ANNUAL REPORT 2025

SERIS is a research institute at the National University of Singapore (NUS). SERIS is supported by NUS, the National Research Foundation Singapore (NRF), the Energy Market Authority of Singapore (EMA) and the Singapore Economic Development Board (EDB).

SOLAR ENERGY RESEARCH INSTITUTE OF SINGAPORE

SERIS

Vision

A leading solar energy research institute in the world, contributing to global sustainable development

Mission

To develop and commercialise solar technologies suited for urban and tropical applications, and support industry development and the energy transformation towards higher solar adoption

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Feedback from Key Stakeholders

National University of Singapore (NUS)

SERIS continues to be a beacon of innovation within the NUS research community, consistently pushing the boundaries of what is possible. This year, their research into the synergy between solar panels and green roofs has provided an elegant and powerful solution for enhancing energy generation in land-scarce cities like Singapore. Their landmark achievement in developing high-efficiency perovskite-organic tandem solar cells also further highlights the institute's leadership in cutting-edge solar technology.

Professor LIU Bin, Deputy President (Research and Technology), National University of Singapore (NUS)

National Research Foundation Singapore (NRF)

Over the years, SERIS has been instrumental in advancing Singapore's solar energy landscape. From developing high-performance solar cell technologies with world-class efficiencies to promoting solar deployment in our urban environment, SERIS has demonstrated exceptional leadership in solar innovation and research. Their success in translating cutting-edge research into practical applications showcases how R&D investment strengthens Singapore's sustainable development.

Mr NI De En, Director (Urban Solutions & Sustainability) of the National Research Foundation Singapore (NRF) and member of the SERIS Supervisory Board

Energy Market Authority (EMA)

SERIS has been a key driving force in Singapore's energy transition journey. Their efforts to facilitate innovative deployments such as vertical and floating solar, and to support the Singapore Government in deployment planning and technical assessments have been crucial in helping us achieve ambitious solar deployment targets.

Mr LOW Xin Wei, Assistant Chief Executive, Energy Market Authority of Singapore (EMA) and member of the SERIS Supervisory Board

Singapore Economic Development Board (EDB)

SERIS is a critical element in attracting new players to Singapore's solar ecosystem. With its unique R&D capabilities and world-class results, the institute opens doors for companies across the solar value chain, ranging from manufacturers (aiming to improve solar cell efficiencies or venturing into tandem solar cells) to technology providers (trying to better understand their performance in tropical or urban environments) and investors (aiming to de-risk novel technologies). SERIS also regularly engages in industry capability building through targeted workshops, symposia, and standards development meetings, enhancing the capabilities of professionals in the solar industry.

Ms Josephine MOH, Senior Vice President and Head, Energy and Renewables, Singapore Economic Development Board (EDB), and member of the SERIS Supervisory Board

CEO's Foreword

Prof Armin ABERLE
SERIS CEO, 19 Dec 2025

This year marks the 10th anniversary of the Paris Climate Agreement. Global temperatures have continued their relentless rise since then: the past decade are the 10 hottest years on record, according to the World Meteorological Organisation. Climate action is therefore becoming more urgent with each passing year. Many countries, including Singapore, are responding to this accelerating crisis by decarbonising their energy systems and committing to net-zero by 2050.

Solar photovoltaics (PV) are a central part of the energy transition, now supplying more than 7% of global annual electricity, and their share is set to grow rapidly as PV leads global power capacity additions. Global installed PV capacity (direct current, DC) is expected to exceed 6 terawattpeak (TW_p) by 2030, up from about 2.5 TW_p at the end of 2025.

Singapore is a signatory to the Paris Agreement and has committed to achieving net-zero emissions by 2050. The nation's "Energy Story" outlines four supply switches - natural gas, solar PV, regional power grids and low-carbon alternatives - to transform and decarbonise the energy sector. These measures align with Singapore's broader sustainability agenda, including the SG Green Plan 2030. The nation's installed PV capacity (DC) is now at more than 1.7 gigawatt-peak and is growing steadily.

