

Development of Stable and Optimized Bandgap Halide-Chalcogenide Perovskite Materials for Photovoltaic Applications

Eze, Val Hyginus Udoka

Department of Publication and Extension, Kampala International University, Uganda

Udoka.eze@kiu.ac.ug

ABSTRACT

The toxicity and instability of some metal-halides has made it unfovarouble to be used for the development and fabrications of perovskites despite its good Power Conversion Efficiencies (PCE). The need to suggest good perovskites absorber materials that has excellent Dimensionality, optical band gap, and power conversion efficiencies to substitute lead in photovoltaic application is very essential in the recent research. This research work reviewed and suggested the combinable good perovskites absorber materials that can substitute lead in the perovskites. This research further discussed the possible alternative elements to replace lead in metal halide perovskites and the properties of the corresponding perovskite materials based on recent theoretical and experimental studies. In this research work other elements such as germanium, copper, antimony, bismuth, and the corresponding perovskite compounds are already showing promising properties.

Keywords: Perovskites, optimized bandgap, photovoltaic applications, Solar Photovoltaic Fabrications, Metal-halides, lead.

INTRODUCTION

Energy from the sun can be considered as the main source of all types of energy. There are several generations of PV technology which perovskite is one of the most recent researching generations that is gaining ground. Solar PV technology is one of the renewable technologies which have a potential to shape a clean, reliable, scalable and affordable electricity system for the future. Perovskite cells are lead-halide base with crystal structures[1][2]. The performance of solar cells based on hybrid halide perovskites has an unparalleled rate of progress and understanding of underlying physical chemistry of these materials trails behind [3]. The most viable area of application of perovskites materials is in building-integrated PV systems. The low cost, flexibility and negligible thickness requirement of perovskites materials make it an ideal for building integrated PV systems. Its high absorption coefficient, tunable bandgap, low processing temperature and abundant elemental components give it an advantage over

other thin film absorber materials [4]. Recently, the Perovskite-based solar cells have been developed and their power conversion efficiency (22.1%) has surpassed the efficiencies of other solar technologies for building-integrated PV systems such as thin-film PV cells (copper-indium-gallium-selenide (CIGSe :12%), copper-indium-gallium-sulfide (CIGS), cadmium-telluride (CdTe :11%), amorphous silicon (a-Si :8%), organic PV cells (dye-sensitized (10%) and polymer (3%) [5].

A perovskites material is a hybrid solar cell material known as organic-inorganic solar cell materials. The general chemical formula for perovskite material is given by ABX_3 where A is organic or inorganic cation (Na^+ , $CH_3NH_3^+$ etc), B is inorganic cation (Pb^{2+} , Sn^{2+} , Zn^{2+} , Fe^{2+} etc) and X is inorganic anion (Cl^- , Br^- , I^- , O^{2-}). It is produced from the by-products of crude oil (methyl ammonium and ethyl ammonium) and inorganic compounds (lead iodide, tin iodide, zin oxide). Recently, organic-inorganic hybrid

perovskites have attracted attention as light harvesting materials in mesoscopic cells [6]. Perovskite materials have been extensively used as light-absorbing material in solar cells because of their

unique properties such as direct optical band gap, broadband light absorption, bipolar transport, long carrier diffusion length and flexibility [7].

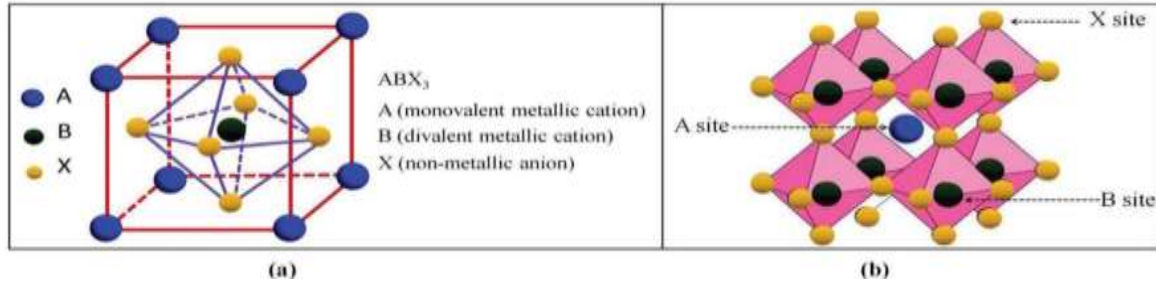


Figure 1: a) Schematic view of cubic perovskite crystal structure for ABX₃ compound, b) 3D crystal structure in which the A site is confined within a cage determined by the octahedral coordination of B site with X site [8]

