PVSAT 2025

2–4 April 2025
Swansea University – Bay Campus, Swansea, UK

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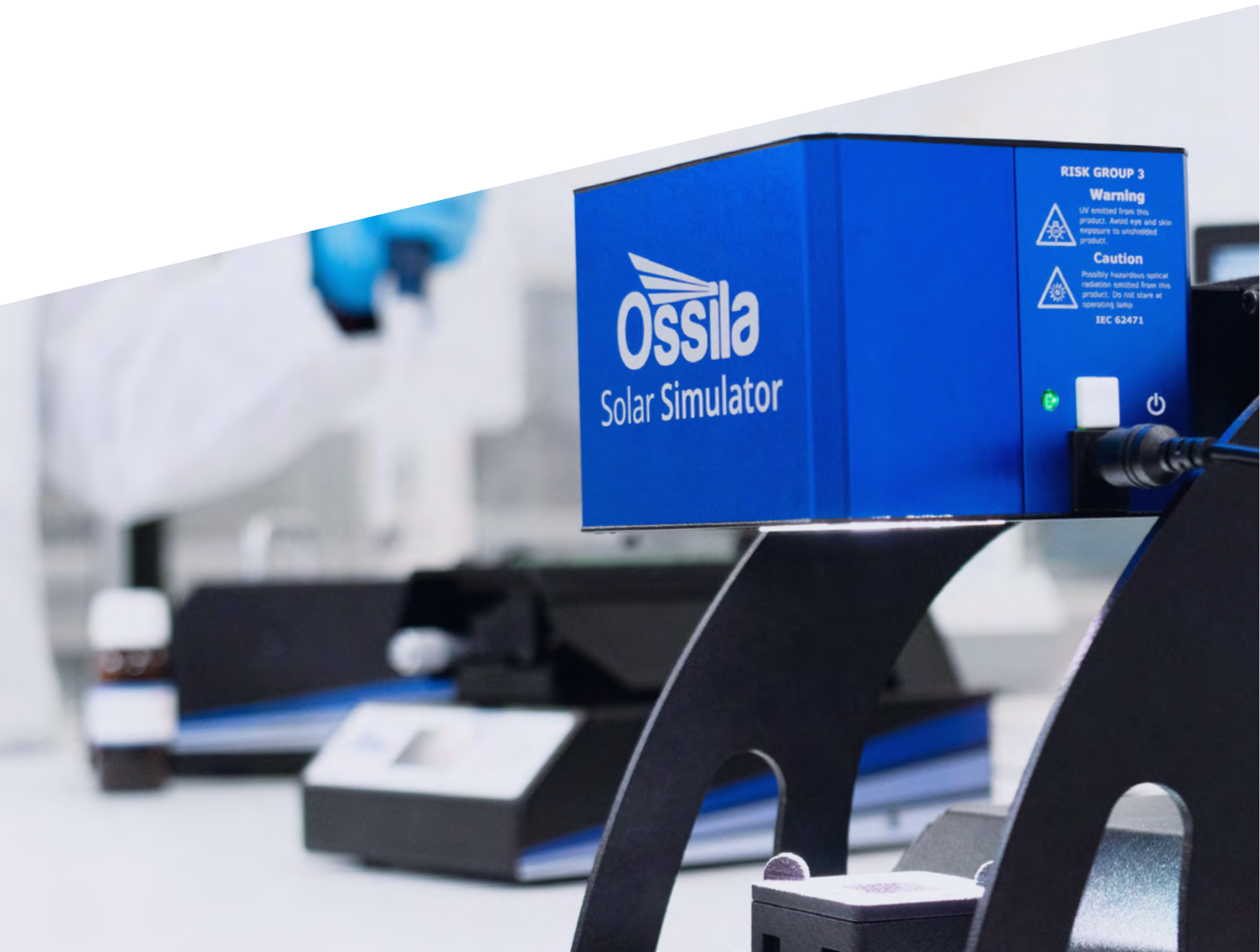

PVSAT Programme

Wednesday, April 2, 2025

11:00 Welcome
Tasmiat Rahman (Conference Chair), **Helen Griffiths** (Pro-Vice Chancellor for Research and Innovation) and **George Koutsourakis** (Programme Chair)

Session 1 - Advances in Photovoltaics
Chair: Tasmiat Rahman, University of Southampton

11:15 (Invited) Tackling the industrial leap for printed perovskite solar cells
Trystan Watson, Swansea University

11:45 Advances in gallium doping for high-performance silicon photovoltaic cells
John Murphy, University of Warwick

12:00 Surface Strains Dictate Local Photoluminescence Properties in Halide Perovskites as Revealed by 3D Multimodal Imaging
Kieran Orr, Stanford University

12:15 The effects of the dilute-donor strategy the recombination mechanisms and device performance of scalable OPVs for semi-transparent application
Eva Mazzolini, Imperial College London

12:30 Lunch

13:30 **Poster Session A**
Chair: **Sophie Pain,** University of Warwick

Session 2: Characterisation and Testing for Photovoltaics
Chair: George Koutsourakis, National Physical Laboratory

15:00 (Invited) Beyond Efficiency – Scientific and Engineering Requirements to Introduce a New Cell Technology to The Market
Ralph Gottschalg, Fraunhofer Center for Silicon Photovoltaics

15:30 Digital light processing applications for advanced characterization of photovoltaic devices
Daniel Parsons, National Physical Laboratory

15:45 Design and Development of a New Smart Portable I-V Tracer
Navid Tavakoli, Institute for Photovoltaics, University of Stuttgart

16:00 Photoexcited muon spin spectroscopy for studying carrier lifetime in silicon for photovoltaics,
Anup Yadav, University of Warwick

16:15 Tea Break

Session 3: Application Targeted Integrated Photovoltaics

Chair: **Greg Burwell**, University of Swansea

16:30 ATiP project: Application Targeted Integrated Photovoltaics
Silvia Villarroya-Lidon, ATIP Project

16:40 Identifying Optimal Materials and Architectures for Semi-Transparent Agrivoltaics
Austin Kay, Swansea University

16:55 The Influence of Energetics and Morphology on Charge Transfer in Organic Photovoltaics
Jenny Nelson, Imperial College London

17:10 Insights into Degradation Pathways of Triple-Cation Perovskite Thin Films under Outdoor and Indoor Conditions: A Comparative Analysis
Muhammad Bilal, Queen Mary University of London

17:25 Printed Nanoparticle Interlayers Enable High-Quality Organic Electron Transport Layers in Scalable Perovskite Solar Cells
Charlie Henderson, Imperial College London

17:40 Industry Technology Session

18:00 Welcome Reception and Light Dinner

19:30 Buses Depart

Thursday, April 3, 2025

Session 4: Perovskite and Organic Photovoltaics

Chair: **Elizabeth Gibson**, Newcastle University

9:00 (Invited) Sustainable development of deployable perovskite solar cells
Xuan Li, Helmholtz-Zentrum Berlin

9:30 Back-contact Perovskite Solar Cell Modules Fabricated via Roll-to-Roll Slot-die Coating: Scale-up Towards Manufacture
Nathan Hill, Power Roll Ltd

9:45 From small to large-area PV devices – addressing the scalability challenge associated with organic or perovskite-based solar modules
Dimitar Kutsarov, University of Surrey

10:00 Charge Generation in Non-Fullerene Acceptors
Linnea Lind, Imperial College London

10:15 3D Printing: Dies for Perovskite, Devices, and De-escalation of Scale Up Costs
Bethan Miles, Swansea University

10:30 Coffee Break

Session 5: PV Sustainability
Chair: **Tasmiat Rahman**, University of Southampton

11:00 Sustainability considerations for manufacturing and deployment of multi-terawatt silicon photovoltaics
Neil Beattie, Northumbria University

11:30 Characterisation of PV Waste: An assessment of the toxicity of antimony embedded in PV glass
Matt Burnell, University of Exeter

11:45 Forecasting UK solar module waste in the United Kingdom
Sophie Pain, University of Warwick

12:00 Whole system efficiency of energy harvesting devices powered by next-generation PV technologies
Zaid Haymoor, Swansea University

12:15 Metal-Organic Nanosheets: Bridging Solar harvesting and Storage
Kezia Sasitharan, Newcastle University

12:30 Lunch

13:30 **Poster Session B**
Chair: **Nigel Mason**, PV Consulting

14:45 Tea Break

Session 6: Application Targeted Integrated Photovoltaics
Chair: Paul Meredith, Swansea University

15:00 Key Molecular Perspectives for High Stability in Organic Photovoltaics
Ji-Seon Kim, Imperial College London

15:30 Enabling Large-Area Organic Photovoltaics with High Performance Metal-Grid Transparent Electrodes
Nicholas Burridge, Swansea University

15:45 Auxetic Rotating Triangle c-Si Solar Modules with Adjustable Light Transmittance
Chen Cao, University of Southampton

16:00 Non-geminate recombination kinetics in organic solar cells optimized for target applications
Dichard Adam Pacalaj, Imperial College London

16:15 Advanced Dielectrics for Solar PV Coatings
Shimra Ahmed, Swansea University

16:30 Comfort Break

16:45 CISM and SPECIFIC tours

19:00 Buses Depart for Brangwyn Hall

19:30 Reception and Conference Dinner (Brangwyn Hall)

Friday, April 4, 2025

Session 7: Technological Advancements from Materials to Systems

Chair: **Stuart Boden**, University of Southampton

9:15 (Invited) Solar PV in real world – what are the challenges?
KT Tan, Viridian Solar

9:45 The significance of measuring the bulk lifetime for high efficiency silicon solar cells
Nicholas Grant, University of Warwick

10:00 Diffuse Irradiance Estimation Using a Dual-Stream Sky Image-Based Computer Vision Approach
David Hamlyn, University of Southampton

10:15 Variation of Cell-Bonded 4-domed Optic Material to Improve Concentration Factor for Concentrator Photovoltaics
William Cameron, University of Exeter

10:30 Low resistivity contacts for high-efficiency next-generation silicon solar cells
Edris Khorani, University of Warwick

10:45 Coffee Break

Session 8: Perovskites and Organic Photovoltaics

Chair: **Aruna Ivaturi**, University of Strathclyde

11:00 (Invited) Flexible perovskite solar cells: fabrication and applications
Francesca Brunetti, University of Rome "Tor Vergata"

11:30 Investigating the Scalability Potential of an SnO2 Derived Electron Transport Material Using Established Criteria and Experimental Procedures
Erin Lambert, University of Liverpool

11:45 In-Situ Photoluminescence Investigation of Defect Mitigation and Non-Radiative Recombination in Aerosol-Treated Perovskites
Madsar Hameed, Queen Mary University of London

12:00 Photocapacitive Behavior of Carbon-Based Triple-Cation Perovskite Solar Cells in a PMMA based Solid-State Electrolyte Framework
Sandeep Pandey, University of Strathclyde

12:15 Closing Remarks

12:30 Lunch

13:30 Close and Depart

Poster Programme

Wednesday, April 2, 2025

Poster Session A

Chair: **Sophie Pain**, University of Warwick

P1 The Impact of Crystallinity in Low-cost Donor Blends on Charge Generation for Organic Photovoltaics
Keren Ai, Imperial College London

P3 Development of fully non-toxic ink for the scalable deposition of perovskite thin layers
Ehsan Rezaee, University of Surrey

P5 Low synthetic complexity and scalable donor polymers for organic solar cells
Martina Rimmele, Imperial College London

P7 Development of Novel Photovoltaic Devices Combining Ferroelectric Nanostructures with Perovskite Solar Cells
Raphael Viana, Queen Mary University of London

P9 Photovoltaics for Nigerian Rice Processing – Social Perspective
Abdul-Azeez Yusuf, University of Exeter

P11 Correlation of soiling losses of distinct mega cities considering accumulation variance
Ali Alqahtani, University of Exeter

P13 Theoretical Study on the Effect of Doped Carbon Back Electrode on Lead-Free and Hole Transport-Free in $CsSnGeI_3$ -Based Concentrating Perovskite Solar Cells
Mai Alharbi, University of Exeter

P15 High-Performance Indoor Photovoltaic Mini-Modules with Carbon Electrodes for Sensor Power Generation
Sahil Verma, St Andrews University

P17 ZnO nanorod hemispherical light scatters for thin film solar cell applications
Yongtao Qu, Northumbria University

P19 Deposition and Characterization of RF Magnetron Sputtered High Mobility ITiO for PV Devices
Ana Jurado Estrada, Crest - Loughborough University

P21 Optical dependency characterization of semi-transparent solar module for Agrivoltaics
Yusuf Nadabo Chanchangi, University of Exeter

P23 Enhancing Non-fullerene Organic Photovoltaics Performance via Prethermal Treatment: Interface Morphology Optimization and Trap Suppression
Enas Moustafa, Imperial College London

P25 Synthesis and characterization of Ce-doped BaSnO3 for performance enhancement of concentrated perovskite solar cells
Nouf Alkathran, University of Exeter

Thursday, April 3, 2025

Poster Session B

Chair: **Nigel Mason**, PV Consulting

P2 Mind the sub-gap: exploring the impact of sub-gap features on the thermodynamics of disordered photovoltaics.
Drew Riley, Swansea University

P4 Building Integrated Photovoltaics (BIPV): A Comprehensive Review of Architecture, Technical Advancements, Lifetime Cost and Industrial Progress
Qandeel Rehman, University of Engineering and Technology

P6 Ambient and Solution Processable Organic Photovoltaic for Indoor Application
Ram Datt, Swansea University

P8 Encapsulation of perovskite devices using UV-curable ink jetted materials
Walter Stroud, University of Surrey

P10 Proton Radiation Hardness of Solar Cells and Ion Beam Analysis Investigation by Experiments Performed using particle accelerators
Pierre Couture, Surrey Ion Beam Centre

P12 Complex formation of ferrocene derivatives with electron-transporting layers enables improved performance and photostability in organic solar cells
Zhuoran Qiao, Imperial College London

P14 Combining Machine Learning with Physics-based Models for Day-Ahead Solar Forecasting
Rong Gu, Department of Engineering Science, University of Oxford

P16 Evaluating Biochar-Based Carbon Electrodes in Printed Mesoscopic Perovskite Solar Cells
Amy Neild, Newcastle University

P18 Enhancing Energy Estimation for Floating Photovoltaic Systems Using Machine Learning Techniques
Yiliao Zhou, University of Southampton

P20 Perovskite Printing for Flexible Thin-Film Microgroove Modules
Samual Ngombe, Specific Ikc

P22 Accurate Yield Modelling of a Semi-transparent Façade Agri-PV System
Lavanya Malarkannan, National Physical Laboratory

P24 Understanding the growth kinetics of MAPbI3 thin films on metal oxide vs organic semiconductor charge extraction layers and their indoor photovoltaic properties.
Edwin Pineda De La O, University of St Andrews

P26 Advancements in Solar Spectral Irradiance Modelling for Photovoltaic Systems: A Machine Learning Approach Utilizing On-Site Data
Haoxiang Zhang, University of Southampton

Invited Presentation

Tackling the industrial leap for printed perovskite solar cells

Trystan Watson[1],

[1]Swansea University, UK

This talk will consider the challenges of scale for transferring perovskite solar cell technology from the laboratory to the factory floor. Considering two specific examples - a continuously manufactured roll to roll scenario and low capital cost sheet to sheet scenario, the methods of manufacture and their challenges will be considered. In particular the role that fundamental process engineering can play in translating typical laboratory practices (spin coating, evaporation, glove-box usage) to those more suitable for commercial production (slot-die coating, carbon layers, ambient processing). The talk will consider practical approaches for fabricating perovskite solar modules that use commonly available machinery rather than relying on novel or highly industrialized equipment. For example, the use of screen-printing or slot-die coating methods significantly reduce financial barriers, making advanced solar technology more accessible, especially in under-resourced areas. By focusing on machinery and tools that are widespread and easily obtainable globally, this approach democratizes the production of solar modules, ensuring that even communities in less affluent economies can participate in renewable energy advancements. The overall aim is to foster a more inclusive approach to renewable energy technology, making it a feasible option for a broader range of global communities.

Advances in gallium doping for high-performance silicon photovoltaic cells

John D Murphy[1], Tim Niewelt[1,2], Sophie L Pain[1], Pietro P Altermatt[3], Nicholas E Grant[1]

[1]School of Engineering, University of Warwick UK, [2]Fraunhofer Institute for Solar Energy Systems ISE, Germany, [3]Trina Solar Limited, China

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Over the past five years, the dopant of choice for silicon used for solar cells made from *p*-type substrates has changed from boron to gallium. Although previously thought to be unfeasible due to gallium's very small segregation coefficient in the melt, advances in crystal growth have enabled the routine production of mass-volume gallium doped wafers for high-efficiency passivated emitter and rear cell (PERC) structures. The motivation for switching to gallium doping was to avoid the need to apply additional stabilisation processes during cell production that were necessary to stabilise boron doped cells, which have been known for more than 50 years to degrade under illumination due to the formation of a boron-oxygen complex which acts as a recombination centre.

We will present the latest results of our work to demonstrate the advances in Ga doped silicon substrates, which we have found to be superior in terms of carrier lifetime than B doped counterparts. We demonstrate that Ga doped silicon is not always immune to performance-related degradation as was initially assumed [1, 2]. In the first generations of Ga doped PERC, illumination-induced degradation was detectable, although considerably less than in the boron case (Figure 1). Our most recent cell-level data [3] demonstrate that processes have been developed to make the degradation levels insignificant (Figure 2). The industrial adoption of tunnel oxide passivated contact (TOPCon) cells has recently necessitated another substrate dopant switch (to *n*-type phosphorus doping), although many of the crystal growth, characterisation, and testing lessons learned from the work on Ga doping are transferrable. Furthermore, Ga doped *p*-type substrates are suitable for use in silicon heterojunction cells.

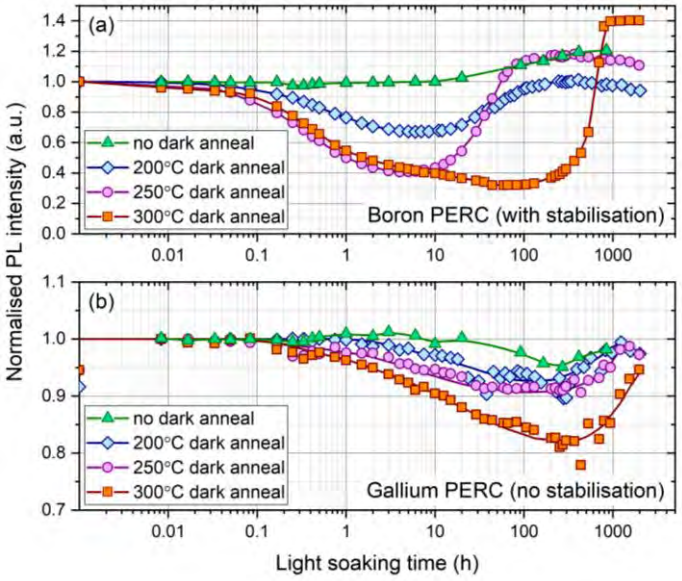

Figure 1. Results of stability testing of an early generation of PERC cells (reproduced from [1]), showing degradation with Ga to be considerably less than with B.

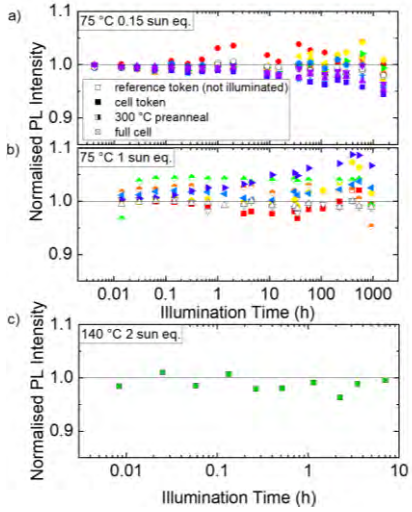

Figure 2. Data for a later generation of Ga doped PERC cells (reproduced from [3]), which show Ga PERC to be stable regardless of the resistivity (different colour data points) under a range of testing conditions.

[1] N. E. Grant, J. R. Scowcroft, A. I. Pointon, M. Al-Amin, P. P. Altermatt, J. D. Murphy, *Solar Energy Materials & Solar Cells,* **206** 110299 (2020), doi: 10.1016/j.solmat.2019.110299.
[2] N. E. Grant, P. P. Altermatt, T. Niewelt, R. Post, W. Kwapil, M. C. Schubert, J. D. Murphy, *Solar RRL,* **5** 2000754 (2021), doi: 10.1002/solr.202000754.
[3] T. Niewelt, F. Maischner, W. Kwapil, E. Khorani, S. L. Pain, Y. Jung, E. C. B. Hopkins, M. Frosch, P. P. Altermatt, H. Guo, Y. C. Wang, N. E. Grant, J. D. Murphy, *Solar Energy Materials & Solar Cells,* **266** 112645 (2024), doi: 10.1016/j.solmat.2023.112645.

Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Surface Strains Dictate Local Photoluminescence Properties in Halide Perovskites as Revealed by 3D Multimodal Imaging

Kieran W. P. Orr[1,2], Samuel D. Stranks[2]

[1]Stanford University, CA 94305, USA, [2]University of Cambridge, CB3 0HE, UK

Corresponding author: kwporr@stanford.edu

Strain is known to affect the macroscopic optoelectronic properties (*e.g.* bandgap, charge carrier dynamics *etc.*) and stability of semiconductors.[1] However, ***the precise ramifications of nanoscale strains on local optoelectronic performance is yet to be characterised and understood in detail*** despite its pertinence given the significant disorder, strain, and heterogeneity present in many state-of-the-art semiconductors including, notably, the halide perovskites. I will present our current unpublished work correlating local tensile/compressive strain with photoluminescence (PL) properties in a single crystal of the canonical $CsPbBr_3$ halide perovskite using advanced synchrotron-based Bragg ptychography 3D strain mapping[2] in combination with temporally and spectrally resolved PL microscopy (schematic in Fig. 1a).

Even though single crystals are free from the grain boundaries, high defect densities, and orientational disorder characteristic of classical spin-coated perovskite thin films, we find the PL properties of large (10s of μm laterally) single crystals (Fig. 1b) to be strikingly heterogeneous (*e.g.* the nanoscale changes in PL lifetime in Fig. 1c). By performing Bragg ptychography strain mapping measurements on the same regions characterised with PL microscopy (Fig. 1c & d), ***we find that regions of higher tensile strain show shorter PL lifetimes (Fig. 1e) as well as weaker and red-shifted PL emission.*** Crucially, and in contrast to traditional scanning probe X-ray diffraction techniques, Bragg ptychography can resolve strain fields in 3D with resolution across the sample thickness, enabling us to discover that ***it is only the surface strains which dictate the nanoscale distribution of PL properties in halide perovskites***. Consequentially, we demonstrate that thickness-averaged strains cannot be used to infer local PL properties and *vice versa*, an important realization as it limits the predictive power of each technique on its own.

