for solar energy harvesting 2 D materials have been integrated into OPV layers to enhance organic photovoltaic heterojunctions. These materials aid in improving the dispersion lengths of E–H pairs (photo created excitons) within the range of 1.0nm to 10.0nm and increasing binding energies between 0.100eV and 1.00eV.

In addressing challenges such as limited sunlight absorption bands due to the use of materials with ranges [100.0nm 200.0nm] two dimensional materials have been instrumental in enhancing the output, efficiency and stability of OPVs. Furthermore graphenes physical properties have made it a valuable component in developing cells and organic photovoltaics, with heightened efficiencies. The distinctive anisotropic formations, variation, in band gap and enhanced mobilities are among the characteristics that have encouraged the application of black phosphorus in organic solar cells to efficiently carry charges leading to improved efficiency and performance, in energy capture.

These materials are widely used as efficient interlayers in OPVs, leading to the achievement of better stability, efficiencies, and performances of OPVs for harvesting solar energy applications. For instance, doping black phosphorous in poly(styrene sulfonate) to spin-coat it, and Chemical exfoliation before being used in OPV-interlayers has resulted in enhanced power conversion efficiency by 8.0-11.0%. Figures 3.0e-f illustrate the use of these 2-D materials to achieve greatly-efficient and stable perovskite solar cells.

The development of the three perovskite lattice is influenced by the methylammonium cations and the band structure created by Pb/I atoms. This results in a cell that produces more charge carriers and is more efficient, at capturing light due to its characteristics, including a higher light absorption coefficient across a wider spectrum of light and a direct band gap of 1.550eV.

As a result the use of these materials has enhanced the strength and effectiveness of solar cells. For instance the integration of molybdenum disulfide and graphene into perovskite cells has increased their power conversion efficiency to 20.0% (Marinova et al., 2017; You et al., 2019).

Innovative Approaches and Ideas

Nanostructured materials exhibit characteristics, like heightened absorption. Improved refractive index, which aid in absorption for better energy capture efficiency. Examples of materials include core shell nanostructures, plasmonic nanostructures and photonic nanostructures. Plasmonic nanostructures facilitate reduced losses. Enhanced photovoltaic efficiency, by enabling higher rates of radiation absorption. These materials are predominantly utilized in film cells.

These structures form greater charge carriers, as well as increase absorption of solar radiation, leading to enhanced harvesting of solar in thin-film solar cells. They enhance the scattering of resonance and light in the cells, resulting in improved short-circuit current density of the solar cells by more than 7.9% and greater absorption of light in greater wavelengths. Integrating periodic structures in PVs will improve the length of the light's optical, as well as decrease reflections and loss of light photons absorbed, resulting in improved perfomance/efficiency of PVs, as shown in Fig. 3.1.

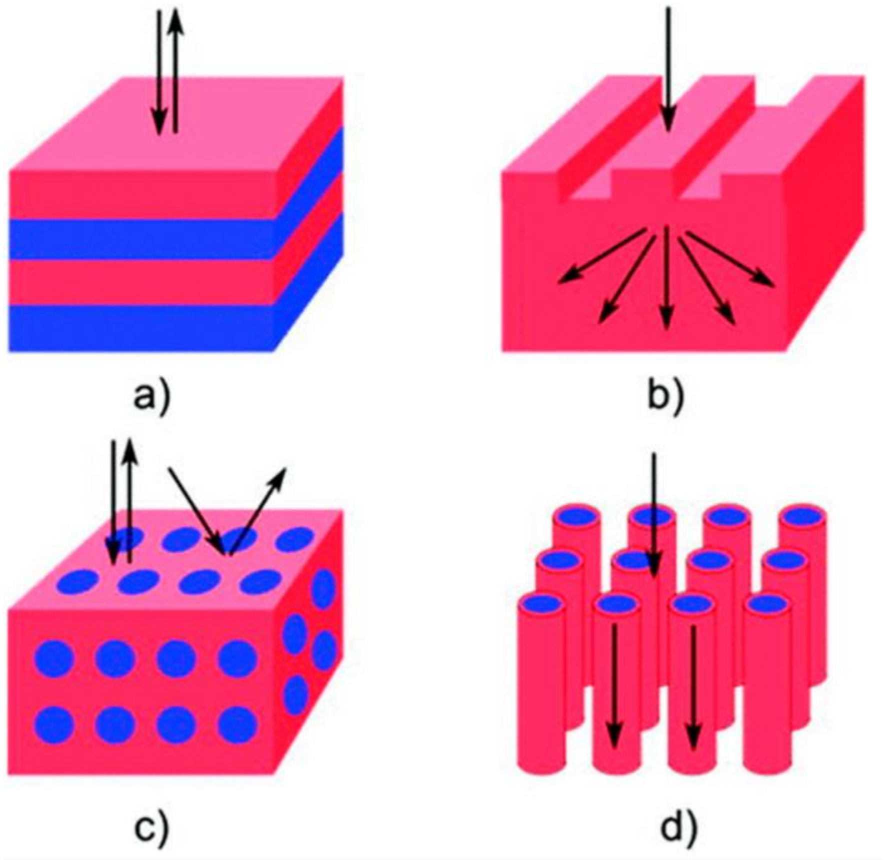


Fig. 3.1 Improving the efficiencies of solar cells using periodic nanostructures.

(2a is one dimensional stack, 2b is two-dimensional gratings, 2c is nanostructured back reflectors, while 2d is nanowires)

Source: Mokkapati and Catchpole (2012).