Figure 1, 'a' and 'b' above showed the schematic crystal structure and 3D crystal structure of Perovskites respectively. Figure one showed the crystal structure of the perovskites with a formula of ABX₃ whereas A is organic or inorganic cation (Na⁺, CH₃NH₃⁺ etc), B is inorganic cation (Pb²⁺, Sn²⁺, Zn²⁺, Fe²⁺ etc) and X is inorganic anion (Cl, Br, I, O²⁻).

Perovskite solar cells hold an advantage over traditional silicon solar cells in the simplicity of their processing. Traditional silicon PV cells require expensive, multi-step processes, conducted at high temperatures (>1000 °C) in a high vacuum in special clean room facilities. Meanwhile, the organic-inorganic perovskites material is manufactured with simple wet chemistry techniques in a traditional laboratory environment. The raw material is readily available from crude oil deposits and inorganic compound deposits [9]–[17]. The high efficiencies and the very low production costs of perovskite solar cells have made it commercially attractive to investors. Because of the high absorption coefficient, a thickness of only about 500 nm is needed to absorb solar energy. Despite the high conversion efficiency of perovskites material, current perovskites materials are unstable in the presence of thermal stress and moisture [18]. Due to the negligible thickness of perovskite solar cells, it degrades quickly in moist environments[19].

The perovskites material uses lead, tin halide-based material or transition metal based as the light-harvesting active layer. At present, most common perovskites material is lead-based material. Hybrid organic-inorganic lead-based perovskites represent a class of light absorbing materials that has led to record-breaking solar conversion efficiencies. The conversion efficiency of lead-based perovskites materials has increased from 3.8% in 2009, 22.1% in early 2016 and 24.6% in 2022, making it the fastest-advancing solar technology [4] [18] [20]. The high efficiencies of lead-based perovskites have mainly been achieved using methyl ammonium lead-halide based perovskites such as methyl ammonium lead (II) iodide (CH₃NH₃PbI₃) and (CH₃NH₃PbI₃-xClx). The CH₃NH₃PbI₃ has diffusion length of 100nm while the CH₃NH₃PbI₃-xClx has diffusion length of 1µm. The application of thermal engineering in FAPbI₃ perovskite material via radiative thermal annealing and in situ XRD, effectively and efficiently monitors the temperature-induced phase transformation dynamics. It also monitors the crystal structural transformation and degradation in FAPbI₃ film but has poor production rate, rapid ramp rates for processing with low throughput [21]. In [22] an approach to further enhance solar spectrum utilization is the graded band gap, but this has not been previously

achieved for perovskites. It demonstrated graded band gap perovskite solar cells with steady-state conversion efficiencies averaging 18.4%, with a best of 21.7%, high fill factors of ~75% and short circuit current densities up to 42.1 mA/cm², all without reflective coatings. These cells, which are based on a novel architecture of two perovskite layers (MASnI₃ and MAPbI_{3-x}Br_x), incorporating GaN, monolayer hexagonal boron nitride, and graphene aerogel, display the highest efficiency ever reported for perovskite solar cells but still have the shortcoming of toxic effect of the lead [22]. However, the poisonous nature of lead has made further research in lead-based perovskites materials unattractive [5].