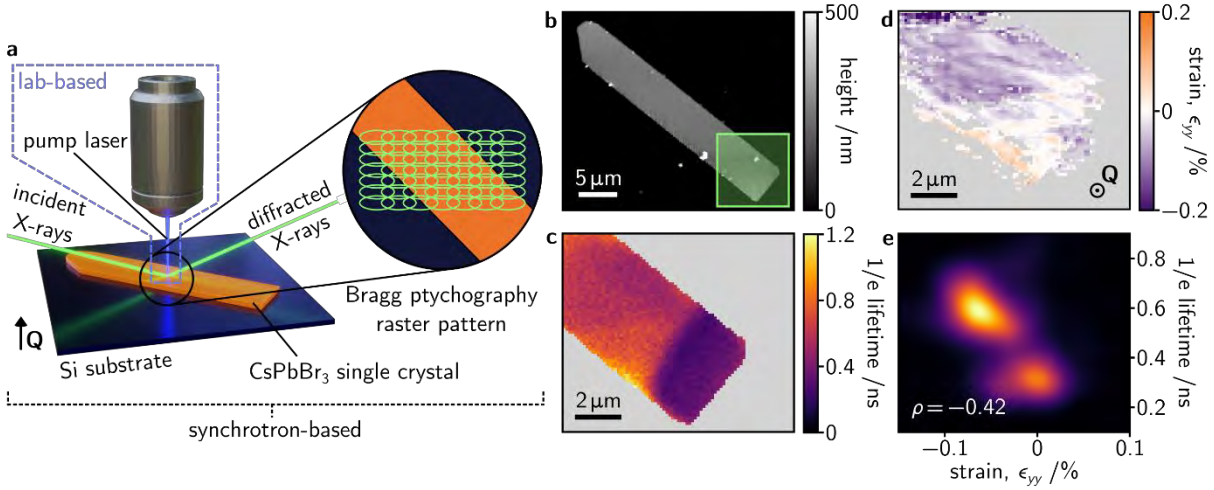

Figure 1: a Schematic of multimodal imaging measurements. **b** Atomic force microscopy image of sample $CsPbBr_3$ crystal. The region highlighted in green is depicted in panel **c** as a photoluminescence lifetime map and in panel **d** as a tensile/compressive (orange/purple) strain map. **e** Kernal density plot showing the negative correlation of strain with photoluminescence lifetime for the same region as shown in panels **c** and **d**. The statistically significant Spearman's rank correlation coefficient, ρ, is given.

References

[1] D. Liu, D. Luo, A. N. Iqbal, K. W. P. Orr *et al.*, *Nat. Mater.* **20**, 1337–1346 (2021).

[2] P. Godard *et al.*, *Nat. Commun.* **2**, 568 (2011).

PV applications

The effects of the dilute-donor strategy on microstructure, recombination mechanisms, and device performance of scalable OPVs for semi-transparent applications

Eva Mazzolini[1], Richard A. Pacalaj[2], Francesco Furlan[2], Stanley A. Cazaly[3], Pascal Kaienburg[4], Rachel Kilbride[5], Flurin Eisner[3], James R. Durrant[2] and Nicola Gasparini[2]

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[2] Imperial College London, Department of Chemistry and Centre for Processable Electronics, London W12 0BZ

[3] Queen Mary, University of London, School of Engineering and Materials Science, London E1 4NS

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Semitransparent organic photovoltaics (ST-OPVs) have gained significant attention over the past decade due to their promising applications in building-integrated photovoltaics (BIPV) and agrivoltaics (agriPV) [1]. One key strategy for enhancing transparency while maintaining high power conversion efficiency (PCE) involves using near-infrared (NIR)-absorbing materials, prompting the development of novel donor polymers and non-fullerene acceptors (NFAs)[2]. Another straightforward approach to increasing average visible transmittance (AVT) is reducing the active layer thickness, which inevitably results in current losses. To avoid this drawback, ST-OPVs can be optimized by employing a dilute-donor strategy. This approach adjusts the donor-to-acceptor ratio to enhance NFA absorption while reducing that of the donor, resulting in higher AVT [3]. This strategy allows high-efficiency, opaque OPV blends to achieve greater transparency without compromising performance, as demonstrated in several recent studies [4]. In this work, we investigate this approach on three known OPV blends, using donor polymers PM6, PTQ10, and FO6-T with the NFA Y12. We demonstrate highly efficient, blade coated devices with reduced donor content in all three blends, with active layer AVTs up to 62% and PCEs above 12%. We then investigate the generation and recombination mechanisms in the blends via bias-dependent photoluminescence, transient photovoltage, and space-charge limited current measurements. Our findings show that charge generation is the main loss pathway for PTQ10:Y12, indicated by a strong field-dependence. Furthermore, we find that PM6:Y12 is mostly governed by bimolecular recombination, while FO6-T:Y12 suffers from both mechanisms.

[1] K. Forberich, *et al*., Energy Technology **10**, 1051-1058 (2015).

[2] F. Liu, *et al.*, Adv. Materials. **29**, 1606574 (2017).

[3] A. Sharma *et al.,* Adv. Materials. **36**, 2305367 (2024)

[4] S. McAnally *et al.,* ACS Appl. Mat. & Int. **16**, 28958-28968 (2024)

Invited Presentation

Beyond Efficiency – Scientific and Engineering Requirements to Introduce a New Cell Technology to the Market

Ralph Gottschalg[1],

[1]Fraunhofer Centre for Silicon Photovoltaics, Germany

Key performance indicators (KPIs) evolve significantly from laboratory development to energy production. The ultimate goal of any photovoltaic (PV) technology is to generate low-cost energy, measured in €/kWh. However, in the laboratory, the primary KPI for cell development is efficiency, expressed as kW/m². For a new cell technology to succeed in the market, it must be competitive with existing technologies. This paper will demonstrate that the common belief that high efficiency leads to low cost is only partially accurate. It will highlight the gaps between these KPIs and explore relevant research questions.

The cost of energy is calculated as the sum of all expenses over the lifetime divided by the lifetime energy yield. To be competitive, an innovative technology must outperform the current standard. What is necessary to achieve this?

The costs of a PV module are determined by its rating (kWp/module), which is assessed at the end of the production line. Producers must minimize claims, ensuring modules meet contractual minimum standards, typically exceeding a specified value (underrating is generally excluded). To ensure accuracy, measurement uncertainties must be subtracted from the rating. The factory rating of a meta-stable tandem device with unknown production variations in less than 15 seconds introduces significant uncertainties (>10%). In contrast, calibration laboratory measurements are conducted over 30+ minutes, with prior characterization of the mismatch factor to achieve 3% uncertainty. Consequently, the sales rating must be 10% lower than the measurement, making the new technology less competitive. This paper will identify the main sources of uncertainty and propose management strategies.

A high-efficiency solar cell does not necessarily produce more energy than a lower-efficiency one. The transfer function here is kWh/kWp over the lifetime, i.e., the lifetime energy yield over the sales rating. Critical issues include energy rating, lifetime, durability, and electrical stability. Energy rating is less favorable for tandem technology compared to bifacial technology.

The current lifetime is significantly shorter, impacting energy costs, and there is a technological risk of unforeseen failures. Silicon technology degradation rates are currently below 0.5% per year, which is extremely challenging to improve. Stability of electrical parameters is often overlooked, but changes in these parameters can lead to significant bill of materials (BOM) related losses. This paper will discuss the impact on costs and required mitigation strategies.

Characterization, testing and performance measurements for photovoltaic materials, devices, and modules

Digital light processing applications for advanced characterization of photovoltaic devices

Daniel E Parsons[1], James C Blakesley[1], and George Koutsourakis[1]

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Abstract

There is always a need to continuously develop and improve metrology techniques for accurate characterisation of photovoltaic (PV) devices. This need is relevant for established PV technologies, emerging technologies such as perovskite and organic PV, as well as for PV reference cells and outdoor PV sensors. Accurate characterisation offers insights about degradation profiles of PV systems, upscaling challenges of emerging PV technologies, traceability in measurements, as well as accurate environmental monitoring and modelling.

In this work, we are presenting the new capabilities of NPL's Digital Light Processing system for advanced characterisation of photovoltaic devices [1][2]. This consists of a high-power Xenon light source coupled with a digital micromirror device (DMD), a series of bandpass filters and a projection module. The system enables spatial control of broadband or monochromatic light from the UV to the NIR wavelengths (390 nm to 1064 nm). A new high resolution angular response capability has been developed, validated with comparison activities with Physikalisch-Technische Bundesanstalt (PTB, Germany). With the angular response capability, spectral angular response measurements can be delivered, which can help identify spectral-dependent optical losses and performance differences under direct and diffuse solar spectral irradiance [3]. The system can additionally achieve spatially resolved absolute spectral response measurements. Monochromatic light is modulated at a user-controlled frequency using the DMD, a differential method is then used to extract the photocurrent from the monochromatic source. Combining absolute spectral response for the full device with spectral current mapping enables the construction of a spatially resolved absolute differential spectral response data cube at 11 distinct wavelengths. Comparison results of the DMD system with NPL's conventional differential spectral response system has validated the accuracy of the new method, which allows spectral response mapping of PV devices.

These new methods will offer higher accuracy in the measurements of the performance parameters of established and emerging PV devices, sensors and reference cells, which is significant for accurate modelling, power rating and evaluation of real performance and degradation profiles of PV technologies in the field.

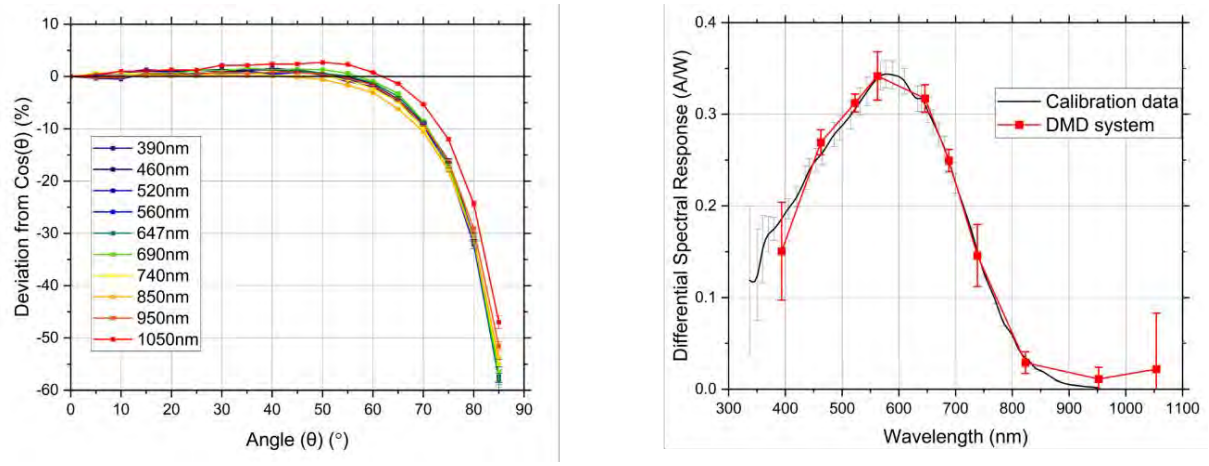

Figure 1. Typical capabilities of the new DMD characterisation system at NPL. On the left, Spectral Angular Response of a mono-crystalline Si reference cell. On the right, comparison between the calibrated and measured differential spectral response of a KG5 reference cell. Current maps at these wavelengths can be acquired with the system, delinering spectral response maps for PV devices.

References

1. G. Koutsourakis, A. Thompson, and J. C. Blakesley, Sol. RRL **6**, 2100467 (2022).
2. G. Koutsourakis, T. Eales, I. Kroeger, and J. C. Blakesley, Meas. Sci. Technol. **32**, 055901 (2021).
3. F. Plag, I. Kröger, T. Fey, F. Witt, and S. Winter, Prog. Photovoltaics Res. Appl. **26**, 565 (2018).

Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Design and Development of a New Smart Portable I-V Tracer

Navid Tavakoli[1], Pascal Koelblin[1], Michael Saliba[1,2*]

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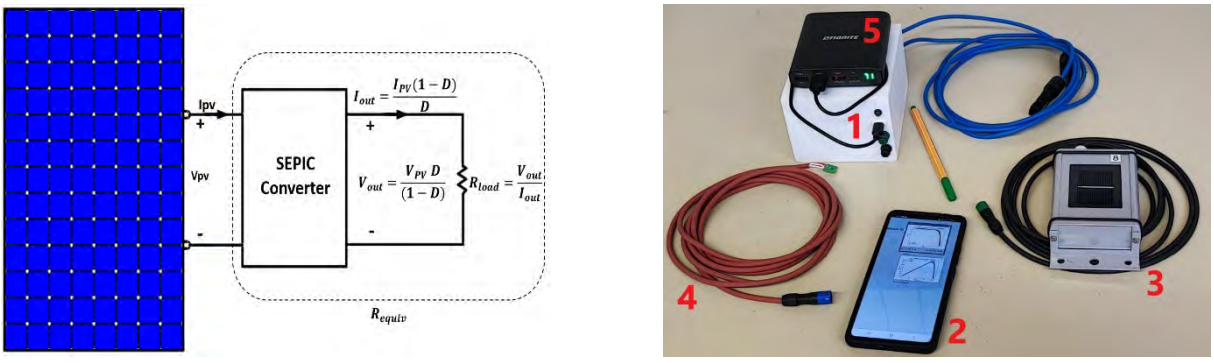
Accurately characterizing photovoltaic (PV) modules is essential for ensuring their efficiency and reliability, especially in the face of growing global solar power installations. Existing I-V tracers face challenges such as dependency on high irradiance, noise interference, and cost-prohibitive designs. This study introduces SEPIV, a novel I-V tracer based on an optimized single-ended primary inductance converter (SEPIC). The acronym "SEPIV" is the modified version of “SEPIC”. In devising the name 'SEPIV,' the 'SEP' from 'SEPIC' was retained, and the 'IV' was appended to denote its function in measuring I-V characteristics. SEPIV demonstrates a high degree of accuracy comparable to advanced laboratory units while surpassing conventional commercial solutions. Figure 1 (a) illustrates the connection between the SEPIC converter and the PV module. The generated power from the PV module is equal to the power consumed by the equivalent resistance R_{equiv}. In this setup, V_{PV} represents the PV module's output voltage, and I_{PV} is its output current. The SEPIC converter drives a load resistance R_{load}, with its outputs being I_{out} and V_{out}. From the PV module's perspective, R_{equiv} effectively characterizes the load conditions presented by the SEPIC converter. Key highlights of SEPIV include the ability to capture I-V curves for PV modules up to 650 W, a maximum V_{OC} of 60 V, and I_{SC} of 20 A, independent of irradiation levels as low as 200 W/m². SEPIV integrates Internet of Things (IoT) connectivity for remote measurement and long-term monitoring, offering unparalleled portability and affordability. Figure 1(b) depicts the entire SEPIV setup. The SEPIV system was experimentally validated using two distinct I-V tracing methods: the PVPM 1000 C 40, a commercial I-V tracer that employs the capacitive load technique, and the WAVELABS SINUS-3000 PRO, a four-quadrant power supply tracer. The accuracy of the capacitive load method is influenced by the charging response and the equivalent series resistance (ESR) of its capacitor. While the WAVELABS SINUS-3000 PRO delivers high precision, its large size restricts portability, rendering it unsuitable for field applications. By effectively addressing these limitations, the SEPIV system demonstrates exceptional precision, faster response times, and enhanced measurement reliability, establishing itself as a robust and versatile tool for photovoltaic (PV) characterization in both laboratory and field settings.



(a) (b)

Figure 1 a) The SEPIC converter is connected to a PV module as equivalent resistance R_{equiv}, seen by the PV generator. Figure 1 b)The SEPIV unit (1), smartphone (2), irradiation sensor (3), temperature sensor (4), and power bank (5) is used to supply the entire setup.

Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Photoexcited muon spin spectroscopy for studying carrier lifetime in silicon for photovoltaics

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Understanding charge carrier recombination kinetics is critical in optimizing photovoltaic materials and devices. Photoexcited muon spin spectroscopy (photo-μSR) is a novel method for probing carrier dynamics in semiconductors [1]. This pump-probe technique – available at the UK's ISIS Neutron and Muon Source – involves generation of excess charge carriers by laser excitation followed by implantation of positive muons into a sample. Muon spin relaxation, induced by the interaction between muons and excess carriers, is directly related to the excess carrier density, enabling depth-resolved lifetime measurements of silicon wafers and partially processed or even finished solar cells and other devices [1-3].

Our presentation will first provide an overview of photo-μSR and highlight its potential for characterising semiconductor materials and PV devices. We then show how photo-μSR is applied to aluminium oxide (Al_2O_3) passivated silicon wafers (surface recombination velocity <1 cm/s), as shown in Figure 1. By implanting muons at three distinct depths (Figure 1(b)), we map the depth-resolved effective lifetime profile of silicon wafers passivated with Al_2O_3 on both surfaces. Our results show how the photo-μSR method can be used to decouple surface and bulk effects in well-passivated wafers, an essential measurement for fabricating high efficiency solar cells. At the cell level, we apply the technique to passivated emitter and rear cell (PERC) devices, where traditional methods like photoconductance decay (PCD) and photoluminescence (PL) are often limited by the presence of metallization and diffused layers. Our results show an increase in effective carrier lifetime with substrate resistivity. These findings underscore the versatility of photo-μSR for advanced PV materials and device architectures, where conventional methods may be impractical.

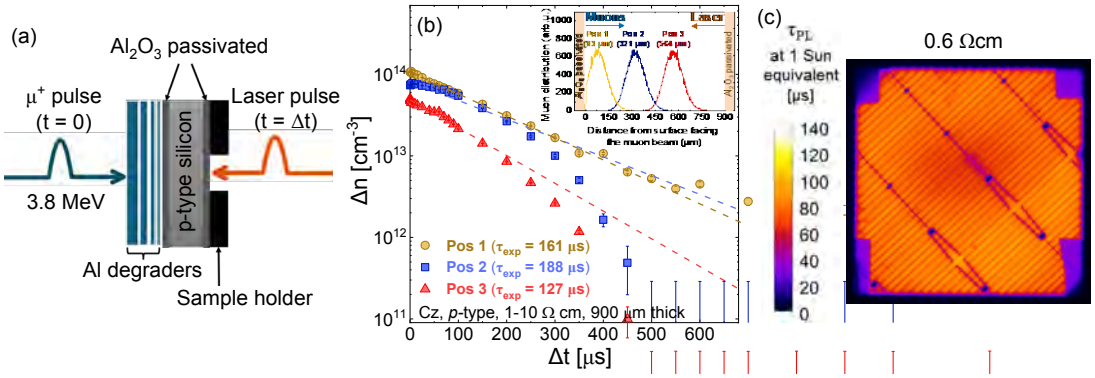

Figure 1. (a) Schematic of muon implantation and laser excitation. (b) Depth-resolved carrier lifetime spectra for the silicon wafer. (c) Calibrated PL lifetime image of a Ga-doped PERC solar cell (150 μm, 0.6 Ω cm) under 1 Sun illumination following photo-μSR [3].

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Identifying Optimal Materials and Architectures for Semi-Transparent Agrivoltaics

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Contributing up to 22% of global greenhouse gas emissions,[1] the agricultural sector is an important focal point in the pursuit of a net-zero society. Several innovative approaches are being actively explored to reduce these emissions, including agrivoltaics – which provide locally-generated, clean energy via the integration of (semi-transparent) photovoltaics with greenhouses, polytunnels, and fields of crops/livestock, as illustrated in **Figure 1**.[2]

Designing efficient agrivoltaic systems can be a complex process, however, as the Sun's light must be shared between the photovoltaics and any crops below. Herein, optical and geometric considerations are described for optimising the light-utilisation efficiency (LUE) of agrivoltaic systems – an important measure that quantifies how much light is either converted to electrical power or made available to the crops.[3]

By applying a custom-made computational tool, which is freely available online [4] and utilises location-dependent geo-meteorological data from the National Solar Radiation Database [5], the LUEs of a variety of inorganic, organic, and perovskite-based photovoltaics are compared throughout a typical year; thus informing material and architectural design choices.

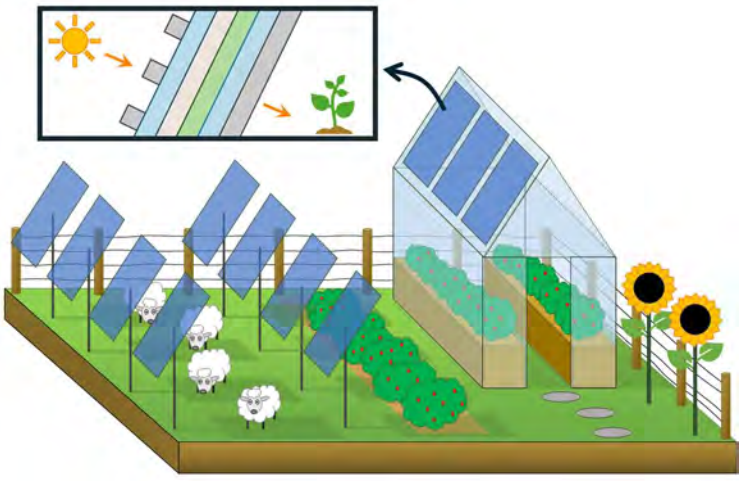

Figure 1: Illustration of agrivoltaics, where semi-transparent photovoltaics are combined with fields of livestock, fields of crops, and greenhouses.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

The Influence of Energetics and Morphology on Charge Transfer in Organic Photovoltaics

Jolanda S Muller[1], Jun Yan [2], Xinrong Yang[3], Marc Comi[4], Flurin Eisner[5], Mohammed Azzouzi[6], Jack Coker[1], Arianna Quesada Ramirez[7], Diego Herrera Ruiz[1], Salahuddin Sayedshabbir Attar[4]; Mariano Campoy Quiles[7], Mohammed Al-Hashimi[4], Jie Min[3], and Jenny Nelson[1]

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There has been a sharp increase in efficiencies in organic photovoltaics (OPVs) in recent years; however, best performing bulk heterojunction (BHJ) devices suffer from poor long-term performance stability, due to de-mixing of the different materials in the blend when the device is exposed to light and heat. A promising approach to tackle the stability issue is the use of single-component macromolecular semiconductors [1], which have shown significant improvements in conversion efficiency reaching >13% in a block co-polymer system while maintaining good performance stability [2]. We investigated material systems that combine the state-of-the art polymer donors and non-fullerene acceptors (PBDB-T and PYT material groups) into different morphologies including block co-polymers and bulk heterojunctions. We used chemical modifications to the building blocks to tune the energetics in the system in order to understand the impacts of energetic offsets and the interplay between through-space and through-bond charge transfer. The material systems were analysed using optoelectronic measurements, quantum chemical and device-level modelling. We uncovered factors that are limiting charge-generation in systems with low energetic offset [3]. We further found low non-radiative voltage losses and bright inter-molecular charge transfer states in the block co-polymer systems. Combining the advances in efficiency thanks to novel chemical design of donors and acceptors with the long-term stability of the block co-polymer structure may enable more industrially viable alternatives to the popular bulk heterojunction devices [4].