In very thinner film solar cells, nanostructures (i.e., nanocone gratings) are used to improve optical wavelengths and increase the amount of sunlight absorbed, resulting in higher efficiencies (see Fig. 3.2).

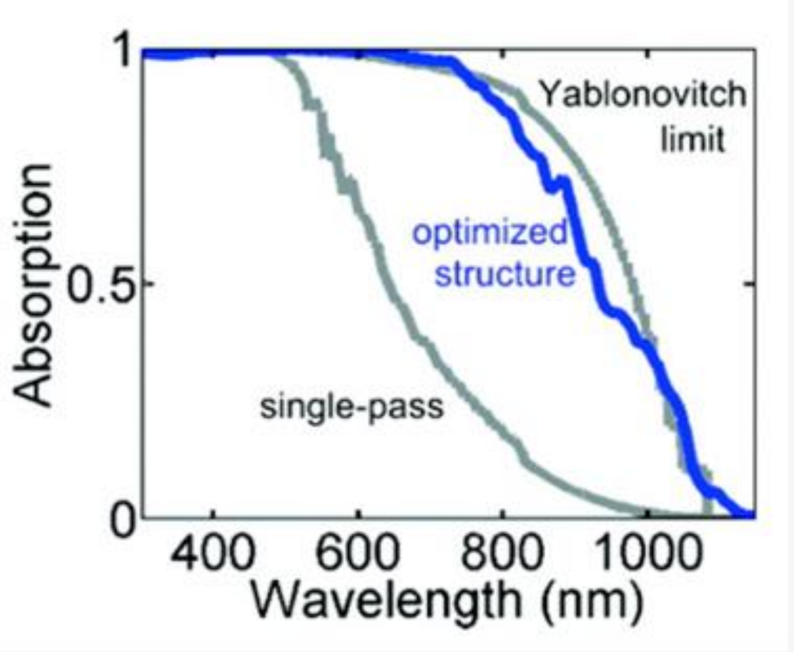


Figure 3.2. Enhancing absorption of solar cells for greater energy harvesting.

Source: Adapted from Wang et al. (2012)

Material and technological advancements have resulted in the production as well as the utilization of materials with high transparency, absorption rates, and conductivity. These materials are currently used in windows and PVs to harvest solar energy. The use of innovative strategies has resulted in the fabrication of emerging materials with electrical and thermal conductivities, and greater optical transparency, like indium titanium oxide, which is used in solar cells, windows, or even touch screens to harvest solar energy (Balaji et al., 2024; Kim et al., 2023).

Solar panels and windows also use PEDOTs, another substance, to sunlight, for generating energy.. This material boasts conductivity, high transparency and resistance to deterioration while being incredibly thin. These qualities enhance the reliability, longevity and effectiveness of panels incorporating this substance (Srivastava et al., 2023).

6. Challenges Related to Material Usage, in Energy Harvesting and Future Prospects

Research indicates that emerging materials have revolutionized energy harvesting. However the performance of cells or photovoltaics is hindered by the durability and stability of these materials.

The materials discussed in the journal also degrades over time when exposed to environmental factors. For example, based on the findings discussed in this paper, it is evident that graphene has a significant contribution to solar harvesting due to its exceptional attributes. However, there are key challenges that have hindered its effective application as the ideal material for improving the performances of solar cells and increasing the amount of solar harvested. One of the key challenges is its inadequate band gaps. It also has toxic features, experiences structural changes, is vulnerable to chemical alterations, as well an increased risk of being oxidized, which will affect its stability and durability in PVs used to harvest solar energy.

Exposure to environmental factors affects the stability of some materials used in solar cells, which further limits the light-harvesting efficiencies of solar cells. Therefore, future studies should focus on addressing these challenges by providing innovative solutions, which will enhance the effective use of these materials to harvest solar. Moreover, future studies should focus on enhancing the properties of the materials to reduce their vulnerabilities to degradations/oxidations. Addressing/overcoming these challenges will not only enhance the scalability, stability, and durability of these materials but also promote the use of these materials for larger-scale harvesting solar energy to meet growing demands of renewable energy.

7. Conclusion

The efficiency of solar cells is determined by the solar thermal absorber material, as well as the collection, separation, subsequent formation of charge carriers, and efficacy of light absorption (Wurfel et al., 2015). Black phosphorus, Molybdenum disulfide, as well as graphene, are some of the materials used in OPVs because they have lower-temperature conditions of processing, and meet the necessities of OPV layers, which include transparency, mobilities, as well as band gap (Lin et al., 2019). These 2-D materials have enhanced the cells' performances as well as improve the overall efficacy and stability of PVs/OPVs for harvesting energy from sunlight. The findings show that the advancement of nanostructures, nanofluids, as well as 2D materials, have paved the way for the future incorporation of these materials in solar cells to improve efficiencies and performances. Three-dimensional nanophotonic structures are used as effective omnidirectional reflectors in ultrathin/tandem solar cells.

The use of novel materials to harvest solar has decreased costs, enhanced lifespan, improved durability, and increased efficiencies of PVs. For instance, the use of Si, which is strong, robust, and lower - volume-weight ratio, as well has exceptional electrical-optical attributes has increased the light conversion efficiencies of solar cells by more than 26%. Nanomaterials and absorbers have significantly contributed to the harvesting of solar power because they increase the light conversion efficiency and perfomance of PVs. Advanced use of nanofluids has also resulted in the improvement of the efficacy of harvesters. Based on these conclusions, this paper recommends that constant material research for solar cells should be undertaken through a multidisciplinary approach to find the most ideal materials with exceptional attributes for a larger scale solar harvesting application.

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