The attempt to replace toxic lead-based perovskites using non-toxic tin-based perovskites has met challenges. The drawback of tin-based perovskites was its low conversion efficiency and it degrades faster compared to lead-based perovskites [23][24]. To overcome the drawbacks of group (IV) elements such as instability, low efficiency and its toxic nature, the new research is focused on improving the fabrication process when using tin or making use of transition metal-based perovskites materials. In the work done in [25], copper, silver and gold were proposed to replace the toxic lead component of current perovskites material. In [26] and [24], an alternative method to obtain lead free halides was introduced and it is based on semiconducting (hybrid) lead halide perovskites structure, where monovalent organic cation are methyl ammonium (CH₃NH₃⁺, MA⁺), formamidinium (CH(NH₂)₂⁺, FA⁺) or an inorganic cation (K⁺, Rb⁺, Cs⁺), divalent Pb²⁺ metal cation and the X-site of the perovskite structure is occupied by halide counterions (Cl⁻, Br⁻, I⁻). These elements were selected because they are the best conductors in existence. Other transition materials can also be used to replace the lead

The properties of lead perovskites can be tuned by changing A-site or X-site ions and also mixed ion approaches turned out to be beneficial for the performance of the perovskites in photovoltaic devices.

This project will be nanotechnology based which will focus on the development of alternative Perovskite materials composed of non-toxic elements, probable non-carcinogenicity and/or presenting improved stability. Key challenges will involve fabricating new Perovskite materials, incorporating the materials in photovoltaic solar cells, and characterization of device's performance.

Limitations of the existing Photovoltaic Fabrications and Optimizations

The existing Perovskite materials for photovoltaic applications have some limitations which I want to overcome in this research. Some of the limitations are:

- Tin-based perovskites material has low conversion efficiency and it is unstable in the moist and hot environment. These two properties make it unsuitable for building-integrated PV systems.
- Lead-based perovskites material is toxic and has probable carcinogenicity, thus, unstable in the moist and hot environment. These three properties make it unsuitable for building-integrated PV systems.
- Existing transition metals-based Perovskite materials have low conversion efficiency.

Aim of the Study

This research work basically aimed at:

- Proposing some Perovskite materials that will overcome the problems of existing toxic, probable carcinogenicity and/or stability problems of existing Perovskite materials.
- Suggesting the suitable way of characterizing and fabricating a new formed material.

METHODOLOGY

Materials that can Substitute lead in Perovskites**Tin-based Perovskites (MASnX₃)**

Tin-based perovskites (MASnX₃) according to research has revealed a direct bandgap of 1.20-1.35 eV, electron mobility of 2320 cm² V⁻¹ s⁻¹, hole carrier mobility of 322 cm² V⁻¹ s⁻¹, and long charge carrier diffusion length of more than 500 nm. The alteration of Br⁻/I⁻ ratio in MASnI^{3-x}Br_x has resulted in large value of VOC (0.88 V) in MASnBr₃ and JSC (12.33 mA cm⁻²) in MASnBr₂. The absorption band can be tuned by altering the composition of halide anions in MASnX₃ perovskites. However, Sn-based perovskites suffer from degradation in air due to oxidation of Sn²⁺ into Sn⁴⁺. The incorporation of additives has resulted in reduced oxidation and better stability in air. The A-site cation has a significant effect on photovoltaic performance. The use of diethylammonium (en) and FA⁺ at the A-site of ASnX₃ has resulted in wider bandgaps and improved stability. An efficiency of 8% has been achieved for (FA)_{0.75}(MA)_{0.25}SnI₃ with a VOC (0.61 V) and bandgap (1.33 eV) [8], [27], [28].

Germanium-based perovskites (AGeI₃)

Germanium-based perovskites has an optical bandgap of 1.63 eV, excellent hole and electron conducting behavior, and better stability in air. Using DFT calculations, it has been reported that with increase of size of halide anion, the bandgaps have decreasing values of 3.7, 2.81, and 1.61 eV, respectively. The replacement of the iodide content in AGeI₃ by bromide results in enhanced photovoltaic performance and stability to a slight extent. Mixed Ge-based perovskite RbSn_{0.5}Ge_{0.5}I₃ exhibits a better optical absorption and effective masses for higher carrier mobility and good stability in water. By engineering the size of A-site cation, its doping with another suitable cation and size of halide anion, it is possible to fabricate a Ge-based perovskite as an efficient light absorber [8], [27], [28].