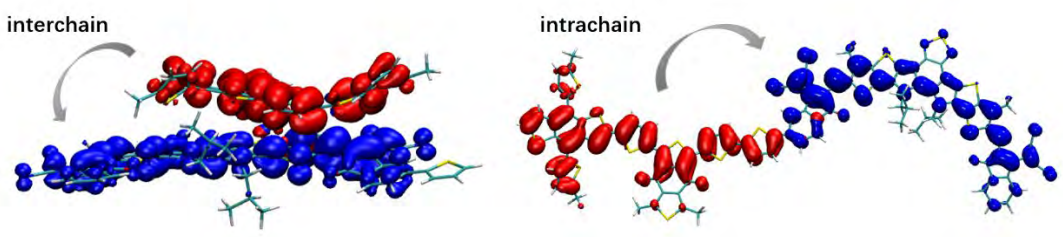

Figure 1 Change in hole and electron density distribution for the CT excitation of a donor and acceptor segment that neighbouring through-space (interchain) and bonded (intrachain).

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Perovskite, organic, tandems and DSSC photovoltaics

Insights into Degradation Pathways of Triple-Cation Perovskite Thin Films under Outdoor and Indoor Conditions: A Comparative Analysis

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The remarkable tunability of perovskite materials perfectly aligns with the requirements of indoor photovoltaic applications, presenting a promising alternative to conventional batteries for powering the Internet of Things (IoT) [1]. The power conversion efficiency (PCE) of mixed perovskite solar cells under indoor conditions has exceeded 40%, but there is a lack of rational data on the stability and degradation pathways of perovskites under indoor low-light conditions [2].To address this challenge we investigates the degradation pathways of triple-cation perovskite $Cs_{0.05}(FA_{0.77}MA_{0.23})_{0.95}(I_{0.77}Br_{0.23})_3$ thin films, under controlled outdoor and indoor environments. Using a combination of XRD, SEM, UV-Vis, and XPS and PL analyses, we explored how high and low light intensities under inert, pure oxygen, and humidity conditions influence structural, morphological, and chemical stability. Results indicate distinct degradation pathways in outdoor and indoor conditions. Outdoor light exposure accelerates degradation via lead iodide formation and phase transitions to orthorhombic structures, while indoor lighting preserves the tetragonal phase with minimal degradation. Humidity was identified as a critical factor, causing severe structural breakdown and the formation of lead-based oxide and carbonate complexes. These findings underscore the promising potential for perovskite-based devices to achieve enhanced long-term stability under controlled, low-light environments, where degradation is significantly minimized compared to high-intensity or outdoor light exposure.

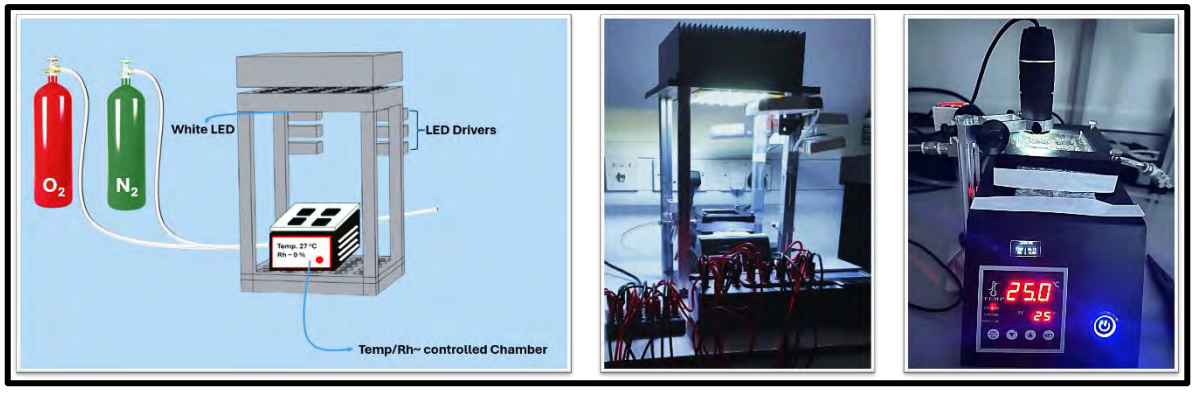

Figure 1 Experimental framework for investigating stability in perovskite thin film

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Printed Nanoparticle Interlayers Enable High-Quality Organic Electron Transport Layers in Scalable Perovskite Solar Cells

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As lead halide perovskite solar cells (PSCs) mature as a technology, increasing interest from industry is being observed, with numerous businesses currently working on commercialising the material. Scalable methods such as blade and slot die coating are therefore of great industrial relevance. However, fabrication methods and solution formulations which work well for small, spin coated films often do not translate well to large area printing.[1]

In this work we investigate the deposition of electron transport layers (ETLs) on roll-to-roll (R2R), slot-die printed perovskite films. Devices fabricated using evaporated C_{60} ETL films exhibit high, reproducible performance (power conversion efficiency (PCE):~11(±1.2)%, device size 25 cm^2, active area 8x0.55 cm^2). However, the devices perform poorly with low reproducibility when C_{60} is replaced with blade coated, slot-die R2R compatible PCBM (PCE:~2(±2)%). This is despite PCBM being a widely used ETL material, compatible with spin coating onto perovskites. By depositing a non-continuous layer of metal-oxide nanoparticles prior to PCBM deposition a significant increase in PCBM film quality is observed. This enables the fabrication of high performing, fully solution processed, scalable p-i-n PSCs (PCE:~9.5(±0.8)%). Using a combination of energetic and spectroscopic probes and scanning microscopy we have further developed a systematic understanding of the significant impact of these interlayers on device performance.

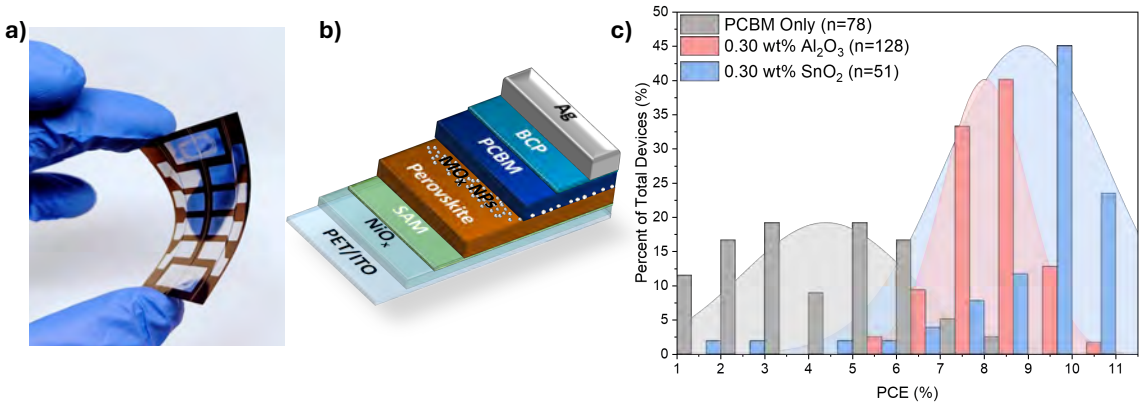

Figure 1 a) Photograph showing a typical finalised flexible device, b) diagram illustrating the device structure used in this work, c) statistical PCE distributions of three optimised device types.

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Invited Presentation

Sustainable development of deployable perovskite solar cells

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Halide perovskite photovoltaics (PV) offer tremendous potential as a cost-effective and high-efficiency solution for renewable energy conversion. Transitioning from lab-scale prototypes to commercially viable, large-scale solar modules present significant challenges. This talk focuses on the critical issues surrounding the technological upscaling of perovskite PVs, with a particular emphasis on the solution-processable slot-die coating technique. Slot-die coating is promising for its compatibility with roll-to-roll manufacturing and potential for high-throughput production, but achieving uniform, defect-free films across large areas remains a challenge. Key factors influencing film quality, such as ink formulation and the importance of carefully monitoring and controlling crystallization dynamics, will be discussed. Furthermore, the talk will highlight the tremendous importance and potential with the establishment of systematic data dissemination and sharing platforms, such as the Perovskite Database (www.perovskitedatabase.com) and research data management based on FAIR data principles. Open Data sharing platforms could enable the research community to make more efficient use of published data, promoting transparency, reproducibility, and innovation. However, such platforms need a much more focused and dedicated effort by the entire research community to enable emerging technologies such as halide perovskites to more quickly and sustainably enable the development of sustainable and mass-deployable energy conversion technology.

Back-contact Perovskite Solar Cell Modules Fabricated via Roll-to-Roll Slot-die Coating: Scale-up Towards Manufacture

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We fabricate using a fully Roll-to-Roll (R2R) process, a type of back-contact perovskite solar cell based on 1.5 µm width grooves, that are embossed into a plastic film whose opposing 'walls' are selectively coated with either n- or p-type contacts. [1] A perovskite precursor solution is then deposited into the grooves, creating individual photovoltaic devices. Each groove device is series connected to its neighbours, creating mini modules consisting of hundreds of connected grooves. Here, we report on the fabrication of groove-based devices using slot-die coating to deposit the perovskite precursor and explore the structure of the perovskite in the grooves using a range of microscopy and spectroscopy techniques. Significantly, our devices do not contain any expensive or scarce elements such as indium, indicating this technology is both sustainable and low-cost. Furthermore, all coating processes explored here were performed using roll-to-roll processing techniques. Our technology is therefore completely scalable and is consistent with high-throughput, low-cost manufacture.[1]

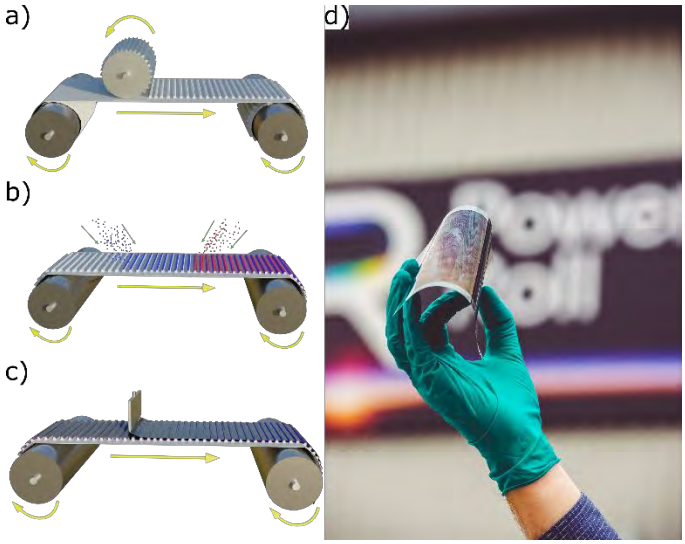

Figure 1 Schematics of R2R process: a) Embossing process, b) Directional vacuum coating process, c) Slot-die perovskite coating process. d) Imaging showing a 10cm x 10cm module with more than 56,000 grooves.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

From small to large-area PV devices – addressing the scalability challenge associated with organic or perovskite-based solar modules

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Among most emerging thin film photovoltaic (PV) technologies, organic and perovskite-based solar cells (OSC and PSC, respectively) have attracted unprecedented attention in academia and industry in recent decades. Starting with power conversion efficiencies (PCE) as little as few percent, the efficiency of OSCs has almost reached 20% already.[1] In comparison, the PCE of PSCs has exceeded 26%.[2] Similar trends can be seen for the operational stability of both PV technologies. However, most of the reported high-efficiency and stable devices are not only small (rarely exceeding a photoactive area of 1 cm^2) but also fabricated by means of using industry irrelevant non-scalable fabrication methods. Furthermore, the increase in photoactive area needed for the generation of variable power in real world applications inevitably means that single devices cannot be used. This is mainly due to resistive losses caused by the physical properties of commonly used window electrode materials such as indium tin oxide (ITO). Therefore, modular connection of single PV cells is needed to overcome this challenge. Furthermore, the fabrication of functional materials over larger areas requires a highly reproducible and scalable deposition method. Precise process control is additionally necessary for reducing and ideally eliminating any coating defects that can occur during the deposition process and lead to reduced device PCE and stability. To address these challenges, we show the development of an industrially applicable process for the fabrication of large area OSC or PSC modules, which is based on a laser assisted scribing for modular designs. Furthermore, the scale-up process from single small-area cells to small and medium sized mini modules will be shown by giving examples of the successful transfer of small-area device fabrication methods to large-area deposition techniques compatible with industry standards. This is achieved by the careful optimization of the coating quality, which was studied by large-area opto-electrical characterisation methods such as photoluminescence and electroluminescence measurements. Finally, mini modules with different laser designs and photoactive areas ranging from 3.8 cm^2 to 11 cm^2 modelled by theoretical studies and corresponding experimental results will be shown. Ultimately, PCEs above 12% for OPV and 15% for PSC mini modules will be demonstrated.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Charge Generation in Non-Fullerene Acceptors

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Organic solar cells rely on the intimate mixing between two materials of different energetics, one acceptor and one donor material. Excitons formed upon irradiation of the cell are split into free charges at the interface between the two materials, since the energetic offset helps overcome the exciton binding energy.[1] State-of-the-art organic solar cells feature a polymeric donor and a small molecular acceptor, often referred to as non-fullerene-acceptor to distinguish from the previous use of fullerenes. The non-fullerene-acceptors can easily be varied in chemical structure, which has led to a tremendous improvement in power-conversion efficiency of organic photovoltaics now reaching 20%.[2]

Interestingly, recent studies have shown that some of the most efficient non-fullerene acceptors (e.g. Y6) can achieve relatively high charge-generation efficiency in the absence of a donor-acceptor interface.[3] This challenges the current understanding of how photogenerated excitons dissociate into free charges in organic semiconductors.[1,4] It further raises questions on whether a donor-acceptor interface is necessary for achieving high-efficiency solar cells, or whether a simpler geometry such as a bilayer could work as well. Uncovering these questions could have significant implications for the cost and stability of organic photovoltaics, as well as photodetectors, solar fuel cells, and light-emitting diodes. Our study probes charge generation in solar cell devices featuring only a non-fullerene acceptor material as the active layer. In this way we can learn about the fundamental properties controlling charge generation, and compare why some molecular structures perform better than others.

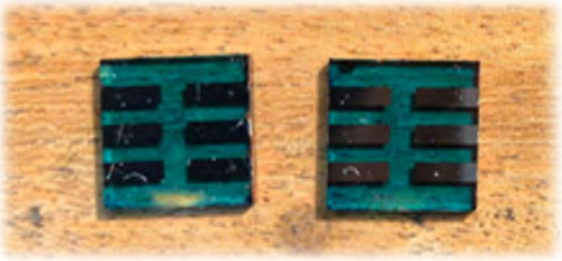

Figure 1. Single component solar cell devices used in the study.

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3D Printing: Dies for Perovskite, Devices, and De-escalation of Scale Up Costs

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The importance of being able to scale up towards commercial-scale perovskite solar cell production has recently highlighted the critical need for continuous deposition techniques. While spin coating and evaporation techniques remain the dominant methods for high-efficiency devices at laboratory scale, industrial viability demands alternative approaches. Slot-Die coating has emerged as a promising technique due to its adaptability. However the costs involved with scale up suitable set ups can be prohibitive to groups looking for proof of concept. Additionally the cost of slot die heads themselves and fears of contamination through using multiple materials in the same head can be a limitation to adoption.

3D printing has allowed for laboratories to prototype and even manufacture components and tools, this is used to create cheap and lightweight slot die heads heads. This work presents a comparative study of deposition techniques, examining spin coating, commercial steel slot die coating heads, and 3D printed slot die coating, with particular focus on film uniformity and edge definition. The study investigates the potential of open-source 3D printed slot die heads, which offer several distinct advantages: dramatic cost reduction compared to commercial heads (>90% cost saving), significantly reduced weight for easier integration, rapid prototyping capability for internal geometry optimization, and the ability to tailor head designs to specific material viscosities. Layer thickness control and deposition uniformity are examined.

This work contributes to the broader discussion of scalable fabrication methods by providing insights into the relative merits of these deposition approaches for perovskite layer formation, particularly focusing on how adaptable, lightweight 3D printed slot die heads could accelerate, and universalize process optimization and scale-up efforts.

Figure 1. Comparative films printed with commercially available slot die head (left) and 3D printed PLA slot die head (right).

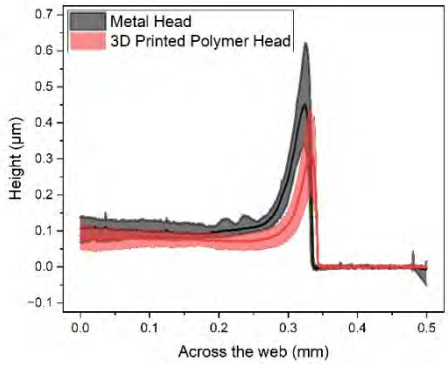

Figure 2. Comparative film thickness for films printed with commercially available slot die head (black) and 3D printed PLA slot die head (red).

Invited Presentation

Sustainability considerations for manufacturing and deployment of multi-terawatt silicon photovoltaics

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Silicon photovoltaics has enjoyed enormous success over the past 15 years with approximately 2 TW cumulative installed globally [1], and nearly 18 GW in the United Kingdom at the end of 2024 [2]. Moreover, as our demand for electricity increases to support a world population of 10 billion people by 2050, photovoltaics is forecast to grow significantly more to around 75 TW [3]. Given this projected growth, it is essential to understand the environmental impact of photovoltaics and identify opportunities to minimise this through research and development (R&D).

In this work, we use life-cycle assessment (LCA) to quantify the environmental impact of industrial scale silicon photovoltaics. In particular, we compare the sustainability of passivated emitter rear cell (PERC) to tunnel oxide passivated contact (TOPCon) architectures. This is timely because the global silicon photovoltaics manufacturing industry is currently transitioning from PERC to TOPCon in the pursuit of even higher efficiency. Our LCA results demonstrate that TOPCon is superior to PERC in 15 out of 16 environmental impact categories (including *climate change*) and therefore offers sustainability advantages. The only environmental impact category in which TOPCon is inferior to PERC (by 15.2%), is *material resource demand* as a consequence of increased silver use at the bottom electrical contact. This motivates R&D to reduce or replace silver in photovoltaics manufacturing.

Over the next 10 years, photovoltaic module production will include contributions from both PERC and TOPCon architectures. We incorporate projections for these contributions and expected performance improvements from the International Technology Roadmap for Photovoltaics [4], with our LCA modelling to forecast the environmental impact of global PV manufacturing to 2035. In addition, we also account for decarbonisation of electricity supply in the region where the photovoltaic modules are manufactured, by including scenarios from the Energy Information Administration [5] in our LCA modelling. The results indicate a potential reduction in global warming of 8.2 Gt CO_2 eq. by 2035 for manufacturing in Europe compared with China. We emphasise that these results are sensitive to the electricity mix used in the scenario and demonstrate the opportunity to achieve significant environmental savings through future photovoltaics manufacturing.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Characterisation of PV Waste: An assessment of the toxicity of antimony embedded in PV glass

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The UK has witnessed a significant increase in solar deployment since 2010, with a cumulative capacity of over 15 Gigawatts (GW) installed by 2024. This equates to over 60 million solar panels now in operation in the UK, or 120,000 tonnes of waste.

In 2023, the UK government announced ambitions to increase solar deployment fivefold by 2035. This strategy includes revamping and repowering degraded utility-scale solar assets, adding to the exponential growth of PV waste significantly earlier than expected. Therefore, there is an urgent need for the UK to develop the necessary infrastructure and processes to handle large quantities of PV waste and a coherent policy framework to match.

The exact quantities and chemical composition details of various PV waste materials currently remain proprietary information for solar manufacturers, which presents a challenge when considering appropriate methods of PV recycling and extracting value from recycled materials. Subsequently, PV waste, including glass, is incorrectly identified as a homogenous entity and a universal waste stream.

This study challenges this notion, using XRF-WD testing from 5 different glass samples of PV modules retrieved from the waste stream manufactured between 2002 and 2022, comparing varying characteristics, including *manufacturer, year of manufacture, bifacial glass-glass, etc.*

Key findings of this study show that, of the PV glass (which remains approximately 70% wt of the module) *antimony* (Sb) is embedded in PV glass at up to 0.22%; and *magnesium* (Mg) at 1-2%, both of which are listed as “high criticality” by the European Commission and potentially hazardous materials. *Arsenic (As), cobalt* (Co)*, iron* (Fe)*, potassium* (K), *sodium (Na), nickel* (Ni)*, phosphorous* (P)*, lead* (Pb), *sulphur* (S)*, titanium* (Ti)*, silicon (Si), tin* (Sn), *strontium* (Sr)*,* & *zirconium* (Zr) are also detected in various quantities across the samples.

Sb, the initial focus of this discussion, is a highly toxic compound linked to a plethora of human health risks[i]. Sb also poses a risk to the environment and can enter the food chain via water[ii] (regulated at 5.0 µgSb/1 in the UK), soil[iii] or air particles as dust[iv]. However, findings of this study suggest that Mg is a far greater risk than Sb when considering ‘worst case’ hazardousness and CRM factor.

Coinciding with discussions around Digital Product Passports (DPP) and the European CRM Act, the output of this study proposes a framework by which a global ‘recyclability index’ for PV panels is mandated on PV product datasheets. Suggestions for inputs are based on the variations in chemical composition of materials found in PV waste and availability in relation to CRM assessments and embodied carbon of mining virgin material.

It is proposed such an approach will facilitate transparency for PV buyers with a renewed focus on ESG requirements. In turn, it is expected that this approach will encourage PV manufacturers to divest from using depleting, toxic, resources and better design PV modules with end-of-life and sustainability in mind from the outset.

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Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Forecasting UK solar module waste in the United Kingdom

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Photovoltaics (PV) play a key role in the United Kingdom (UK) meeting its net-zero goals. In recent years, various targets have been set to increase UK PV generation: including reaching 10 GW_{peak} by 2020 [1] and 100 GW_{peak} by 2050 [2], and a recent intermediary target of 70 GW_{peak} by 2035 [3]. To meet these targets, UK PV panel installations are growing year-on-year. As of November 2024, UK capacity stands at ~16 GW_{peak} [4]. Although PV modules play a vital role in UK renewable energy generation, modules have a finite lifespan and will eventually come offline. In this analysis, we draw on governmental datasets and projections, technical data from across the photovoltaic manufacturing industry and technoeconomic research to determine the UK's path to meeting its renewable deployment targets, and consequential waste processing needs. We focus on forecasting module quantities, not just capacity, as it provides more useful metrics in terms of recycling workflows. We consider various causes for modules coming offline, including warranty expiry, within-warranty failures and module replacements/upgrades – with the cumulative number of modules determined to come offline in each case, in addition to a combination thereof, shown in Figure 1.

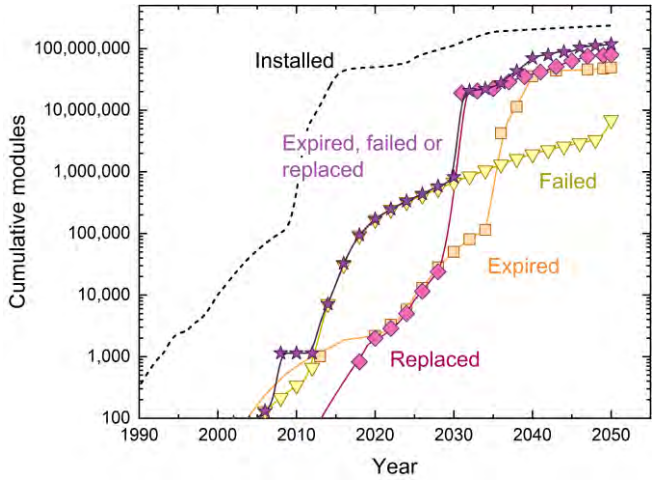

Figure 1. Calculated cumulative UK PV modules coming offline due to warranty expiry (orange squares), failures within warranty (yellow triangles), replacement/upgrades (pink diamonds) and a combined projection (purple stars), *vs* installations (dashed line, adapted from [4]). Module 'expiry', failure rates and module replacements/upgrades determined based on [5, 6], [7] and [8, 9], respectively.

In our analysis, we demonstrate the need for sustained annual installation of ~10m individual PV modules over the coming decades to meet UK targets. We model various scenarios for solar modules coming offline, determining that end-of-life UK PV modules will exceed 100m by 2050, though the volume of UK solar waste is expected to exceed the current pan-European solar waste recycling capacity by 2035 [10]. We also determine the impact that removal of end-of-life modules will have on UK PV capacity and the need to compensate for these shortfalls.

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Whole system efficiency of energy harvesting devices powered by next-generation PV technologies

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Self-powered devices are increasingly being integrated into the Internet of Things (IoT) ecosystem, enabling sustainable and autonomous operation in various environments. Photovoltaic (PV) modules, particularly those optimised for indoor lighting, are emerging as an energy source for such devices. This study evaluates the practical energy efficiency of PV modules integrated into IoT systems under varying indoor lighting conditions. Unlike standard measurements based solely on the maximum power point (MPP) data, this research considers the real-world energy storage and utilisation performance influenced by factors such as MPP deviation, electronics conversion inefficiencies, dynamic lighting environments and occupancy effect on indoor areas. Customized devices were developed for energy harvesting and measurements to quantify energy transfer from PV modules to storage elements. The setup incorporated multi-channel logging, time-synchronised data collection, and energy data interpolation to ensure accurate energy yield assessment. Experiments were conducted using a dual-module configuration: one module connected directly to the custom-built portable IoT SMU (Source Measure Unit) for MPP measurement and another routed through an energy harvesting circuit to a storage element. Data collected from the voltage logger, charge counter, and SMU were processed using MATLAB. A classification-based methodology was employed to analyse energy performance under varying lux levels.

The experimental results reveal a performance of the tested PV modules under mixed lighting conditions, with a clear disparity between the energy yields reported by the SMU and the actual harvested energy measured at the storage element. The data categorised by lux ranges highlighted the impact of light intensity and energy harvesting chips on both energy yield and power output, with high deviations primarily observed at higher intensities due to MPP voltage shifts. These findings underscore the importance of optimising energy harvesting circuits for specific lighting conditions to maximise the overall harvesting performance.

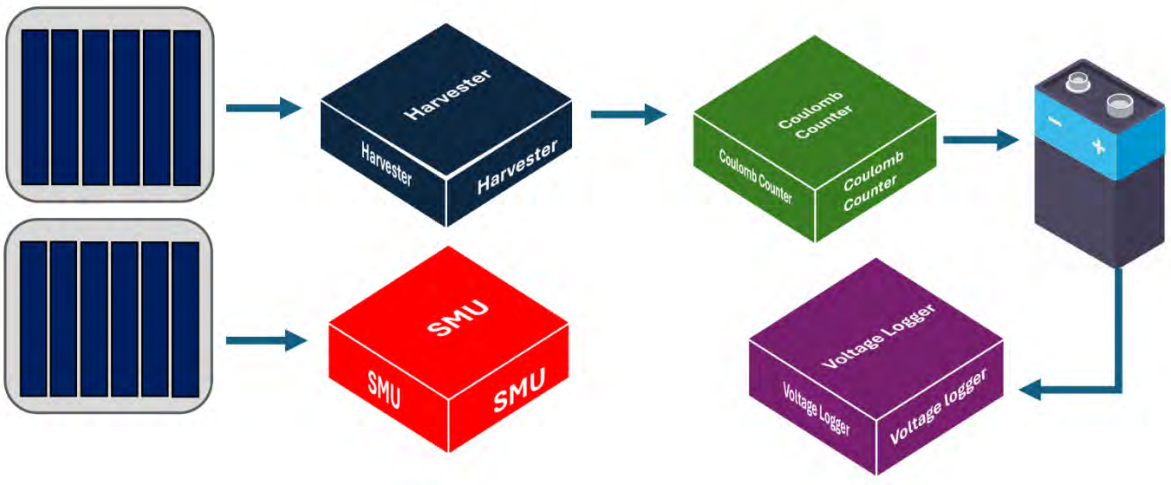

Figure 1: Schematic of the experimental setup used to evaluate the energy harvesting efficiency of photovoltaic modules. The configuration includes a PV module connected either directly to an SMU (red) for maximum power point (MPP) tracking or to an energy harvesting circuit (blue) routed through a coulomb counter (green) and voltage logger (purple). The stored energy is accumulated in a

rechargeable lithium battery, enabling comparison of theoretical MPP energy yield with actual harvested energy under varying light conditions.

Metal-Organic Nanosheets: Bridging Solar harvesting and Storage

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Third-generation solar cells offer significant promise for advancing renewable energy solutions, aiding in the decarbonization of our economy, and powering wearable devices. Among these, dye-sensitized solar cells (DSCs) have demonstrated exceptional performance under indoor, diffused light conditions, making them strong candidates for powering the next digital revolution within the Internet of Things (IoT). When integrated with an energy storage system, such as an electric double layer capacitor (EDLC), DSCs can serve as photocapacitors, providing reliable and uninterrupted energy output.

In this talk, I will introduce Metal-Organic Nanosheets (MONs), which are hybrid materials composed of earth-abundant, non-toxic metals and organic linkers. These materials form robust two-dimensional networks, and their molecular modifications allow for the tuning of bulk electrical properties, making them promising candidates for energy storage applications. The talk will present evidence showing that, when interfaced with thin-film photovoltaic devices, MONs can enable a new generation of energy-storable solar cells.

This work demonstrates that highly interconnected networks of polymeric nanowires, formed through epitaxial assembly, significantly enhance conductivity and facilitate better contact with dye molecules. Additionally, modulator-assisted bottom-up synthesis of MONs results in stacked 2D layers with 1D cylindrical channels, improving ion conduction. This architecture forms an efficient interface when DSCs are coupled with EDLCs in a photocapacitor configuration.

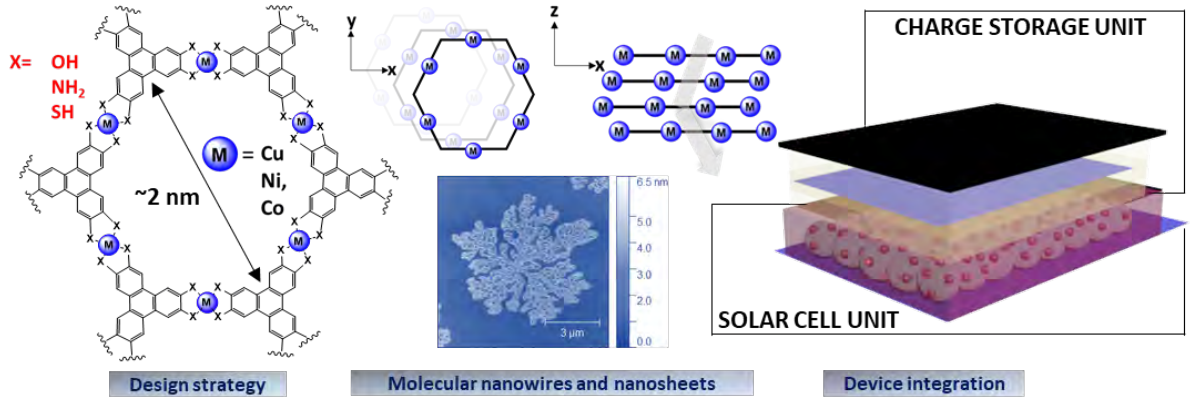

Fig 1. Schematic representation of the metal-organic nanosheet based interface for energy storage

Furthermore, I will discuss the environmental aspects of this work, evaluating the sustainability of the device design. The material design routes developed aim to ensure a sustainable approach during fabrication and enable devices that are "refurbish-able" and "upgradable," with MONs replaceable over multiple product generations without loss of functionality. This talk will also identify features that promote circular economy principles and highlight barriers to resource efficiency, offering potential solutions and future research priorities.

This research paves the way for highly efficient, environmentally sustainable energy capture and storage devices, advancing the development of next-generation solar technologies.

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Invited Presentation

Key Molecular Perspectives for High Stability in Organic Photovoltaics

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Organic photovoltaics (OPVs) have rapidly improved in efficiency, with single-junction cells now exceeding 19% efficiency. These improvements have been driven by developing new non-fullerene acceptors (NFAs) and fine-tuning of their molecular structures. Although OPVs are highly efficient, they often show extremely poor operational stability, primarily due to the complex interplay between the morphological instability of the blended bulk heterojunction photoactive layers and the intrinsically poor photostability of the organic semiconductor materials themselves. To realize commercialization, it is vital to understand the degradation mechanisms of these organic materials to improve their photostability. Efficiency increases have, in part, been driven by the rational molecular design of materials [1]. In this talk, I will discuss key molecular design parameters and show how each parameter impacts different degradation pathways with a particular focus on NFA molecular planarity, rigidity, end groups [2, 3] and donor polymers [4]. I will also discuss the impact of morphological and photochemical instabilities on OPV device stability [5]. The fundamental understanding of the molecular origin of OPV stability is one of the key requirements for next-generation OPVs.

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Enabling Large-Area Organic Photovoltaics with High Performance Metal-Grid Transparent Electrodes

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Organic photovoltaic (OPV) materials are an emerging technology that have great potential in flexible devices, semitransparent devices, and have applications in agricultural and indoor settings.[1-3] Additionally, devices can be scaled-up due to the solution processability of OPV materials via methods such as roll-to-roll and slot-die coating.[4,5] However, scaling OPV poses electro-optical challenges. A dominant challenge is the large performance losses upon scaling up, mainly attributed to the relatively high series (sheet) resistance of state-of-the-art transparent conducting electrodes (TCEs) such as indium- or fluorine-doped tin oxide. The balance between the sheet resistance and transmittance exists of a TCE must be optimised to enable high transmittance and low sheet resistance. In prior work by the authors, TCEs were combined with a planar metal grid/glass substrate (g-TCE) and demonstrated a promising solution that decoupled the electrical and optical properties of the TCE, providing an aluminium doped zinc oxide g-TCE that achieved a sheet resistance of 0.5 Ω/□ and average visible transmittance greater than 77 %.[6-8] The g-TCE is emerging as an enabling technology for large, single-cell solution-processed OPV devices that overcome the scaling barrier, potentially competing with Si-PV in specific applications, due to the reduced necessity of singulation and shading from the front contact electrode. Herein, the integration of g-TCEs into large-area OPV devices is demonstrated, with a focus on the relative performance when using traditional monolithic TCE films (m-TCE).

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Auxetic Rotating Triangle c-Si Solar Modules with Adjustable Light Transmittance

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Traditional monocrystalline silicon solar panels are rigid and installed on buildings or the ground using fixed frames, making them unsuitable for covering surfaces with complex morphologies. This fixed installation method also presents a common issue in both Building-Integrated Photovoltaics (BIPV) and agricultural photovoltaics (AgriPV): the inability to adjust the shading area of the photovoltaic devices—and thus control the intensity of transmitted light—as needed. For buildings, using sunshades does not fully utilize excess solar energy. Semi-transparent photovoltaic glass with thin-film solar cells can provide shading and harness solar energy, but their fixed nature results in unchangeable shading during low-light conditions, leading to additional energy consumption for temperature control and lighting [1]. In AgriPV, the ability to vary how much sunlight is directed to solar panels and crops as conditions change would enable a more optimum balance between power generation and agriculture to be achieved [2].

This study builds on previous work by the group on Auxetic Rotating Square (ARS) modules to introduce lightweight, stretchable solar modules featuring Auxetic Rotating Triangle (ART) structures. The modules are fabricated by cutting commercial monocrystalline silicon PERC solar cells into smaller sections, reconstructing the circuit with soldered wires, and encapsulating the assembly with highly transparent polyurethane rubber. The key innovation is that during expansion, the triangular units rotate and separate, creating adjustable gaps that allow unobstructed light transmission thus adjusting the overall light transmittance by stretching or relaxing the structure. This improves on designs that rely on elastomer-coated interconnects with pre-stretched structures. The study examines the transmittance of 4×2 ART modules across a rotation range of 0° to 45°, utilizing three methods: a simple geometric model, mechanical simulations with COMSOL, and analysis of photographs of fabricated prototypes. The ART module achieves variable transmittance from approximately 42% to 86%, a significant improvement on the range achieved with similarly sized ARS modules (~40-65%). Electrical and mechanical properties of the ART modules will also be presented.

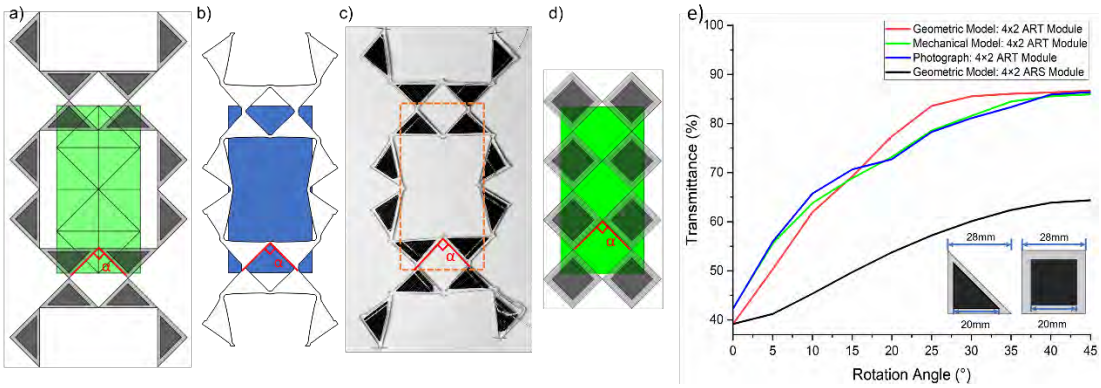

Figure 1 (a-c) *4×2 ART modules at 45° rotation: (a) Geometrical model; (b) COMSOL mechanical simulation; (c) Photograph of prototype module. (d) Geometrical model of 4×2 ARS module at 45° rotation. (e) Transmittance vs. rotation angle plots for 4×2 ART and ARS module, with schematics of unit cells of each design.*

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Non-geminate recombination kinetics in organic solar cells optimized for targeted applications

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Organic photovoltaics have recently achieved impressive power conversion efficiencies exceeding 19% [1]. These achievements were made using bulk heterojunctions (BHJ) of complimentary absorbing donor (visible) and acceptor materials (NIR) at roughly equal weight fractions. The recombination kinetics in such blends are often analyzed using an effective medium approach where the concentrations of holes and electrons are assumed to be constant throughout the active layer.

However, many of the application targets for organic solar cells such as agrivoltaics or indoor photovoltaics are not optimized for performance under 1 sun conditions but instead require different characteristics like semi-transparency in the visible range or a high photovoltage to power IoT devices, respectively. The former is commonly achieved by reducing the content of the visible light absorbing donor [2]. An increased photovoltage may be achieved by employing planar heterojunctions (PHJ) with a reduced donor/acceptor interface for non-geminate recombination [3]. Figure 1 schematically depicts these alternative active layer configurations.

Both, donor dilution and the use of PHJs, lead to electron and hole distributions in the acceptor and donor phases, respectively, that can no longer be described using an effective medium approach – rendering the comparison of a bimolecular recombination coefficient determined from measurements of the charge carrier density unsuitable to compare the charge recombination kinetics (see Figure 1).

In this presentation, I will provide an overview of experimental data for a range of different donor/acceptor ratios and PHJs underlining this point. Analyses based on charge carrier density and lifetime are complimented by voltage loss analyses utilizing electroluminescence and external quantum efficiency measurements to elucidate the role of the volume fractions of the donor and acceptor phases as well as the interfacial area. The findings will guide further optimization of device architectures for target applications such as semi-transparent and indoor performance.

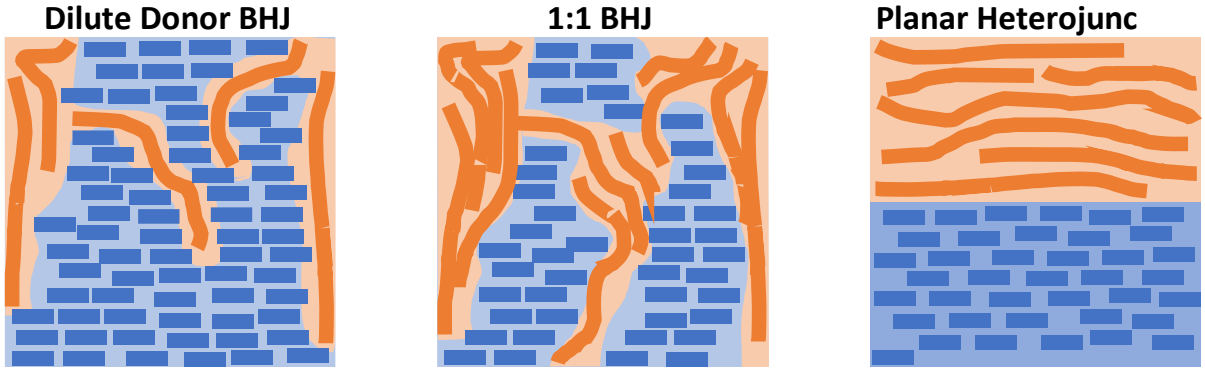

Figure 1. Schematic illustration of a BHJ with roughly equal donor and acceptor content (optimized for 1 sun performance), a dilute donor BHJ (optimized for agrivoltaics) and a PHJ (to increase open circuit voltage for IoT power supply indoors).

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Inorganic thin film, inorganic multijunction and concentrator photovoltaics

Advanced Dielectrics for Solar PV Coatings

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Anti-reflection coatings (ARCs) can be utilised to improve the efficiency of various photovoltaic (PV) technologies by minimising optical losses [1]. ARCs consisting of alternating layers of dielectrics are a scalable option for PV devices used in various contexts. Molecular Vapour Deposition (MVD) is a thin-film deposition technique, capable of depositing films at low temperatures (35° C) on substrates with low thermal budgets. MVD is an ideal deposition method for ARCs with several advantages. Firstly, MVD allows for precise thickness control at a molecular level with high levels of uniformity, which is essential for ARCs to achieve desired optical properties [2]. Furthermore, the tool can deposit a wide range of materials which can be used interchangeably, allowing the user to develop multiple layers with varying refractive indices within one ARC [2]. In this work, ARCs comprised of MVD-deposited TiO_2 and Al_2O_3 were designed for multi-junction PV devices intended for space applications [3]. These are shown to improve the specific power of multi-junction PV devices in a coating which is compatible with batch processing [4].

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Invited Presentation

Solar PV in real world – what are the challenges?

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In a fast-moving industry, what are the challenges of solar PV in real world? The presentation discusses the latest technology and trend in the PV industry, and outlines the obstacles that may hinder solar deployment in the energy transition to net zero targets.

The significance of measuring the bulk lifetime for high efficiency silicon solar cells

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The bulk lifetime of high-quality silicon wafers is becoming ever more important as the efficiency of the solar cells increases to record levels (i.e. >27%). As such there is a growing need to measure τ_{bulk} directly. Until now, such a technique has not existed because surface recombination, despite progression in passivation techniques, still masks the underlying bulk lifetime of high-quality silicon. Consequently, it has been difficult to directly assess the impact of thermal processing, light-induced degradation and the electronic quality of silicon wafers, especially as the demand for high lifetime material increases. Nevertheless, in this work we utilise the passivation quality of atomic layer deposited (ALD) aluminium oxide (Al_2O_3), in combination with corona charging (CC), to showcase a novel non-destructive method to measure the injection-dependent bulk lifetime of both *n*- and *p*-type silicon. To elucidate this method, the silicon material is first coated with ~20 nm of ALD Al_2O_3 after which the passivation is 'activated' by annealing the material at 450 °C for 30 min. Secondly, the Al_2O_3 passivated silicon wafer/sample is subject to corona charging at set intervals (calibrated to deposit 3.5×10^{11} qcm^{-2} electronic charges every five seconds) until a minimum lifetime is achieved (*i.e.* to a point where the net charge is zero). Finally, by ascertaining the fill-factor of the decaying lifetime (due to corona charging), and by using a calibration curve, the bulk lifetime can be determined at any given injection level. To verify this methodology, we perform theoretical simulations to validate the technique, and then experimentally apply the method to *n*- and *p*-type silicon to extract the injection-dependent bulk lifetime and surface recombination velocity. From this sensitive technique, it will be possible to ascertain recombination losses in very high efficiency solar cells and test structures, thereby aiding development in cell and module longevity (i.e. cells/modules can be used for >50 years).