Bismuth-based perovskite (MA)₃Bi₂I₉

The bismuth-based perovskite (MA)₃Bi₂I₉ has displayed low values of solar power conversion efficiencies up to 1.64 eV up till now, yet they have exhibited excellent stability in ambient air at room temperature and against exposure to humidity. The morphology of (MA)₃Bi₂I₉ films can be enhanced by addition of various concentration of NMP into the precursor solution that not only controlled the rate of crystallization but also enhanced the efficiency and stability in a relative humidity of 50-60%. The concentration of perovskite solution and substrate temperature also impacts its efficiency and stability. The wide bandgaps of lead-free perovskites can be engineered to a narrow bandgap by incorporating triiodide into P(4-methyl piperidinium)₃Bi₂I₉((MA)₃Bi₂I₉) that exhibited a bandgap of 1.58 eV in comparison to 1.5 eV of MAPbI₃. The various deposition methods have a direct influence on morphology of films. Cs₃Bi₂I₉ has displayed an efficiency of 8% with a pure crystalline phase and stability [8], [27], [28][12], [13].

Bismuth-based double perovskite (Cs₂AgBiBr₆)

Bismuth-based double perovskite like Cs₂AgBiBr₆ exhibited an indirect bandgap of 2.19 eV. The DFT calculations have further revealed that the family of 3D double perovskites have optical bandgap in the visible range and low carrier effective masses. Bismuth-based perovskites can be thoroughly investigated for enhancement in their efficiency as these materials have excellent stability in ambient air and in relative humidity. In antimony-based perovskites, the size of cationic or anionic species and the employed processing technique determines the structure. When A-site cation Cs⁺ is replaced by a smaller cation Rb⁺, a 2D layered phase is achieved with a formation energy difference of 0.25 eV in comparison to Cs-based counterparts. The addition of additive in OD (MA) 3Sb2I9 films has resulted in enhanced light absorption in the visible

wavelength regions up to 400 nm. The use of chalcogenide and mixed perovskite materials can be an effective strategy for formation of efficient, cheap, and stable solar cells. $\text{Cs}_4\text{CuSb}_2\text{C}_{12}$, besides having photo and thermal stability and resistance to humidity, have exhibited excellent photovoltaic properties. There has been a significant effect on photovoltaic parameters on substitution of Sb with Bi in 2D mixed layered perovskites $(\text{NH}_4)_3(\text{Sb}_{1-x}\text{Bi}_x)_2\text{I}_9$. By proper substitution of Bi into antimony-based perovskites, it is possible to fabricate light harvesters with high efficiency and stability [12], [13].

Copper-based perovskites ($(\text{MA})_2\text{CuCl}_2\text{Br}_2$)

Copper-based perovskites usually form 2D layered structure owing to their smaller ionic radii. By proper tuning of Cl-/Br- ratio, the optical absorption of Cu-based perovskites can be extended in the near-infrared region. The $(\text{MA})_2\text{CuCl}_2\text{Br}_2$ and $(\text{MA})_2\text{CuCl}_{0.5}\text{Br}_{3.5}$ have reported better stability under ambient conditions. The divalent cations of alkaline earth metals like Mg^{2+} , Ca^{2+} , and Sr^{2+} can be effective replacement for lead. The perovskite solar cells based on transition metals Ti, Ni, and Cd-doped BiFeO_3 as a light absorber have displayed VOC values of 0.77, 0.56, and 0.49 V, respectively. By suitable selection of A and B-site cations and halide anions, their alteration in composition and synthesis method, it is possible to fabricate lead-free perovskites with maximum efficiency and stability without any toxic influence on environment [12], [13], [16].