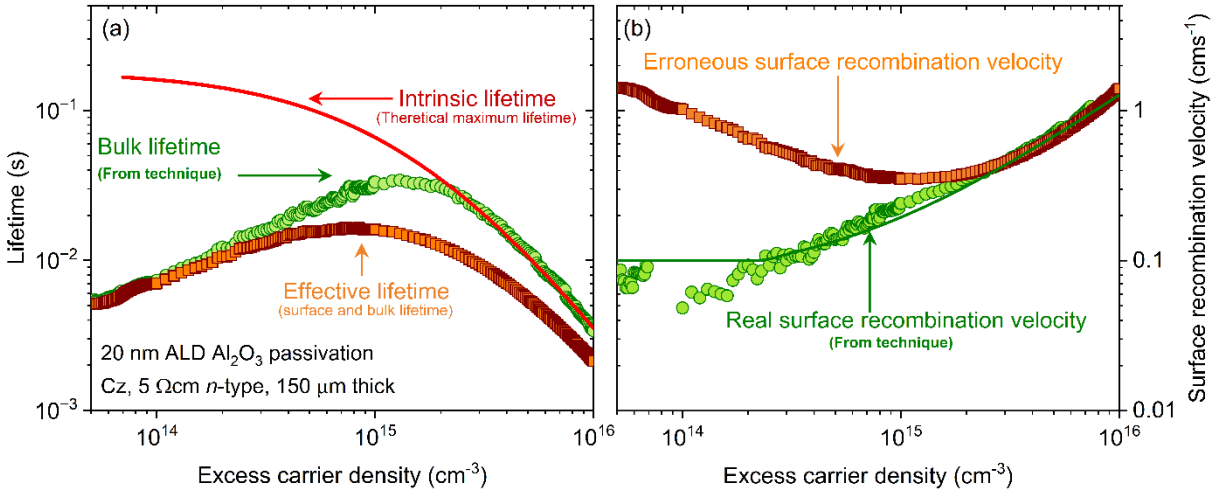

Figure 1 a) injection-dependent effective lifetime (orange squares) when passivating 5 Ωcm n-type silicon with ~20 nm of ALD Al_2O_3 and annealed at 450 °C for 30 min. Also plotted is the intrinsic lifetime and the reconstructed bulk lifetime, as determined form the technique. b) Injection-dependent S before (orange squares) and after (green circles) correcting for the real bulk lifetime. For clarity, the solid green line only serves as a 'guide to the eye'.

Photovoltaic Systems, Solar Irradiance & Monitoring, Policy, Sustainability, Market Development & Life Cycle Analysis

Diffuse Irradiance Estimation Using a Dual-Stream Sky Image-Based Computer Vision Approach

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As the global transition toward greener technologies and net-zero emissions accelerates, enhancing solar irradiance estimations become increasingly critical for optimizing photovoltaic (PV) power generation and integrating renewable energy into the broader energy infrastructure. The growing deployment of PV systems necessitates highly accurate and reliable measurements such as Global Horizontal Irradiance (GHI) and Diffuse Horizontal Irradiance (DHI) to effectively evaluate and predict power generation. Advances in machine learning (ML) and computer vision, through the analysis of sky images, offer promising methods for improving irradiance prediction whilst mitigating dependence on costly measurement instruments [1].

This study introduces an innovative method for estimating DHI using data from the Chilbolton Observatory. Feature importance analysis highlights Estimated Theoretical Irradiance (ETI) as a pivotal derived input, integrating sun position, time, and atmospheric conditions. A dual-stream architectural framework processes both standard fisheye images and systematically transformed images, utilizing adapted cloud segmentation overlays and threshold-based modifications from [2](e.g., Otsu thresholding or blocked-sun detection) to generate specialized input channels that refine the model's understanding of cloud dynamics and sky conditions. These dual image streams, combined with tabular features like ETI, are fed into a DeiT-based neural network, enabling the model to leverage both visual and numerical data for improved spatial-temporal cloud pattern analysis and atmospheric variability. By effectively combining the dual-stream approach with ETI, this method demonstrates significant gains in performance metrics, including higher coefficients of determination (R^2) and lower root-mean-square errors (RMSE). Furthermore, ETI and the dual-stream framework act as a surrogate for other costly required measurements, achieving equal or superior accuracy. This combination not only validates the potential to replace expensive equipment with advanced computational techniques but also facilitates the development of scalable PV estimation.

Future work will optimize the dual-stream architecture and expand data augmentation strategies to shift from estimation to forecasting, particularly for diverse geographic regions and atmospheric conditions. By emphasizing global applicability, subsequent iterations aim to deliver more efficient, cost-effective solar irradiance forecasts, underscoring the significance of ML-driven sky image processing in advancing sustainable energy.

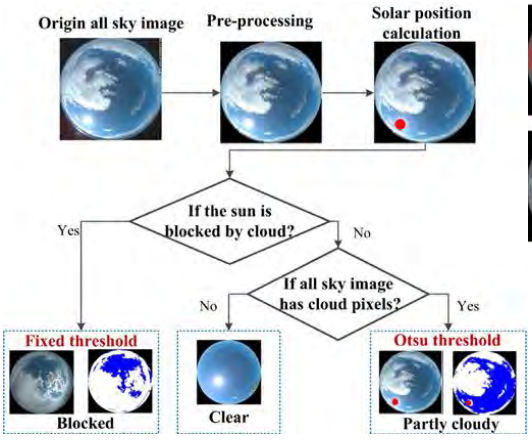

Figure 2 – Image Overlay Process [2]

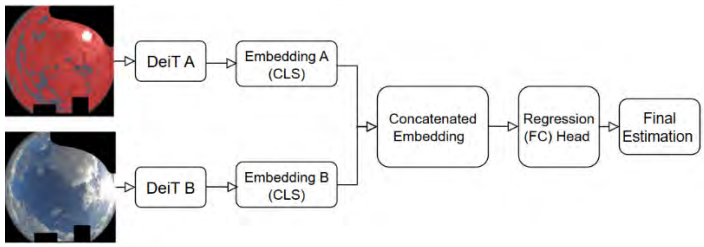

Figure 1 - The left panel (Figure 2) shows the preprocessing pipeline for all-sky images, involving solar position calculation, cloud detection, and classification (clear, partly cloudy, or blocked) via thresholding. Pre-processed images are input to DeiT A in the right panel (Figure 1), whilst normal images are processed through DeiT B. Outputs from both models generate embeddings (A and B), which are concatenated and passed through a regression head for the final estimation.

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Variation of Cell-Bonded 4-domed Optic Material to Improve Concentration Factor for Concentrator Photovoltaics

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For concentrator photovoltaic (CPV) systems to reach more widespread adoption, cost and space efficiency is needed. For this reason, maximising the concentration factor is an important step. This study seeks to achieve the highest possible concentration factor within a 3-stage CPV system by varying the material of the cell bonded optic. Furthermore, the definition of concentration is not consistent within the literature, sometimes being based purely on geometric concentration factors and optical efficiencies. To avoid this confusion, the effective concentration ratio is used, based upon the ratio of electrical output measurements under concentration and under one sun.

The system has previously been experimentally investigated under outdoor real-world conditions and achieved an effective concentration of ~1200 suns [1]. In that study the 4-domed optic material was sylgard-184 with a refractive index (RI) of ~1.40. The aim of the study is to increase the effective concentration by replacing this sylgard-184 with materials of higher refractive indexes. These include sapphire (RI: 1.67), Crystal Clear 200 urethane resin (RI: 1.50), and OptaClear polyurethane (RI:1.62). OptaClear has a hardness high enough to enable an experiment with a variation including an antireflective coating, to increase optical efficiency and hence, effective concentration.

A thorough investigation is conducted using each optic material variant at each stage through indoor and outdoor experimentation. The highest RI optics led to a decrease in optical efficiency which ultimately brought the effective concentration down compared to the 2-stage system with no 4-domed optic. An experimental effective concentration value of 1476 suns is achieved, higher than any value previously reported in the literature. Moreover, indoor experimentation could not effectively predict real-world performance.

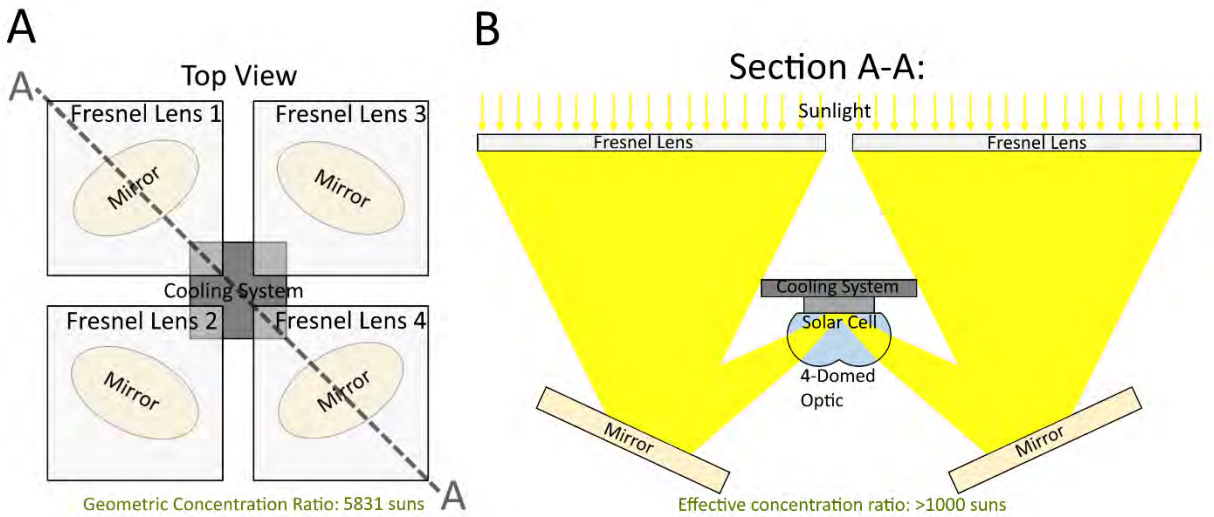

Figure 1 (A) Top view of concentrator photovoltaic system (B) Section A-A view of concentrator photovoltaic system

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Low resistivity contacts for high-efficiency next-generation silicon solar cells

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Beyond the passivated emitter and rear cell (PERC), passivating contact designs, such as the tunnel oxide passivated contact (TOPCon) and c-Si/a-Si heterojunction (HJT), offer improved performance by minimising silicon–metal contact losses and enhancing passivation at the Si/dielectric interface [1]. However, TOPCon still faces challenges with increased processing steps and limitations from Auger recombination in the front emitter, while HJT cells are hindered by parasitic absorption in the front a-Si layer. We are therefore developing an inversion layer (IL) junction design, as an alternative to PERC or TOPCon, that can be produced at low temperatures and eliminates parasitic absorption and Auger losses in the emitter [2].

In this study, we investigate the electrical performance of localised laser-doped contacts under various lasering conditions for IL solar cells. Our goal is to optimize these conditions to reduce the recombination current (j_0) and contact resistivity (ρ_c) in the contacted regions. Photoluminescence (PL) images taken of 20 nm symmetrical atomic layer deposition Al_2O_3 passivation on p-type Si (Cz, Ga-doped, 5 Ω cm, <100>, 120 µm thick) before and after Al metallisation and subsequent laser treatment are shown in Fig. 1(a)-(d). Using the transfer length method (TLM), we also measure ρ_c for different laser treatments, correlating these results with the j_0 study. Figure 1(e) presents the contact resistivity values for several laser treatment conditions (altering frequency and speed). We will present a wider range of laser treatment conditions and explore changes in j_0 and ρ_c further, addressing the underpinning limitations to the electrical performance of such contacts.

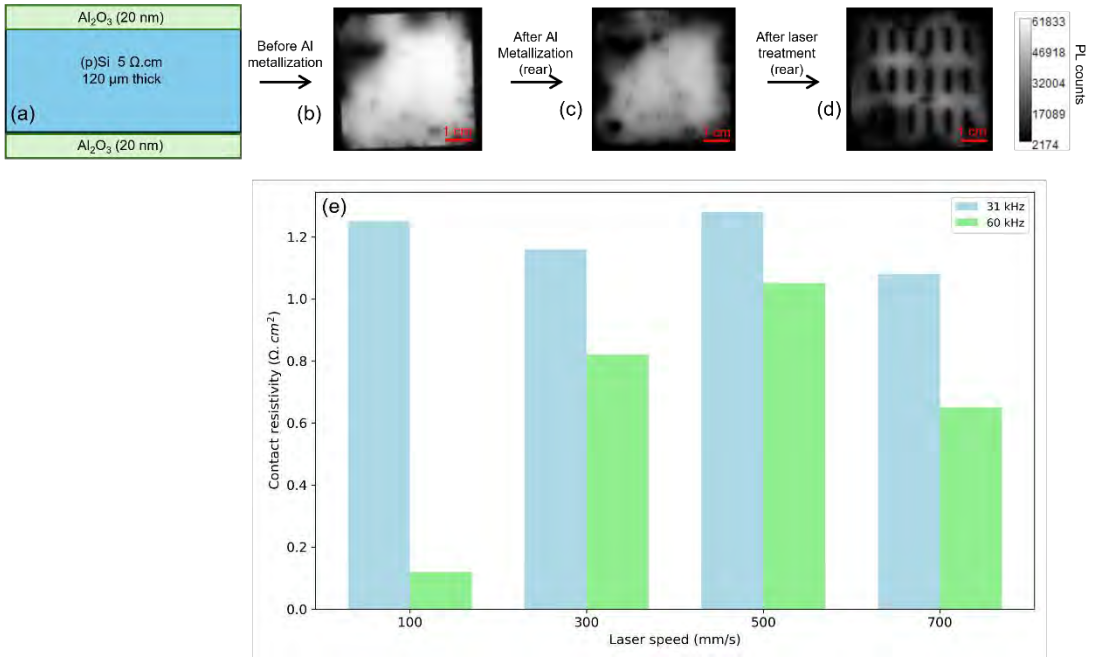

Figure 1 a) Schematic of specimen before metallization, and PL images taken b) before Al metallization c) after Al metallization, and d) after laser treatment on the rear side of Al_2O_3-pSi-Al_2O_3 specimen. e) Measured contact resistivity after laser treatment under different conditions.

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Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Investigating the Scalability Potential of an SnO_2 Derived Electron-Transport Material Using Established Criteria and Experimental Procedures

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The EU Solar Energy Strategy set a goal of a Photovoltaic (PV) capacity of 592GW by 2030[1] which can only be achieved by producing higher Power Conversion Efficiencies (PCE) and increased throughputs of PSC manufacturing. PSCs allow for low-temperature manufacturing processes which reduce the overall fabrication complexity and cost of the device.

When choosing a material for a layer in a PSC several factors must be considered when concerning its scalability; these cover a cost analysis of the material, the printability of the ink, the shelf-life of the material, and the performance characteristics of the full-scale device. All the above factors must be analyzed to decide if the chosen material has the potential to be scalable and produce high PCEs. The investigation focused on choosing a new material for the ETL, defined by the above criteria. The tests undertaken included measuring the rheological properties and the deposited film morphology of the ink as it aged over eight weeks and, fabricating full devices with a slot-die coated ETL using the ink samples.

Seven candidates for the ink were analyzed where all were derivatives of the commonly used ETL material Tin Oxide (SnO_2). Here we show that the SnO_2 Quantum Dot meets the criteria for a material to be scalable. The SnO_2 Quantum Dot performed the best over the eight-week shelf-life study; there was no presence of agglomerates in the film over this time frame and, when full scale devices were made, the SnO_2 Quantum Dot achieved the highest PCE of 14% while maintaining a low fabrication cost. The established criteria and test procedures can be applied to the whole device architecture. It is hoped that others can use the criteria outlined in this study to analyze the scalable potential of a new material in their own PV device.

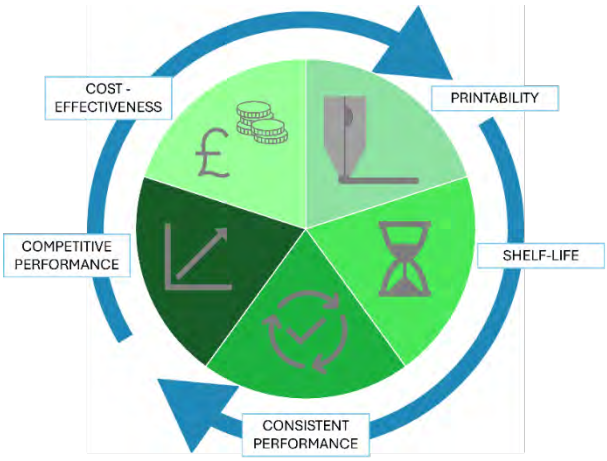

Fig. 1 Process diagram outlining the key criteria in identifying a commercially viable material for a PV device.

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Investigation of perovskite defects reduction and non-radiative recombination kinetics using *In-situ* PL measurements under aerosol treatment

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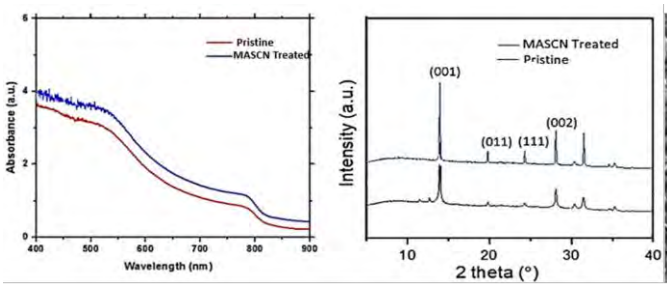
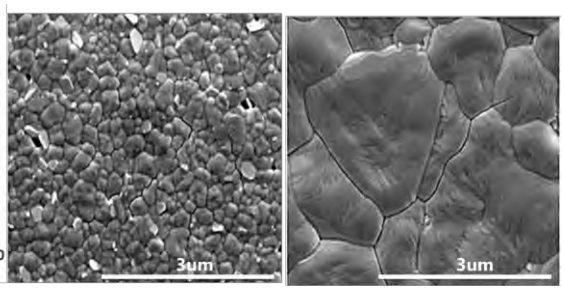
Lead-halide perovskites have firmly established themselves in the fields of photovoltaics and optoelectronics, demonstrating increasingly competitive power conversion efficiencies comparable to traditional solar cells [1]. However, achieving further enhancements in performance necessitates mitigating defect-assisted, nonradiative recombination of charge carriers within the perovskite layers. A comprehensive understanding of perovskite formation and associated process control is essential for effectively reducing defects. In this investigation, we examine the crystallization kinetics of the different lead-halide perovskite $MAPbI_3$, $FAPbI_3$, $CsFAPbI_3$ etc. during thermal annealing under aerosol treatment employing in-situ photoluminescence (PL) spectroscopy.

Previously, we have demonstrated a method for performance and stability improvements in $FAPbI_3$ and other perovskite compositions by crystallization in the presence of a solvent aerosol treatment [2,3].The in situ PL measurements results demonstrate that aerosol treatment induces favorable morphological changes, leading to improved charge transport properties and reduced defect density within the perovskite film. This characterization approach enables the real-time assessment of optoelectronic properties during perovskite formation and development of improved crystals producing a uniform film with improved morphology under the effect of facile and scalable aerosol treatment. These findings not only shed light on the underlying mechanisms governing the aerosol-assisted modification of perovskite materials but will pave the way for the development of more efficient and stable perovskite-based optoelectronic devices.



UV-Vis and XRD analysis of pristine and aerosol treated $FAPbI_3$ based perovskite films



SEM images of $FAPbI_3$ based perovskite films post treated by aerosol treatment

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Perovskite, organic, tandems and DSSC photovoltaic

Photocapacitive Behavior of Carbon-Based Triple-Cation Perovskite Solar Cells in a PMMA based Solid-State Electrolyte Framework

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The integration of the energy harvesting and storage within a single device structure has opened a new window for the self-powered power packs [1,2]. Carbon-based perovskite solar cells (c-PSCs) has already proven their capability for next generation cost effective and sustainable energy harvesting devices due to their ease of manufacturing and long-term stability [3]. Recently, perovskite based photosupercapacitors devices showed their candidacy to develop advance self-powered power packs, which triggered the need of the mechanistic view of the photocapacitive behaviour of the PSCs itself to develop efficient perovskite photosupercapacitors [4]. This study investigates the photocapacitive behaviour of carbon-based triple-cation PSCs within a poly(methyl methacrylate) (PMMA) solid-state electrolyte framework, tailored for photosupercapacitor applications. The incorporation of PMMA as a solid-state electrolyte not only ensures strong ionic conductivity but also provides mechanical stability and moisture resistance, which is mandatory for perovskite-based device longevity. The carbon-based triple cation PSCs showed the dual behaviour of energy conversion and storage, hence demonstrates excellent photocapacitive behaviour. Sandwich style supercapacitor (1 cm2 area) were fabricated with a novel solid electrolyte consisting polymethyl methacrylate, phosphoric acid and an ionic electrolyte. One of the c-PSC behaves as the photo electrode, while the another worked as the capacitive electrode. Electrochemical and photo-electrochemical energy storage performance of the c-PSC based supercapacitors was analysed via CV, EIS and photo-assisted charge-galvanostatic discharge methods. The c-PSC based photo-supercapacitor device showed an exceptional capacitance enhancement than its initial capacitance (dark). Furthermore, the device showed promising peak overall and storage efficiencies, suggesting the efficacy of the c-PSCs to develop next generation power packs for self-powered miniature devices. The present work opens a new window towards the photo-assisted C-PSC based supercapacitors for adaptable and versatile integrated energy applications.

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The Impact of Crystallinity in Low-cost Donor Blends on Charge Generation for Organic Photovoltaics

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Recent progress, particularly with Y-series non-fullerene acceptors (NFAs), has propelled the power conversion efficiency (PCE) of single-junction organic photovoltaics (OPVs) beyond 19%.[1] This improvement pushes the need to design new donor polymers that effectively pair with NFAs. However, many high-performing donor polymers are expensive due to complex synthesis processes and costly raw materials. Thus, the design of low-cost donor polymers is crucial for large-scale production and commercial adoption. Achieving this goal requires not only innovative material design but also a comprehensive understanding of charge generation mechanisms and device performance.

In this study, we investigate the charge dynamics and device performance of the low-cost donor polymer FO6-T. We identify two distinct polaron states in FO6-T: one associated with disordered domains and the other with crystalline domains, as evidenced by cyclic voltammetry (CV) and spectroelectrochemistry (SEC) measurements. These findings align with the reported FO6-T's semi-crystalline morphology[3]. Charge generation dynamics in the FO6-T/$PC_{71}BM$ blend were studied using femto-second transient absorption spectroscopy (fs-TAS). Upon photoexcitation, FO6-T excitons rapidly converted into polaron states within a few picoseconds (ps). Polaron states in the disordered domains near the donor/acceptor (D/A) interface transferred to crystalline phases via an energy cascade within 20 ps. The crystalline phases played an important role in stabilizing the separated polarons, which exhibited lifetimes extending into the microsecond (μs) range, as shown by μs-TAS measurements.

Then we studied the high-performing FO6-T:L8-BO blend with reported PCE 15%[3]. The two polaron states of FO6-T persist in the FO6-T/L8-BO blend, revealed by fs-TAS. Furthermore, Förster resonance energy transfer (FRET) was observed under donor excitation, supported by the TAS kinetic analysis. The highly overlapping emission spectrum of FO6-T and the absorption spectrum of L8-BO also support the FRET observation. To investigate the impact of findings discussed above on device performances, a series of D/A ratio studies was conducted. The FO6-T/L8-BO blend exhibited exceptional tolerance to D/A ratios ranging from 2:1 to 1:10. These findings underscore the potential of low-cost, simple donor polymers like FO6-T in achieving high-efficiency and semi-transparent OPVs, paving the way for broader commercialization and innovative applications.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Development of fully non-toxic ink for the scalable deposition of perovskite thin layers

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Perovskite solar cells (PSCs) have rapidly gained attention in the field of photovoltaics due to their remarkable efficiency and potential for low-cost production. The versatility of perovskite materials allows them to be processed using a variety of deposition techniques, ranging from solution-based methods to vapor deposition. Recent advancements have focused on enhancing the stability, efficiency, and scalability of perovskite solar cells, making them a strong contender for commercial solar energy applications.[1] Developing environmentally friendly and scalable manufacturing processes is crucial to facilitate the transition from laboratory-scale experiments to large-scale production, ensuring sustainable and eco-friendly solar energy solutions. Our research began with the development of perovskite inks based on pure acetonitrile, a commonly used but toxic solvent. Recognizing the need for safer alternatives, we embarked on a systematic approach to replace up to 70% of the toxic acetonitrile with non-toxic solvents.[2] Building on this success, we further refined our formulation to eliminate the toxic component, ultimately creating inks that utilize alcohol-based and ether-based non-toxic green solvents. This progression not only maintained the superior quality of the perovskite films but also ensured a more sustainable and eco-friendly manufacturing process for perovskite solar cells. The developed $MAPbI_3$ perovskite ink was designed for use with high throughput manufacturing deposition methods such as slot-die coating, bar or blade coating. Regardless of the deposition method used, thin layers with exceptional perovskite quality were coated over large areas. The developed deposition process for perovskite thin films operates at room temperature and eliminates the need for high-temperature post-annealing, making it suitable for both flexible and rigid substrates. The perovskite thin films were used for the fabrication of perovskite solar modules (PSMs) with active area of 11.5 cm^2, and the device structure of ITO/SAMs/$MAPbI_3$/C_{60}/BCP/Ag. The devices were fabricated without the use of spin coating technique, and power conversion efficiencies as high as over 18% were achieved (Figure 1).

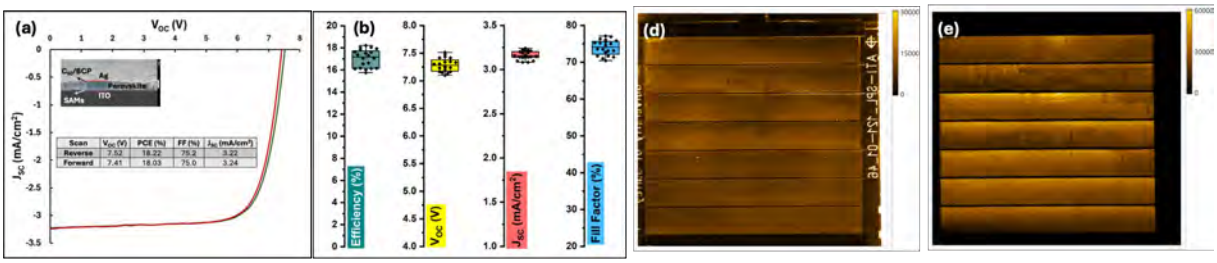

Figure 1. (a) J-V curve of the champion PSM consisting of 7 sub-cels connected in series and with the active area of 11.5 cm2. The inset image depicts the cross-section SEM image of the full stack of the device. The inset table presents the performance parameters of the champion device. (b) The performance parameter distribution for 10 fabricated modules. (c) The photoluminescence (PL) mapping image of the bar-coated perovskite film using non-toxic ink on ITO coated glass substrate. (d) PL image (30 ms exposure time) of a PSM device (e) Corresponding EL image (350 ms exposure time at 1 V, 18 mA).

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Perovskite, organic, tandems and DSSC photovoltaics

Low synthetic complexity and scalable donor polymers for organic solar cells

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The efficiency of polymer solar cells (PSCs) has made impressive progress in the last few years, but the synthetic complexity of some of the best performing materials is high and is a possible bottleneck towards scalable commercial applications. In this work we present a new class of donor polymer that can be prepared in just two steps from commercially available starting materials.[1] The simplicity of the synthesis allowed a library of polymers with differing alkyl-chain lengths and comonomers to be readily prepared and investigated. The thermal, electrochemical and photophysical properties of the resulting polymer library helped towards the development of structure-property design guidelines. The polymers were furthermore investigated as donor materials in solar cell devices with Y6 and L8BO as acceptor, with the best performing material FO6-T showing highly promising power conversion efficiencies (PCEs) of 15.4 %. Recently, we also showed that our polymer FO6-T is compatible with green solvents such as 1,2-xylene and 2-MeTHF.[2] In order to study the scalability and commercial viability of the newly synthesised donors compared to state-of-the-art materials, I conducted a synthetic complexity (SC) analysis, which takes into account different industrially relevant parameters, such as hazardous chemicals involved and the number of synthetic steps, and we found that our material shows one of the lowest SC for well-performing donor materials to date.

We believe that these materials are highly promising for commercial application in PSCs due to strong device performance and a low cost and truly simple two step synthetic protocol.

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Development of Novel Photovoltaic Devices Combining Ferroelectric Nanostructures with Perovskite Solar Cells

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Lead halide perovskite solar cells (PSCs) have achieved remarkable progress over the past 15 years, yet challenges in stability, scalability, and carrier transport optimization remain [1]. A key factor in carrier collection efficiency is the built-in electric field (BEF), determined by the work function difference between the electron and hole transport layers. PSCs typically exhibit a low BEF due to band alignment constraints, mobile ions, and thin-film architectures [2]. Enhancing the BEF could improve carrier separation and mitigate non-radiative recombination at defect sites. Ferroelectric materials, such as barium titanate (BTO), offer unique opportunities for boosting BEF and device performance. Their non-centrosymmetric crystal structures enable externally switchable polarization via poling, generating intrinsic electric fields. Additionally, ferroelectrics exhibit the bulk photovoltaic effect (BPVE), producing anomalously high photovoltages under illumination [3]. By integrating the high photocurrents of PSCs with the large photovoltages and BEF of ferroelectrics, there is significant potential for increasing power conversion efficiency (PCE).

This work presents a novel N-I-P device architecture incorporating a sol-gel-derived mesoporous BTO scaffold infiltrated with methylammonium lead iodide (MAPI). Poling the BTO scaffold, either electrochemically or through applied voltage, enhanced the open-circuit voltage from 0.31 V to 0.92 V and improved the PCE from 0.23% to 6.01%. A non-ferroelectric mesoporous strontium titanate control device showed no comparable performance gains, highlighting the role of ferroelectric polarization. Further optimization efforts are underway, focusing on improving MAPI infiltration, pore structure, and poling conditions. Preliminary SEM and EDS imaging confirm successful infiltration, though low photocurrent suggests suboptimal contact with the electron transport layer. Kelvin probe force microscopy (KPFM) is being used to quantify BEF changes, and ongoing studies aim to elucidate the role of BPVE in device performance.

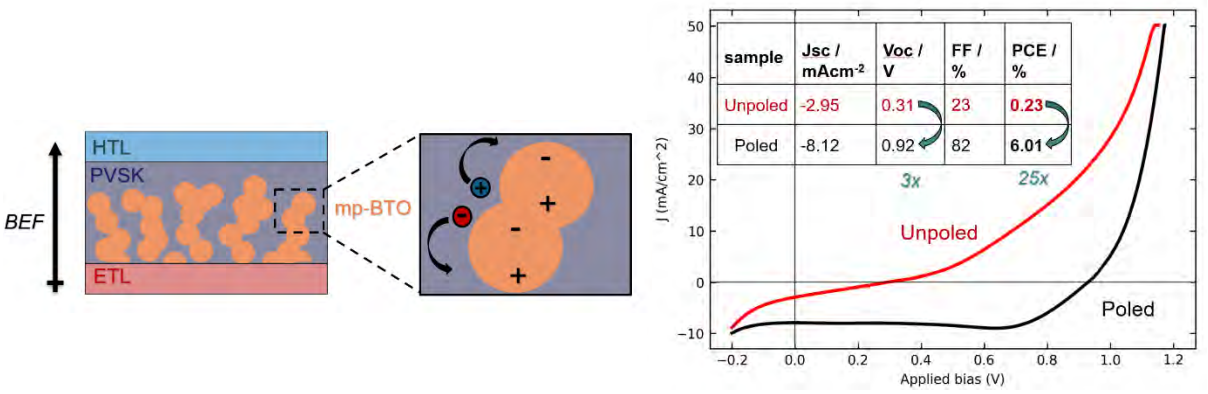

Figure 1) N-I-P device architecture incorporating a sol-gel-derived mesoporous BTO scaffold infiltrated with methylammonium lead iodide (MAPI) and JV curve of poled and unpoled devices.

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Photovoltaics for Nigerian Rice Processing – Social Perspective

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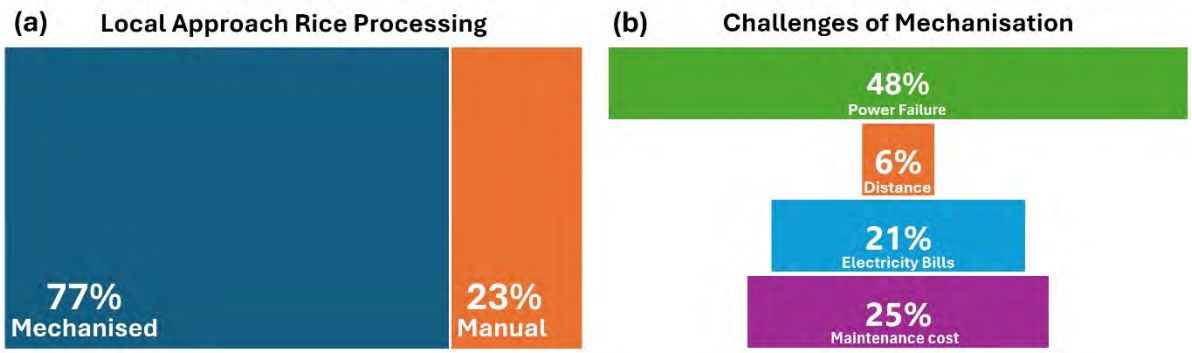
Nigeria is confronting a perilous food security dilemma as its expanding population becomes further reliant on imported foodstuffs [1]. The food crisis may be ascribed to the inadequate agricultural mechanisation in Nigeria [2], which is held back due to reduced energy access at the rural level where most farming activities are carried out [3]. However, the country possesses enormous solar energy potential across all regions [4, 5] that could be harnessed for agricultural activities. Studies recommended that identifying social perspectives on integrated PV Rice processing machines is necessary [6, 7].

This research undertook a stakeholder expectation consultation in Nigeria from May to August 2024 and collected 1,031 responses among some local Rice Farmers, Consumers, Millers, Rice NGOs, Traders and Others with the interest and power to influence Rice production/processing in the country.

Findings from the survey show that mechanisation challenges in rice processing are 48% power failure, 25% maintenance costs, 21% high electricity bills, and 6% distance to mills. On improving Rice processing in Nigeria, 77% of respondents said machine processing is core to improving local rice processing, while 23% said local processing. Figure 1a illustrates the responses to manual and mechanised processing, and Figure 1b shows the challenges of mechanisation.

Solar-powered rice processing machines and gasifying the byproducts to power the system when the sun goes down, on cloudy days or power other agricultural machines in Nigeria and other countries in sub-Saharan Africa (SSA) with similar conditions, could add value to their processing and production toward food security, poverty alleviation and rapid integration of renewable energy resources (RES) to accelerate clean energy access.



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Characterization, testing & performance measurements for PV materials, devices & modules

Correlation of soiling losses of distinct mega cities considering accumulation variance

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Anthropogenic activities play a major role on influencing photovoltaic soiling, particularly in mega cities where urbanization and industrialization are at its peak. This reduces the potential yield, accelerate performance degradation, and elevate maintenance cost. The accumulation of dust on photovoltaic modules can be influenced by numerous factors, including site characteristics, dust properties, wind, temperature, humidity, tilt angle, surface orientation, and the material that constitutes the PV surface [1] [2] [3].

This study investigated the influence biotic and abiotic activities in 2 mega cities (Riyadh and London) on dust accumulation and their relative causes of performance reduction. Low iron glass coupons were exposed on two different sites (East and West) of the individual cities as shown in Fig 1. 6 Glass coupons were angularly installed with 2 on vertical, 2 on tilt (optimal tilt angle of the location), and 2 on horizontal for duration of one month. Samples were collected and characterized by employing spectrophotometer for transmittance losses, Wacom solar simulator for power losses, scanning electronic microscope for morphology, and Energy-dispersive X-ray spectroscopy. Weather parameters for various sites were collected for analysis.

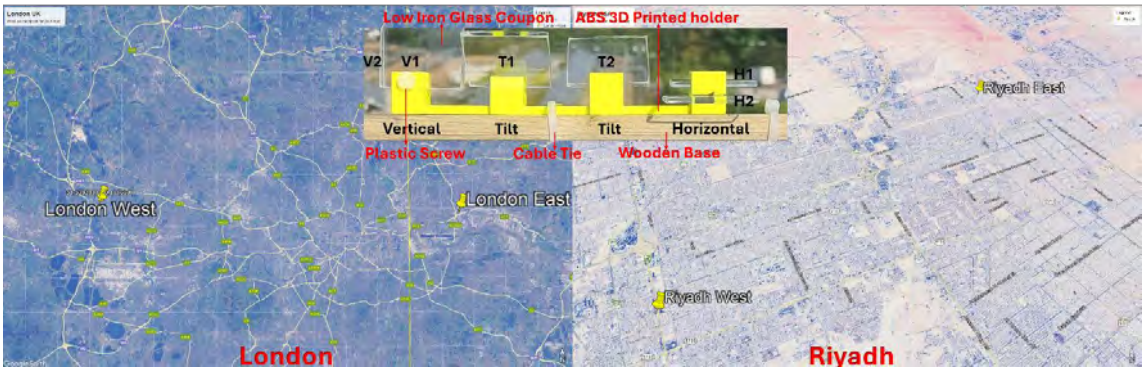

Fig 1: Sites and typical sample holders with description of angular position of low iron glass coupons (with Riyadh East 24.7385844, 46.6578785 and Riyadh West 24.8395241, 46.7723685. While London East 51.5302280, 0.0783819 and London West 51.5392099, -0.4846697).

The results highlighted significant variation mainly influenced by abiotic rather than the other. Finding showed the most significant optical loss was recorded in Riyadh West, while the lowest was recorded in East London. The PV performance losses showed similar pattern of losses. The morphological analysis through microscopic imaging showed huge variation of accumulation of particles on Riyadh samples compared to London samples. The elemental composition of various samples provided the possible highlights on the causes of the deposition, while the weather data confirmed the abiotic influence of soiling.

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Theoretical Study on the Effect of Doped Carbon Back Electrode on Lead-Free and Hole Transport-Free in $CsSnGeI_3$ -Based Concentrating Perovskite Solar Cells

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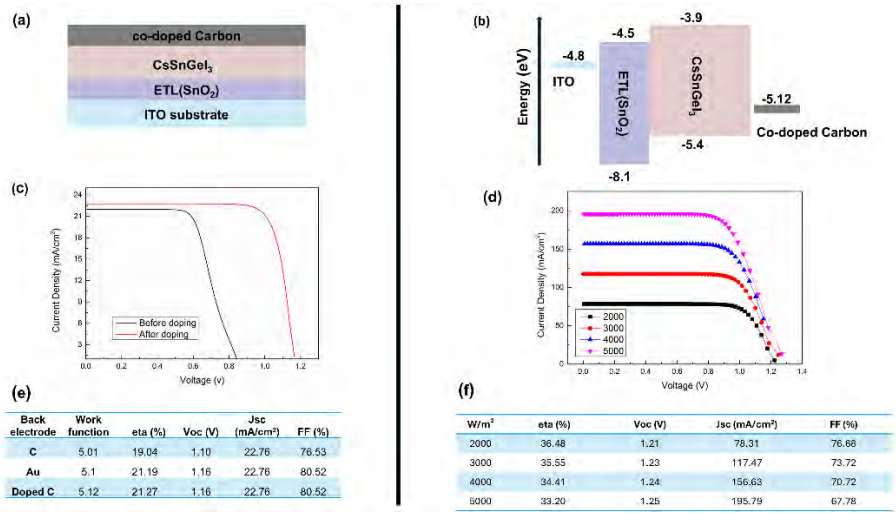
Developing lead-free and highly efficient hole transport layer (HTL)-free perovskite solar cells (PSCs) encounters significant challenges. Herein, we employed chemical doping to tune the work function and electrical conductivity of the carbon back electrode in HTL-free PSCs. In this work, the lead-free and HTL-free perovskite cesium tin germanium halide ($CsSnGeI_3$) solar cells with the boron and phosphorus co-doped carbon as back electrode have been performed by Solar Cell Capacitance Simulator (SCAPS). The thickness, band gap, electron affinity, carrier concentration, and work function have been investigated. As a result, doping the back electrode carbon with the boron and phosphorus increases the work function of pure carbon from 5 eV to 5.12 eV, which is higher than gold (Au) 5.11 eV(1). Moreover, due to the improved hole extraction ability, the doped carbon-based PSC provides a power conversion efficiency of 21.27%, compared to Au-based PSC at 21.19%.Also, Increasing the concentering from 1000 wm^2 to 2000 wm^2 plays a role in improving the PCE.

This study illustrates that replacing the Au electrode with a carbon-doped electrode, which enhanced the work function, plays a critical role in enhancing the performance of the device. Moreover, the economic advantages of the co-doped-carbon electrode render it a substitute for the costly Au electrode.



Back electrode	Work function	eta (%)	Voc (V)	Jsc (mA/cm²)	FF (%)
C	5.01	19.04	1.10	22.76	76.53
Au	5.1	21.19	1.16	22.76	80.52
Doped C	5.12	21.27	1.16	22.76	80.52

W/m²	eta (%)	Voc (V)	Jsc (mA/cm²)	FF (%)
2000	36.48	1.21	78.31	76.68
3000	35.55	1.23	117.47	73.72
4000	34.41	1.24	156.63	70.72
5000	33.20	1.25	195.79	67.78

Figure 1.(a) Schematic device architecture (b) energy level diagram(c) J-V curve for the device before doping carbon and before optimized the device and after doping carbon with the boron and phosphorus (d)) J-V curve for the device with (2000,3000,4000,and 5000) wm^2 (e) the parameters for three different back electrode (carbon, gold, and co-doped carbon with the boron and phosphorus) after optimizing and (f) the parameters with (2000,3000,4000,and 5000) wm^2 after optimizing the device.

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Perovskite, organic, tandems and DSSC photovoltaics

High-Performance Indoor Photovoltaic Mini-Modules with Carbon Electrodes for Sensor Power Generation

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Indoor photovoltaics (IPVs) based on halide perovskites are emerging as a sustainable and efficient energy source for powering the rapidly growing network of wireless sensors in the Internet of Things (IoT). These sensors require low-power, cost-effective, and scalable energy solutions to function reliably in indoor environments. However, expensive metal electrodes, such as gold, hinder the widespread adoption of perovskite indoor PV devices, which pose challenges in stability and large-scale fabrication [1,2]. This study demonstrates that carbon-based electrodes, with their potential to offer a viable, low-cost alternative without compromising performance, could transform the field. We further explore the impact of interfacial engineering by optimizing the interlayer material, highlighting its role in mitigating recombination losses and improving device efficiency. Comparative analysis between devices with gold and carbon electrodes reveals that addressing high series resistance and interface charge accumulation is key to achieving competitive efficiencies with carbon electrodes.

Additionally, we present a practical demonstration of carbon-based perovskite mini-modules (~1 cm²) successfully powering a temperature sensor in indoor conditions. This demonstration showcases the potential of carbon-based electrodes for real-world applications and inspires further research and development in the field. The stability and scalability advantages of carbon electrodes make them a promising pathway for developing cost-effective, sustainable power sources for IoT sensors [3]. This work underscores the importance of integrating material innovations and device engineering to advance the next generation of efficient indoor energy-harvesting technologies.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

ZnO nanorod hemispherical light scatters for thin film solar cell applications

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Compared with the planar transparent conducting oxides (TCO), the highly oriented zinc oxide (ZnO) nanorod (NR) arrays not only can provide abundant surface area for binding absorbers, but also exhibit enhanced electron transport due to the increased direct electron conduction and minimized recombination. Additionally, the path length of light is increased and thus light interaction with the absorber is enhanced due to light scattering of the ZnO NR arrays [1].

In this work, we investigated the impact of solution processed seed layers on the morphology of ZnO NR arrays and their subsequent light scattering properties for thin film solar cell applications. In this study, two types of aluminum-doped zinc oxide (AZO) seed films with different thickness are deposited using slot-die coating. We define the thin seed film as Sample A with thickness of ~100 nm and thicker seed layer as Sample B with a thickness of ~300 nm. An AZO seed film with a thickness of ~100 nm fabricated from traditional vacuum PVD technique was used as a reference and labelled as Sample C. ZnO NR arrays have been successfully fabricated on all three types of seed films using the identical chemical bath growth conditions. However novel hemi-spherical structures have been formed in sample A as shown in Figure 1a, with ZnO NRs grown on and aligned into neighboring NR hemispheres. Based on XRD analysis, we found that lattice shrinkage along c-axis of ZnO NR generates tensile stress and lifts up seed films to form the arched structures.

The light scattering properties of ZnO NR arrays are then studied using optical haze measurements. Sample A, which has the semi-hemispherical light scatters, exhibits a much higher haze throughout the whole spectral range and reaches a maximum valve of 0.92 at a wavelength of 380 nm. We then explore the scattering properties of these ZnO NR samples and understand the light scattering mechanisms with the assistance of COMSOL simulations as shown in Figure 1b. We found the scattering of the primary rays is mostly governed by total internal reflection, with some rays refracted through the walls of neighboring NRs.