Antimony-based perovskites

Antimony halide perovskites are a potential alternative to lead-based perovskite semiconductors for photovoltaic applications to address the chemical stability and the toxicity issue. The trivalent Sb^{3+} metal cation (1) is isoelectronic to Sn^{2+} ($4d^{10} 5s^2$) and has a similar s^2 valence electronic configuration as Pb^{2+} ($5s^2$ lone pair), (2) has a comparable electronegativity (Sb: 2.05, Sn: 1.96, Pb: 2.33) but (3) a significant smaller ionic radius (76 pm) compared to the divalent Sn^{2+} (110 pm) and Pb^{2+} (119 pm) metal

cations. Because of the difference in the oxidation state, antimony halide perovskites have the basic formula $\text{A}_3\text{Sb}_2\text{X}_9$ ($\text{X} = \text{Cl}, \text{Br}, \text{I}$), where A are organic (e.g. NH_4^+ , CH_3NH_3^+ , dimethylammonium, trimethylammonium, tetramethylammonium, guanidinium) or inorganic (e.g. Rb^+ , Cs^+) cations. The structural chemistry and dimensionality of antimony halide perovskites are significantly influenced by the choice of cationic and anionic species. Depending on the dimensionality, the crystal structures of antimony-based perovskites featuring $\text{Sb}_2\text{X}_9^{3-}$ enneahalide ions within the anionic sublattice can be divided into (a) zero-dimensional, isolated double octahedral structures comprising pairs of face-sharing SbX_6 octahedra, which form discrete complex anionic metal halide $\text{Sb}_2\text{X}_9^{3-}$ clusters arranged in dimer units. (b) infinite one-dimensional double chains of corner-sharing SbX_6 octahedra forming zigzag-type polyanionic $\text{Sb}_2\text{X}_9^{3-}$ sublattices (c) two-dimensional corrugated double-layered polyanionic structures based on corner-connected SbX_6 octahedra to $\text{Sb}_2\text{X}_9^{3-}$ [27][29-33].

Methods to adopt using different metals and solvents.

The following approaches are suggested to be adopted by researchers and Photovoltaic developer using a suitable metal:

1. Selection of the appropriate solvent such as Lewis acid reagent, Lewis base reagent and adducts activator Lewis base.
2. Selection of homo and heterovalent metal that can characteristically substitute lead
3. Integrating the developed and/or selected material into photovoltaic system using appropriate techniques.
4. The developer has to be characterized using state-of-art equipment available
5. The data has to be collected experimentally from the laboratory and finally tested.

Summarily, these steps and concepts that were setup in this research paper will be of a great help to the researchers and solar

photovoltaic developers as it has the working prototypes that can be used for a

successful development and fabrications of perovskites photovoltaics.

CONCLUSION

This research work exposes the combinable metals and solvents that can be combined to develop a perovskites material that are free from toxicity, soluble when exposed to the air, low bandgap and low efficiency photovoltaics. This research work detailed the advantages and the disadvantages of using some of the metals and finally recommend some metals to be

used by solar photovoltaic developers depending on what the specifications of developer or what he wants to optimize. It also outlined sequential methods to be used when developing and fabricating perovskite solar photovoltaic panels for effective and efficient power conversion efficiency.

REFERENCES

- [1] Eldin, A. H., Refaey, M. and Farghly, A. (2015). A Review on Photovoltaic Solar Energy Technology and its Efficiency, in *A Review on Photovoltaic Solar Energy Technology and its Efficiency*, no. December, pp. 1-9.
- [2] Kalkman, J., Merhaba, A., Bose, S. and Bradley, H. (2015). Emerging technologies in Solar PV : identifying and cultivating potential winners Content. *Arthur d Little*. pp. 2-16.
- [3] Walsh, A. (2015). Principles of Chemical Bonding and Band Gap Engineering in Hybrid Organic – Inorganic Halide Perovskites. *Journal of Physical Chemistry C*, vol. 119, pp. 5755-5760, doi: 10.1021/jp512420b.
- [4] Song, T. et al., (2015). Perovskite solar cells: film formation and properties. *Journal of Materials Chemistry A*, vol. 3, no. 17, pp. 9032-9050.
- [5] Noel, N. K. et al., (2014). Lead-Free Organic-Inorganic Tin Halide Perovskites for Photovoltaic Applications. *Energy & Environmental Science*, vol. 7, pp. 1-24.
- [6] Kwon, U. et al., (2016). Investigation into the Advantages of Pure Perovskite Film without PbI₂ for High Performance Solar Cell. *Scientific Reports*, vol. 6, p. 35994.
- [7] Dualeh, A., Gao, P., Seok, S., Nazeeruddin, M. K. and Grätzel, M. (2014). Thermal behavior of methylammonium lead-trihalide perovskite photovoltaic light harvesters. *Chemistry of Materials*, vol. 26, no. 21, pp. 6160-6164.
- [8] Kour, R. *et al.*, (2019). Potential Substitutes for Replacement of Lead in Perovskite Solar Cells: A Review. *Global Challenges*, vol. 3, no. 11, p. 1900050, doi: 10.1002/gch2.201900050.
- [9] Eze, V. H. U., Eze, M. C., Chijindu, V., Chidinma, E., Samuel, U. A. and Chibuzo, O. C. (2022). Development of Improved Maximum Power Point Tracking Algorithm Based on Balancing Particle Swarm Optimization for Renewable Energy Generation. *IDOSR Journal of Applied Sciences*, vol. 7, no. 1, pp. 12-28.
- [10] Eze, V. H. U., Oparaku, U. O., Ugwu, A. S., and Ogbonna, C. C. (2021). A Comprehensive Review on Recent Maximum Power Point Tracking of a Solar Photovoltaic Systems using Intelligent, Non-Intelligent and Hybrid based Techniques. *International Journal of Innovative Science and Research Technology*, vol. 6, no. 5, pp. 456-474.
- [11] Eze, M. C., Eze, V. H. U., Chidebelu, N. O., Ugwu, S. A., Odo, J. I. and Odi, J. I. (2017). Novel Passive Negative And Positive Clamper Circuits Design For Electronic Systems. *International Journal of Scientific & Engineering Research*, vol. 8, no. 5, pp. 856-867.
- [12] Eze, M. C. *et al.*, (2021). Solar Energy Materials and Solar Cells Optimum silver contact sputtering parameters for efficient perovskite solar cell fabrication. *Solar Energy Materials and Solar Cells*, vol. 230, p. 111185,