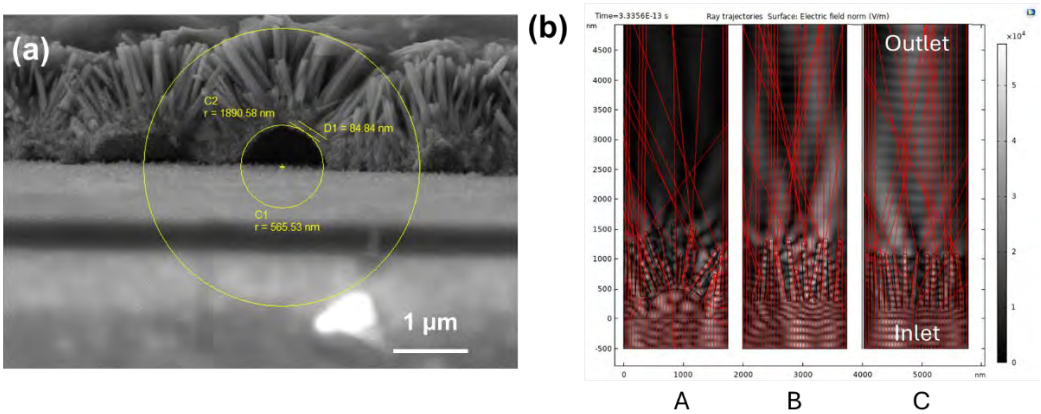

Figure 1 (a) Hemi-spherical structures in sample A; (b) Ray trajectories of sample A-C simulated at 380nm wavelength. The geometry models are built based on SEM images where sample A has semi-hemispherical light scatters with an arch diameter of 1200 nm; sample B has a 300 nm thick seed layer and sample C has a 100nm seed layer. NRs are 1000 ±100 nm long and 85 ±15 nm wide and at random angles relative to seed film. Rays were incident from the inlet port at the bottom of the simulation domain and exit from top outlet port.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Deposition and Characterization of RF Magnetron Sputtered High Mobility ITiO for PV Devices

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Transparent conductive oxides (TCOs) are a key part of photovoltaic devices as they allow for light to be transmitted into the absorber, whilst also collecting the generated charge carriers at the front contact [1, 2]. Currently the thin film PV industry mainly uses fluorine-doped tin oxide (FTO), due to its stability and low manufacturing cost. However, the optical and electrical properties of FTO are not as good as alternatives, such as those based on ZnO and In_2O_3, which typically have higher conductivity and higher transmission. In particular, FTO can suffer from high free carrier absorption which reduces the transmission at wavelengths greater than 750nm, and so alternatives should be explored. In particular, titanium-doped indium oxide (ITiO), which is a high mobility TCO and has very high IR transmission may be a viable alternative to FTO for use in thin film solar cells [3].

This study explores the deposition of thin film ITiO using Radio Frequency magnetron sputtering to achieve high mobility, high transmission, low resistivity, and a uniform deposition of the material. A detailed comparison of electrical, optical, and structural properties between ITiO and FTO shows that ITiO has comparable qualities with FTO and performs better in certain categories. Key findings from these comparisons are the higher mobility ($72.72 cm^2V^{-1}s^{-1}$), carrier concentration ($6.361\times10^{20} cm^3$), and transmission in the near-infrared spectrum. . The stability of ITiO was also investigated using damp heat and UV exposure. These tests indicate that ITiO has comparable stability to FTO.

The significance of this work lies in the potential for ITiO to increase single junction device efficiencies through its high mobility, carrier concentration, and high optical transmission. It also has potential advantages in tandem solar cells.

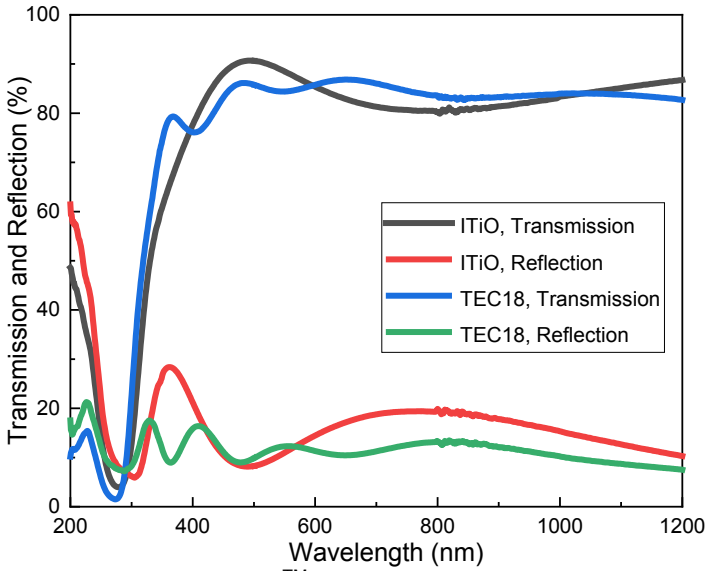

Figure 1. Transmission and reflection of TEC^{TM}18 and ITiO with similar sheet resistance.

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Indoor, space, Agri-PV, vehicle and other applications and new concepts in photovoltaics

Optical dependency characterization of semitransparent solar module for Agrivoltaics

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Agrivoltaics is a concept that negates infringement of solar installation onto agricultural land to promote SDG 2 (zero hunger), 7 (affordable clean and clean), and 13 (climate action). It offers the strategic benefit of cultivating biomass and power concurrently on the same land [1, 2]. However, in widely available conventional PV technologies comes with opaque backend that prevent light or casting shadow on plants underneath it, which might be at the expense of some biomass production [3]. Study lettuce biomass in Montpellier (France) shows 15–30% less than the full-sun conditions [4, 5]. Study of tomatoes in Japan showed about 10% less than conventional agriculture method [6].

Photosynthetic pigments in plants such as Chlorophylls, carotenoids, and anthocyanins have varying absorbed peaks electromagnetic spectrum and similarly the semitransparent PV modules have different absorption spectra [3]. Achieving concurrent optimal yield of both agriculture and solar photovoltaic installation requires examining, understanding and aligning the individual photonic influx demand.

This research investigates optical transmittance, spectral response, and photosynthetic active radiation of a semitransparent CdTe module for agrivoltaics application. A CdTe with 200 x 200 mm dimension was exposed to spectral response characterization using IPCE device. An Avantes spectrometer AvaSpec-ULS4096CL-EVO was employed to examine the optical transmittance of a CdTe module considering 10 mm^2. Similarly, the module was exposed under Wacom solar simulator, where a Danoplus PAR Meter IP68 Quantum Sensor and PPFD Meter Data Logger was employed under the CdTe module to measure the photosynthetic active radiation. PAR value was validated using a Seaward solar survey 200R that was employed concurrently to determined irradiance at a point intended for measurement.

The results shows that the spectral response of the CdTe module ranges from around 300 to 900 nm which aligns with theoretical evidence previously reported. The optical transmittance shows 18% to 21% transmittance across the module. PAR value was recoded above the module shows an average rate of 2001 $\mu mol/m^2/s^{-1}$ while the PAR value recorded underneath the module shows an average rate of 207 $\mu mol/m^2/s$ across similar points of the module. The average irradiance measured above the module shows about 1001 W/m^2, while the one underneath the module is about 108 W/m^2.

The finding shows that transparent module such as CdTe could reduce excess influx that are not required for biomass development. The proportion of the number photon absorption varies with plant, the percentage of transparency CdTe could be adjusted to suit the requirements particular group of plants.

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Indoor, space, Agri-PV, vehicle and other applications and new concepts in photovoltaics

Enhancing Non-fullerene Organic Photovoltaics Performance via Prethermal Treatment: Interface Morphology Optimization and Trap Suppression

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With the world's growing population, the demand for food and electricity is increasing rapidly. To meet these demands, agricultural and energy sectors need to work together to achieve sustainable development. Agrivoltaics is one of the promising approaches that combines the production of crops and renewable energy generation in the same land footprint. However, the use of conventional opaque solar panels in agrivoltaic systems creates shading effects, being unable to share the solar spectrum, given that plants absorb only >1.7 eV photons whilst silicon (or other inorganic) solar cells absorb all photon energies above the near IR. To overcome this issue, low-cost semi-transparent photovoltaic modules produced using ambient scalable manufacturing offer an exciting alternative. Such cells enable wavelengths between 400 and 700 nm, which is referred to as photosynthetically active radiation (PAR) to pass through to the crop. Thus, Organic Photovoltaics (OPV) have gained significant attention due to their ability of harnessing photons in the near-infrared and ultraviolet spectra while allowing visible light to pass through, providing high transparency.

The current state-of-the art power conversion efficiency (PCE) of OPVs exceeds 20% for a single junction OPV[1] and reaches 11% for semitransparent based OPV devices[2], following rapid improvement in recently developed non-fullerene small-molecules acceptors (NFAs) to replace fullerene-counterpart. High potential PCEs are offered by the active layer morphology that play a crucial role that critically influences the performance of the NF-OPVs. These factors mainly control the exciton binding energy and diffusion length to avoid the undesirable static disorder that exhibits intrinsic sources of traps in the devices and in turn affecting the overall performance.

Upon these contexts, several optimization strategies were performed to control the phase morphology of the photoactive layer of the NF-OPVs[3]. Thermal treatment is one of the effective avenues conducted to tune the bulk and interface morphologies to perform an efficient charge separation at the donor/acceptor interface[4]. Accordingly, in the present work, we report pioneer remarkable enhancement in the generated current density (J_{SC}) of 32.62 mA cm^{-2} with a maximum PCE of 17.92% for the optimized single junction NF-OPVs by introducing pre-thermal treatment approach (Pre-TT). Our findings obtained that the Pre-TT approach diminishes the traps and enhances the interface charge transfer through enhancing the carrier dynamics of the treated devices, initiating an effective approach for boosting the J_{SC} along with the PV performance, making the treated device highly promising for agrivoltaic system integration.

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Synthesis and characterization of Ce doped $BaSnO_3$ for performance enhancement of concentrated perovskite solar cells

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Abstract

Barium stannate oxide ($BaSnO_3$, BSO) has been investigated as a promising alternative n-type material for perovskite solar cells (PSCs) due to its unique perovskite structure, optical and electrical properties along with chemical photostability [1]. This work aims to develop a novel electron transport material to improve charge transportation, photostability, and the performance of PSCs under varying light intensities.

Herein, BSO was doped with Ce with different molar concentrations using a facile wet chemical co-precipitation method to enhance the optical and electrical properties. Two different deposition methods: screen printing and spin coating were used for Ce doped BSO thin film coating. The morphology, optical, and electrical properties are studied using SEM, UV-vis spectrometer, and four prob, respectively. The initial result reveals that the Ce doped BSO samples possess an ideal bandgap, excellent optical transparency, and good electrical conductivity making them a suitable choice for use as an electron transport material for PSCs.

In this study, theoretical analyses were conducted using the SCAPS software based on the experimental parameters observed for Ce doped BSO. Figure 1 illustrates that the current density increases linearly with varying light concentrations (1x to 10x), highlighting opportunities to enhance experimental performance. Research is currently going on with different coating methods to understand the experimental efficiency and the barriers between theoretical and experimental performance for Ce doped BSO. This research is useful for understanding the light stability, durability, and functional performance of the Ce doped BSO electron transport material, its applicability in real-world PSC applications, and its possible limits under extended sun illumination.

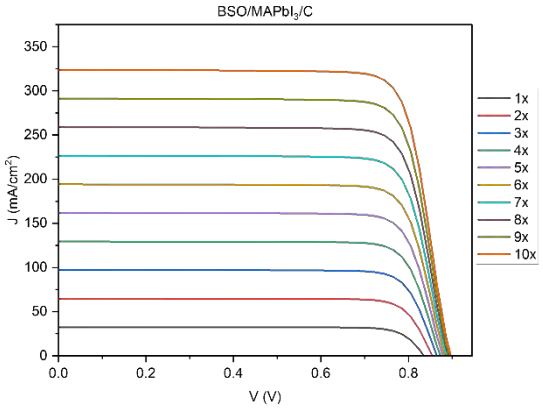

Figure 1: Current density variation of BSO/$MAPbI_3$/C concentrated PSC for varying light intensity.

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Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Mind the sub-gap: exploring the impact of sub-gap features on the thermodynamics of disordered photovoltaics.

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Photovoltaic performance is limited by the radiative limit and reduced by the non-radiative losses of the absorbing semiconductor. The reciprocity theorem suggests that 'a good solar cell acts as a good LED' allowing for the quantification of these limits. However, the electronic states that occupy the energetic region below the bandgap (the so-called sub-gap region) are overlooked in most analyses leading to solar cells and LEDs that are not transposable.

In this talk I will present a body of work designed to measure and comprehend the consequences of the sub-gap absorption features in solar cells. First, I will describe how to perform so-called ultra-sensitive external quantum efficiency measurements with a dynamic range of 100 dB [1]. Then I will describe how interpreting these results properly can preserve reciprocity and predict the PV-limits of any semiconductor. Then I will show how these measurements can lead to insight into equilibrium and non-equilibrium species, energetic disorder[2], low-Q cavity effects[3], and structural order[4]. Although this talk will utilize molecular semiconductors as an exemplary system, the experiments and insights are generalizable to any semiconductor system.

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Indoor, space, Agri-PV, vehicle and new concepts in photovoltaics

Building Integrated Photovoltaics (BIPV): A Comprehensive Review of Architecture, Technical Advancements, Lifetime Cost and Industrial Progress

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Building integrated photovoltaics (BIPV) is rapidly gaining popularity as a prominent means of electricity generation. While silicon-based solar cells have been the traditional choice for BIPV applications, recent developments in thin-film solar cells have garnered significant attention. The incorporation of solar PV modules into building envelopes have given rise to the concept of near zero-energy buildings, which has attracted global investment in BIPV. Presently, researchers and industrial players are focused on enhancing the performance, stability, and compatibility of BIPV modules with building aesthetics in mind. This study presents a comprehensive review of BIPV, covering its historical evolution, recent developments, currently installed capacity and projection of future growth in this sector. The paper also covers technological advancements of technical as well as mechanical BIPV components and the architectural aspect of integrating solar photovoltaic technologies in buildings. Moreover, the feasibility of installation of BIPV systems is investigated by assessing detailed life cycle cost analysis, presenting the cost of different BIPV components, different BIPV products available in the market and key manufacturers of these products.
The review also explores various BIPV module configurations for integrating PV systems and retrofitting techniques in conventional buildings for renovation. The study presents brief overview of advantages of BIPV, current challenges in BIPV market and prospects for further progress in this sector. Thus, this holistic study aims to summarize the advancements in BIPV sector, the viability of integration of PV products in buildings and prospects of growth of BIPV sector.

Ambient and Solution Processable Organic Photovoltaic for Indoor Application

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With the advancement of the Internet of Things, the requirement of indoor photovoltaics is gaining attention to powering low-power-consumption electronic devices using indoor light harvesting. Traditional inorganic photovoltaics suffer from absorption spectrum mismatch, low performance, high cost, rigidity, and incompatibility while integrating with small devices. [1] Whereas, Organic Photovoltaics (OPV), due to their unique properties like flexibility, lightweight, tunable absorption, and ability to perform well under indoor light, shows promising low-cost photovoltaic technologies for indoor applications. [2] Recent developments in OPV's material and device engineering have delivered power conversion efficiency (PCE) up to 29% under 500 lux LED indoor light.[3] Before commercialization, the following issues must be addressed: OPV fabrication under ambient conditions, all layers should be solution-processable, and photostability should be improved. In this work, we have addressed those issues; the device fabricated using PTQ10: FCC-Cl as a photoactive layer under ambient maintained a similar performance (PCE~ 27%, under 1000 lux LED light) as fabricated inside the glovebox. Furthermore, we introduced BM-HTL as a solution-processable hole transport layer (HTL) to gain an all-solution processable layer OPV device structure (inverted). Photostability using solvent additives and changing HTL materials have been studied. BM-HTL-based OPV device maintained 99% and 97% of open circuit voltage (Voc) and fill factor (FF), respectively, under 1000 lux (LED) one month duration.

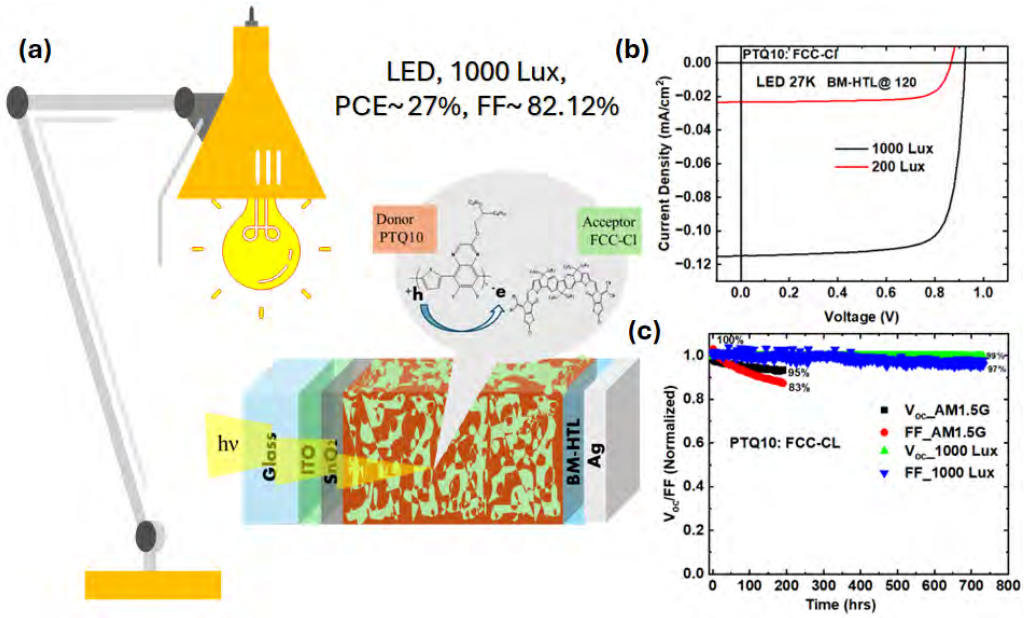

Figure 1 a) Demonstration of OPV device under indoor light. (b) J-V characteristics of BM-HTL based OPV device measured under 1000 and 200 lux indoor light. (c) Normalized photostability data (V_{oc} and FF) measured under 1 Sun and 1000 lux LED light.

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Encapsulation of perovskite devices using UV-curable ink jetted materials

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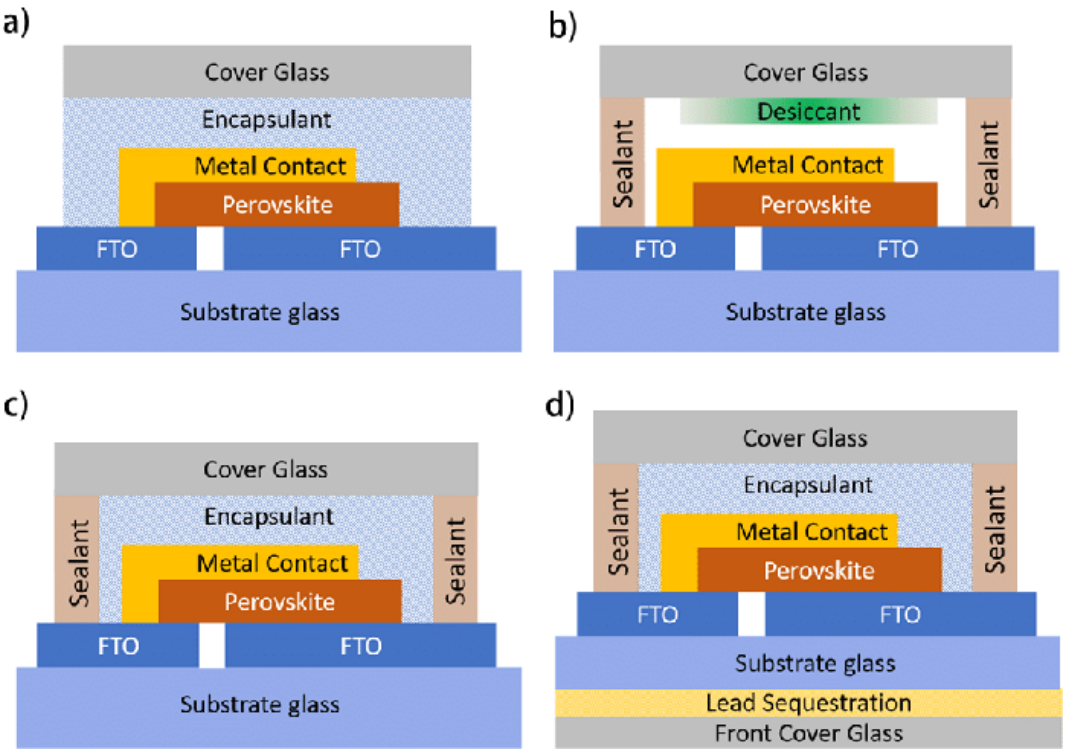
In the emerging field of perovskite solar cells, stability and reliability are key challenges that need to be addressed in order for this technology to achieve commercial viability. Manufacturing methods which can enhance stability as well as having good scalability for production are a key and necessary step towards future commercial success. One such technique that has both good scalability, as well as great flexibility in the application and type of the encapsulant, is inkjet printing. As such, this work investigates different materials for use with perovskite PV mini-modules, primarily using easy to cure UV-encapsulants. These are being tried out using a variety of encapsulation arrangements such as those shown in Figure 1 below. The aim of this work is to deliver scalable and highly efficient packaging options for perovskite PV technologies, improving reliability and accelerating future deployment in the field.



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Conference Topic: Characterisation, testing and performance measurements for photovoltaic materials, devices and modules

Proton Radiation Hardness of Solar Cells and Ion Beam Analysis Investigation by Experiments Performed using particle accelerators

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Environmental conditions are of growing concern as large populations are affected by climate change and pollution, an estimation of millions of people worldwide are dying from lower air quality [1]. Photovoltaic and other green power source are not totally free of emission or pollution, initiatives to improve the design and fabrication are underway to solve those issues [2]. At the Surrey Ion Beam Centre, we have the characterisation technique available to study materials and impurities at extremely low concentration, i.e., content of animal protein level and below [3], also we have investigated Argon contamination of photovoltaic devices stored in an Argon atmosphere glove box. The other aspect of reducing pollution is also in determining the life expectancy of the devices. Knowing the life cycles can help optimising and reducing the number of devices and thus pollution. When designing spacefaring vehicles, the onboard systems such as microelectronics and solar cells require shielding to protect them from degradation brought on by collisions with high energy particles such as protons. At the Surrey Ion Beam Centre, we can irradiate with protons of various energy into solar cells [4,5]. By changing the fluence we can simulate the length of time solar cells are exposed to protons. Allowing us to simulate ageing of solar cells in hours rather than years in space, saving both time and money. In this presentation, we will show the strength of Ion Beam Analysis (IBA) technique with examples on photovoltaic devices and the advantages of Ion Beam irradiation and the methodology to assess potential life expectancy illustrated by both Perovskite solar cells utilizing a mesoporous carbon electrode or an aluminium doped zinc oxide electrode [4,6].