- doi: 10.1016/j.solmat.2021.111185.
- [13] Eze, M. C. *et al.*, (2022). Improving the efficiency and stability of in-air fabricated perovskite solar cells using the mixed antisolvent of methyl acetate and chloroform. *Organic Electronics*, vol. 107, pp. 1-10, doi: 10.1016/j.orgel.2022.106552.
- [14] Okafor, W. O., Edeagu, S. O., Chijindu, V. C., Iloanusi, O. N. and Eze, V. H. U. (2023). A Comprehensive Review on Smart Grid Ecosystem. *IDOSR Journal of Applied Science*, vol. 8, no. 1, pp. 25-63.
- [15] Eze, V. H. U., Olisa, S. C., Eze, M. C., Ibokette, B. O. and Ugwu, S. A. (2016). Effect Of Input Current And The Receiver-Transmitter Distance On The Voltage Detected By Infrared Receiver. *International Journal of Scientific & Engineering Research*, vol. 7, no. 10, pp. 642-645.
- [16] Eze, V. H. U., Iloanusi, O. N., Eze, M. C. and Osuagwu, C. C. (2017). Maximum power point tracking technique based on optimized adaptive differential conductance. *Cogent Engineering*, vol. 4, no. 1. doi: 10.1080/23311916.2017.1339336.
- [17] Ogbonna, C. C., Eze, V. H. U., Ikechuwu, E. S., Okafor, O., Anichebe, O. C. and Oparaku, O. U. (2023). A Comprehensive Review of Artificial Neural Network Techniques Used for Smart Meter-Embedded forecasting System. *IDOSR Journal of Applied Science*, vol. 8, no. 1, pp. 13-24.
- [18] Elumalai, N. K., Mahmud, M. A., Wang, D. and Uddin, A. (2016). Perovskite solar cells: Progress and advancements. *Energies*, vol. 9, no. 11.
- [19] Green, M. A., Ho-Baillie, A. and Snaith, H. J. (2014). The emergence of perovskite solar cells. *Nature Photonics*, vol. 8, no. 7, pp. 506-514”
- [20] Zhang, P., Li, M. and Chen, W.C. (2022). A Perspective on Perovskite Solar Cells: Emergence, Progress, and Commercialization. *frontiers in chemistry*, vol. 10, p. 802690, doi: 10.3389/fchem.802890.
- [21] Pool, V. L. *et al.*, (2017). Thermal engineering of FAPbI₃ perovskite material via radiative thermal annealing and in situ XRD. *Nature Communications*, vol. 8, pp. 1-8, doi: 10.1038/ncomms14075.
- [22] Worsley, M. A. and Zettl, A. (2016). High current, high efficiency graded band gap perovskite solar cells. *Kavli Energy Nanosciences Institute at the University of California, Berkeley, and the Lawrence Berkeley*, pp. 1-19.
- [23] Babayigit, A. *et al.*, (2016). Assessing the toxicity of Pb- and Sn-based perovskite solar cells in model organism *Danio rerio*. *Scientific Reports*, vol. 6, p. 18721.”
- [24] Wang, M. *et al.*, (2021). Lead-Free Perovskite Materials for Solar Cells. *Nano-Micro Letters*, vol. 13, no. 1. Springer Science and Business Media B.V. doi: 10.1007/s40820-020-00578-z.
- [25] Volonakis, G. *et al.*, (2016). Lead-Free Halide Double Perovskites via Heterovalent Substitution of Noble Metals. *Journal of Physical Chemistry Letters*, vol. 7, no. 7, pp. 1254-1259.
- [26] Hoefler, S. F. and Trimmel, G. (2017). Progress on lead-free metal halide perovskites for photovoltaic applications: a review. *Monatshefte für Chemie - Chemical Monthly*, vol. 148, no. 5, pp. 795-826, doi: 10.1007/s00706-017-1933-9.
- [27] Hoefler, S. F. and Trimmel, G. (2017). Progress on lead-free metal halide perovskites for photovoltaic applications: a review. *Institute for Chemistry and Technology of Materials (ICTM) (springer)*, vol. 148, no. 5, pp. 795-826, doi: 10.1007/s00706-017-1933-9.
- [28] Soleimanioun, N., Rani, M., Singh, B., Saini, G. S. S. and Tripathi, S. K. (2020). Potential replacement to lead: Alkali metal potassium and transition metal zinc in organo-metal halide perovskite materials. *Journal of Alloys and Compounds*,

- vol. 861, pp. 1-34, doi: 10.1016/j.jallcom.2020.158207.
- [29] Ahsan, S., Javed, K., Rana, A. S. and Zeeshan, M. (2016). Design and cost analysis of 1 kW photovoltaic system based on actual performance in Indian scenario. *Perspectives in Science*, 8, 642-644.
- [30] Nnamchi, S. N., Mundu, M. M., Busingye, J. D. and Ezenwankwo, J. U. (2019). Extrinsic modeling and simulation of helio-photovoltaic system: a case of single diode model. *International journal of green energy*, 16(6), 450-467.
- [31] Nnamchi, S. N., Sanya, O. D., Zaina, K. and Gabriel, V. (2020). Development of dynamic thermal input models for simulation of photovoltaic generators. *International Journal of Ambient Energy*, 41(13), 1454-1466.
- [32] Rajan, P. K., Ganesan, V., Dennison, M. S. and Kalishwaran, P. (2018). Fabrication and characterisation of hybrid aluminium metal matrix composite with welding slag and flux by using stir casting technique. *International Research Journal of Engineering and Technology*. 25, 24-27.
- [33] Nnamchi, S. N., Oko, C. O. C., Kamen, F. L. and Sanya, O. D. (2018). Mathematical analysis of interconnected photovoltaic arrays under different shading conditions. *Cogent Engineering*, 5(1), 1507442.