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Complex formation of ferrocene derivatives with electron-transporting layers enables improved performance and photostability in organic solar cells

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Organic solar cells (OSCs) are gaining tremendous attention as promising green energy technologies, propelled by designing and developing photoactive materials, i.e. polymer donors and non-fullerene acceptors (NFAs), the power conversion efficiency (PCE) of OSCs have exceeded over 20%.[1] Apart from photo-active materials, electron-transporting layers (ETLs), e.g. metal oxides, organic small molecules, or conjugated polymers, play a vital role in both performance and photo-thermal stability in organic solar cells through tuning the work nm function of electrodes, establishing better Ohmic contacts and increasing charge carrier selectivity. Herein, we explored hybrid organic-inorganic electron transport materials by forming charge transfer (CT) complexes between typical polymer electron transporting layers and newly synthesized ferrocene (Fc)-based derivate, namely ferrocenyl-bis-furyl-2-ketone ($FcFk_2$). Optoelectronic measurements and DFT calculations revealed *Van der Waals interaction* between the components, which modifies the work function of Ag electrode from -4.50 eV to -4.03 eV, improving charge extraction properties and reducing trap-assisted recombination. Furthermore, this strategy leads to improved fill factor (FF) and power conversion efficiency from OSCs for five donor:acceptor blend systems and three ETLs, with FF and PCE exceeding 80% and 19.7% for PM6:D18:L8-BO system, respectively. Additionally, we demonstrated improved photostability for the hybrid ETLs with devices that retained 80% of their initial performance when degraded under operating conditions (ISOS-L-1I) for over 700 hours.

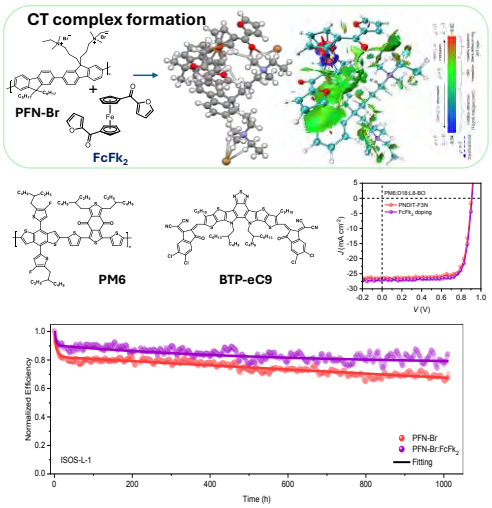

Figure 1 Schematic illustrates the mixing between PFN-Br and Fc-derived molecules; the chemical structures of PM6 and BTP-eC9; *J-V* characteristic curves under AM15G illumination; long-term stability obtained by MPP tracking under 100 mW cm^{-2} illumination within a N_2-filled chamber.

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Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Combining Machine Learning with Physics-based Models for Day-Ahead Solar Forecasting

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This study presents a hybrid forecasting approach for day-ahead solar power and energy prediction by integrating machine learning models, such as Gaussian Processes, with a deterministic physical model chain. Solar energy prediction optimizes photovoltaic (PV) system performance by enabling cost-effective energy distribution and utilization based on the anticipated solar production. Generally, forecasting methods are classified as short-term, medium-term, and long-term based on the forecast horizon. Medium-term and long-term predictions typically have week and month-ahead forecast horizons, which are used for management control in PV power plants, while short-term forecasting is used to predict hours to day-ahead solar power output in household settings due to its ability to capture time-varying behavior more reliably and manage variable power loads. However, there remains a need for accurate short-term prediction models with improved resilience to sudden environmental changes and system-specific anomalies.

Solar power predictions may be forecasted directly from a range of machine learning predictors or calculated using irradiance forecast data produced by numerical weather prediction or sky imagery. Calculation methods can be classified into physical, statistical, or hybrid approaches [1]. Physical methods use bottom-up approaches, such as irradiance-to-power conversion models and electrical simulation models, to calculate the output power of a PV system. However, they are sensitive to the model setup and parameters. In contrast, statistical methods are data-driven, including both classical statistical modelling and novel machine learning algorithms. However, the performance of these is highly dependent on the amount and quality of training data available, and their accuracy is limited without several years of historical data [2]. Hybrid approaches provide a more accurate solution by combining the above approaches to consist of two or more different methods.

Our proposed hybrid model enhances prediction accuracy by addressing variability and systemic losses often overlooked by traditional physical models. Using 5-minute data from a residential PV site, the Gaussian process-enhanced forecasts effectively capture inherent fluctuations in solar power due to environmental factors and system-specific characteristics such as panel and inverter configuration. Consequently, this model exhibits lower mean absolute error and root-mean-squared error compared to various purely statistical models used, such as naïve forecasting, ARIMA, Random Forest, and XGBoost, as well as a physical model for direct PV power forecasting. This research underscores the efficacy of integrating machine learning techniques with physical models, further improving the cost-saving and environmental benefits of solar power usage in household settings.

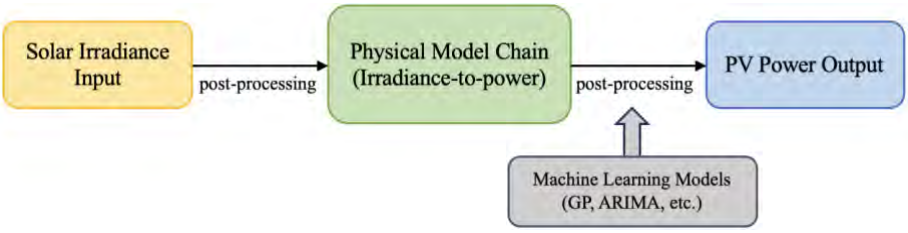

Figure 1 a) A schematic diagram of the proposed hybrid model

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Evaluating Biochar-Based Carbon Electrodes in Printed Mesoscopic Perovskite Solar Cells

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Triple-mesoscopic carbon perovskite solar cells (mCPSCs) have drawn significant attention due to their unprecedented stability, inherent scalability, and potential for cost-effective production [1]. This study explores the application of biochar as a sustainable and low-cost material for carbon electrodes in triple mesoscopic stack perovskite solar cells. Various biochar samples derived from agricultural and forestry waste were tested, focusing on their structural, electrical, and morphological characteristics.

Biochar is a charcoal-like substance, produced by heating organic biomass in the absence of oxygen (pyrolysis) to make it carbon rich and chemically-stable. The use of biochar offers several advantages over conventional carbon black. It is a carbon-negative material that not only sequesters CO_2 but also reduces the carbon footprint of PSC manufacturing. It utilises abundant, low-cost waste resources such as food waste and wood chips, promoting a circular economy by transforming organic waste into high-value materials (Figure 1). Unlike carbon black, biochar properties can be tailored by adjusting feedstock and pyrolysis conditions, enabling better porosity and conductivity [2]. These features make biochar an eco-friendly alternative with the potential to enhance device performance and stability.

This research demonstrates the viability of biochar-based carbon electrodes to advance sustainable photovoltaics, paving the way for scalable and eco-friendly alternatives in next-generation solar technologies.

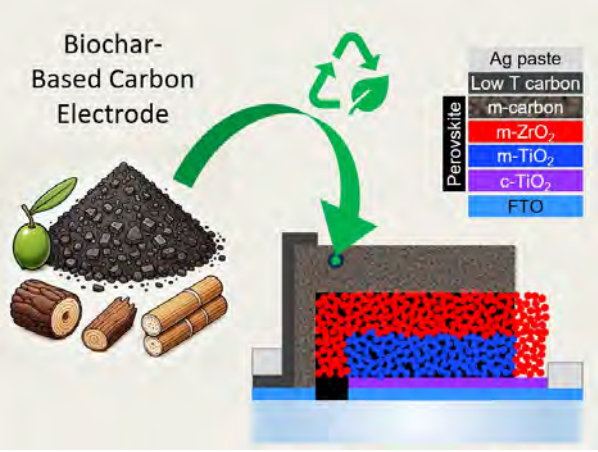

Figure 1. Integration of various biochar samples derived from agricultural and forestry waste into solar cells to improve sustainability in the photovoltaic industry.

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Enhancing Energy Estimation for Floating Photovoltaic Systems Using Machine Learning Techniques

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Despite the growing adoption of floating photovoltaic (FPV) systems, the integration of meteorological data with technical parameters for precise energy output estimation remains underexplored. This study employs Long Short-Term Memory (LSTM) networks and eXtreme Gradient Boosting (XGBoost) machine learning techniques to enhance the accuracy of FPV energy production estimates, benchmarking their performance against the industry-standard PVlib Python library[1]. Using meteorological data—including Global Horizontal Irradiance (GHI), module temperature, relative humidity, albedo, and wind speed—we analyze the influence of these features on power output predictions. Results (Fig 1) reveal that GHI has the most significant impact, followed by module temperature, relative humidity, albedo, and wind speed. As shown in Table 1, both models achieve high predictive accuracy, with R^2 values exceeding 99%, mean absolute error (MAE) around 30, and root mean square error (RMSE) approximately 83, which is better than the estimation result from PVLIB python result, as MAE is 77.68, and RMSE is 171.17. When compare two machine learning modules, LSTM demonstrates superior performance on time-sequential, minute-resolution data, while XGBoost performs effectively with fewer input features. Model evaluation under varying weather conditions indicates enhanced accuracy on clear and stable days, with reduced performance during variable weather.

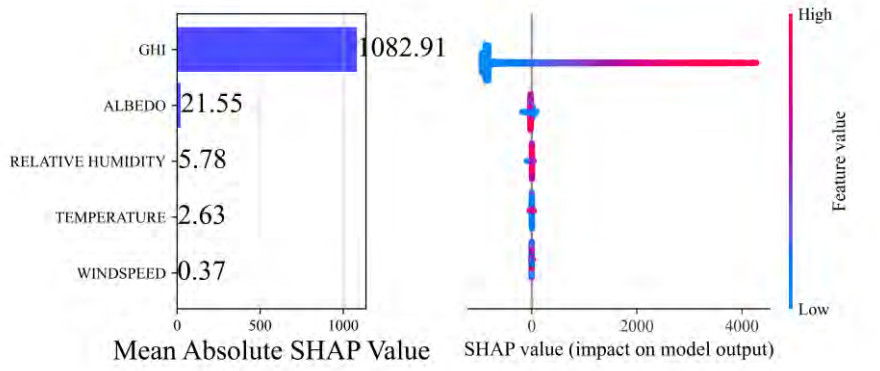

Figure 1 Estimation SHAP result for different parameters when using XGBoost

Table 1 The comparison of power production estimation result based on XGBoost, LSTM, and PVLIB

	XGBoost	LSTM	PVLIB
MAE	30.01	28.05	77.68
RMSE	81.22	83.48	171.17
R2	99.650%	99.630%	98.479%

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Perovskite Printing for Flexible Thin-Film Microgroove Modules

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Over the past decade, perovskite solar cells (PSCs) have garnered significant attention within the photovoltaic (PV) industry, progressing rapidly from concept to high-performance modules. Compared to traditional PV technologies, PSCs offer exceptional properties, including tunable band gaps, high absorption coefficients, large dielectric constants, and low production costs (1). Advances in solution processing have further enabled the development of thin-film, roll-to-roll (R2R) manufacturing. While planar architectures dominate thin-film PSC research, Power Roll's innovative microgroove technology (2) (*Figure 1*) represents a paradigm shift.

Power Roll has pioneered a fully R2R production process based on their novel architecture. This involves embossing microgrooves onto a flexible substrate, followed by directional deposition of electrodes and charge transport layers on opposite faces of each groove. R2R perovskite deposition and encapsulation finish the PV modules in a highly scalable low-cost manufacturing process.

This work focuses on improving the perovskite composition and deposition process for a scalable, stable and high-efficiency module production.

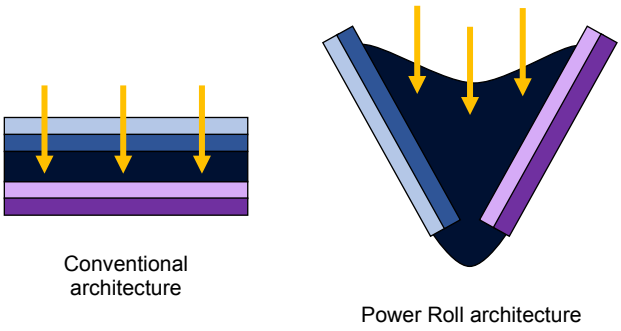

Figure 1. Schematic of the conventional perovskite solar cell architecture (left) and Power Roll architecture (right).

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Photovoltaic systems, solar irradiance and monitoring, policy, sustainability, market development and life cycle analysis

Accurate Yield Modelling of a Semi-transparent Façade Agri-PV System

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Accurate modelling of photovoltaic (PV) systems is vital for the PV industry, in order to predict the yield, evaluate the performance and define the financial aspects of PV systems. Many models and software packages are available, which vary in terms of accuracy and have different advantages and disadvantages. The development of building integrated PV (BiPV) and agri-PV systems creates new challenges for PV modelling, especially when new technologies are used such as bifacial PV modules or semi-transparent products. Integration into such systems also affects the PV module temperature [1] and amount of light they receive. The above create significant challenges in modelling of BiPV and agri-PV systems, which is a limitation for such PV deployment routes.

In this work, an agri-PV system consisting of semi-transparent PV modules, installed at an agriculture glasshouse was studied. PV modules of the same type were measured in the lab at NPL to accurately determine model inputs (bifaciality, linearity, angular response), sensors were installed on-site, and the PV system was modelled using three different models, PVsyst, Pvlib and PVGIS. Actual energy yield of the system was compared to the modelled yield. On-site temperature and irradiance measurements were acquired and used in the models, in order to evaluate the most accurate modelling configuration.

Irradiance modelling was found to be the most important factor, particularly due to the building integrated nature of the PV system. In PVsyst, it was possible to calculate shading on the modules, as well as electrical mismatches between modules. PVlib had good electrical and irradiance transposition models but did not consider shading therefore only performed better than PVsyst when on-site measured irradiance was used. PVGIS was found to be the worst performing modelling resource, showing poor correlation with the measured data. Its main limitations were its weather files not being updated to reflect recent weather and its simplified model, using a singular fudge factor to determine all power losses in the whole system. PVlib and PVsyst were able to get within 7.1% and 2.4% of the actual energy yield respectively.

The results of this work have provided useful insights about modelling BiPV and Agri-PV systems to the industry, which is a crucial step to build confidence and accelerate such deployment routes.

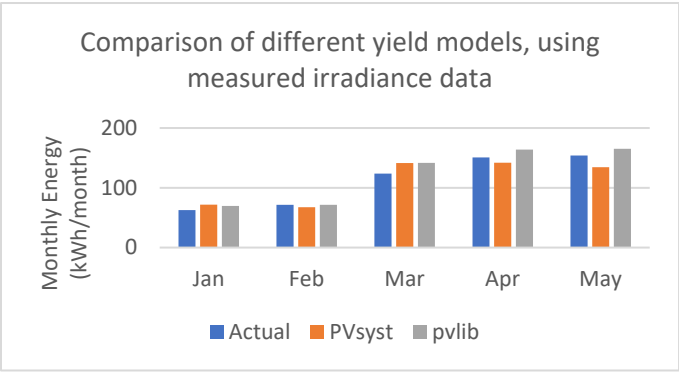

Figure 1 Left: A comparison of the models pvlib and PVsyst against measured energy yield using onsite measured irradiance data as an input. Right: The façade PV system studied.

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Indoor, space, Agri-PV, vehicle and other applications and new concepts in photovoltaics

Understanding the growth kinetics of $MAPbI_3$ thin films on metal oxide vs organic semiconductor charge extraction layers and their indoor photovoltaic properties

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Halide perovskite solar cells are a promising alternative for indoor photovoltaics (IPVs). To take advantage of perovskite's excellent optoelectronic properties, highly tunable optical bandgaps, and simple affordable processing, it is necessary to develop strategies to maximize the power conversion efficiency of IPVs. However, at low intensity from indoor light sources the photoactive perovskite layer does not benefit from the light-induced trap filling and leads defect-related performance losses [1]. This requires improved uniformity of both surface and interface morphology to maximize power conversion efficiency under such conditions.

This poster reports the growth kinetics of $MAPbI_3$ thin films on different metal oxide and organic semiconductor based hole transport layers (HTLs) and the corresponding photovoltaic performance. To understand the influence of different types of transport layers on the halide perovskite films, we investigated the effect of the HTLs on the growth kinetics using synchrotron radiation grazing incidence wide-angle X-ray scattering (GIWAXS). This is a powerful technique for studying the crystalline properties of polycrystalline halide perovskite thin films.

Ex-situ angle-dependent GIWAXS was performed to obtain information on both the surface and bulk regions of the halide perovskite thin films. By varying the angle of incidence, we obtained signals from selected depths. Four different angles were probed 0.1°, 0.2°, 0.5° and 1.0° corresponding to a penetration depth of 3 nm, 7 nm, 200 nm, and 300 nm, respectively, covering both the surface and buried interface. Even though the photovoltaic performance of the organic semiconductor HTL based devices outperformed the metal oxide ones -NiOx & CuOx under both 1 sun and indoor illumination, the crystal structure quality and lattice strain contribution of the $MAPbI_3$ thin films are found to be minimal for this performance disparity [2].

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Advancements in Solar Spectral Irradiance Modelling for Photovoltaic Systems: A Machine Learning Approach Utilizing On-Site Data

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6 January 2025)

In the field of photovoltaics (PV), radiative transfer models (RTMs) and spectroradiometers are commonly utilized to determine spectral solar irradiance, which is crucial for assessing spectral effects. However, these methodologies have inherent limitations; RTMs necessitate precise and complex inputs of aerosol and meteorological data, while spectroradiometers entail significant costs. With the advancement of ML techniques, a data-driven spectral irradiance model is proposed in this study, which only requires GHI measured by pyranometer and reference cell as inputs. Spectral data and meteorological data collected by SERIS at 4 sites across three continents are used for the training and testing of our models. As shown in Fig.1, an exploratory data analysis was performed for statistical measure of the different parameters to better utilize the computational resources, reduce complexity, and gain a better understanding of the feature-to-target relations. We examined the viability on spectra modelling of three machine learning (ML) techniques, including Long Short-Term Memory networks (LSTM), Random Forest (RF) algorithms, and Extreme Gradient Boost (XGBoost). XGBoost achieves relatively good accuracy; additionally, the computational cost is much lower as compared to LSTM and RF. As shown in Fig.2, the proposed ML model shows an overall R2 of 0.974 in comparison to 0.646 of the SMARTS model in the spectrum range 350.4 nm to 1052.4 nm. The ML models outperform the SMARTS model particularly under intermediate and overcast conditions, as shown in Fig.3. We have also shown that a model trained on data from a specific site cannot be effectively applied to other locations. The versatility of the model needs to be improved in future works.

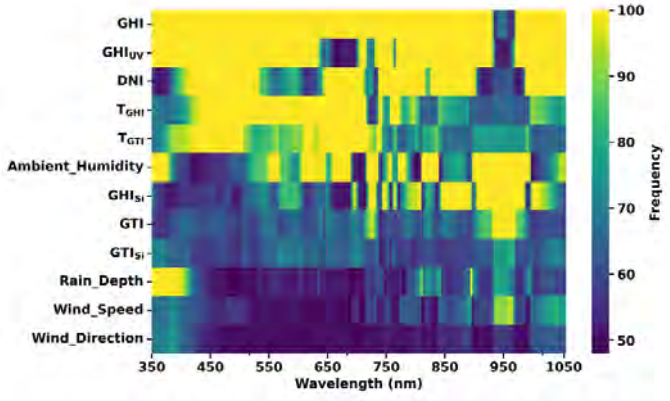

FIG. 1. Feature frequency against wavelength

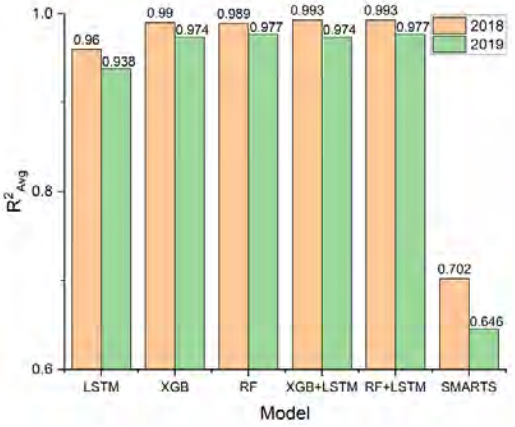

FIG. 2. Model comparisons

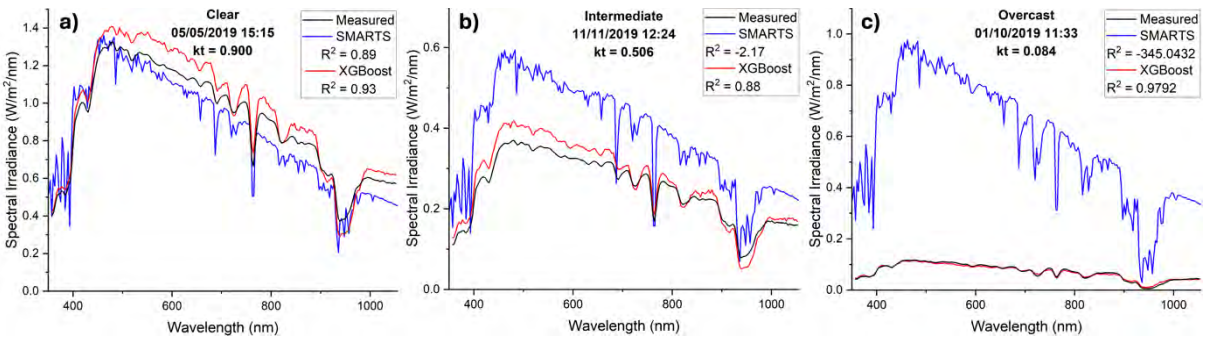

FIG. 3. Comparisons between SMARTS model and XGBoost model

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