The Solar Energy Research Institute of Singapore (SERIS) supports the country's energy transition by developing and commercialising solar technologies tailored to urban, tropical environments, and by fostering industry development and wider solar adoption. A major constraint for PV deployment in the City-state is land scarcity. SERIS addresses this by researching solutions that enable multiple uses of limited space, such as building-integrated PV (BIPV), floating solar, agrivoltaics (dual use of PV and crop production), and solar canopies over existing infrastructures like car parks and flood canals.

Because space is limited in Singapore, installed PV panels must deliver very high efficiencies - typically 23% or more - to maximise energy yield per square metre per year. High-performance panels meeting these requirements are now commercially available, for example from our Singapore-based industry partner REC Solar.

SERIS is currently in its fourth 5-year funding cycle (FY22 - FY26). This core funding supports three flagship projects - perovskite-silicon tandem solar cells, BIPV modules & systems, and floating PV systems - and enables the development and testing of multiple "Urban Solar" deployment options.

In 2025 SERIS made significant progress in many areas:

- The solar cell flagship project continued to advance rapidly. Our single-junction perovskite cells (1 cm^2) reached an efficiency of 26.6%, while our 2-junction perovskite-Si tandem devices improved to 33.3% (1 cm^2). The efficiencies of 16-cm^2 and 244-cm^2 2-junction perovskite-Si tandems improved to 28.2% and 24.1%, up from 25% and 20% a year earlier. These figures are among the highest reported by public research institutions for these device classes. We also converted the large tandem cells into glass-glass single-cell mini-modules, raising module efficiency to more than 21%. Together, these results strengthen our pathway to the project target of 30% efficient mini-modules with an active area of at least 150 cm^2 by March 2027. Our team also made a perovskite-organic 2-junction tandem cell (1 cm^2) with 26.4% certified efficiency, which is a new world record.
- The REC@NUS Corporate Laboratory project made strong progress with establishing a new R&D pilot line at SERIS for ultra-large (up to 440 cm^2, G12 wafer size) 30% perovskite-silicon tandem solar cells using an ultra-fast perovskite deposition process. This pilot line will be ready for R&D in Q1 2026. Using existing labs at SERIS, the Corporate Lab team achieved tandem cell efficiencies of > 25% for 244-cm^2 devices, confirming the robustness and potential of our technology.
- As part of the BIPV flagship project, an entire BIM (building information modelling) workflow was created for adding BIPV products to the overall BIM framework. This includes 3D modelling, PV layouts, energy yield projections and life cycle cost assessments.
- The Floating PV team published 2 papers in top-10% journals assessing the global status and potential of both inland reservoirs (including water savings from reduced evaporation) and off-shore sea spaces. They show that utilising merely 10% of the techno-economic areas could power the entire world today, and even a future 100% renewable energy scenario.
- SERIS signed a MoU with company Geoharbour to jointly develop novel deployment solutions for their ~20% efficient single-junction perovskite solar foils, which open fundamentally new opportunities for integration into the urban fabric (e.g. large-scale over-arching solar canopies).
- SERIS spin-off PV Doctor Pte Ltd, a PV asset performance management and smart O&M company, had a flying start and managed to sign up more than 1 GW_p of 'Assets under Management' (AUM) across 1,300+ sites in 21 countries within its first year, demonstrating strong global reach and establishing itself as one of the fastest-growing digital asset-intelligence platforms in the solar industry.

On behalf of SERIS, I would like to thank all staff, adjunct researchers, and students for their dedication and achievements over the past year. Your hard work has been essential to our progress and impact. We also extend our sincere gratitude to our industry partners and supporters, especially the National University of Singapore (NUS), National Research Foundation Singapore (NRF), Energy Market Authority of Singapore (EMA), Singapore Economic Development Board (EDB), our Supervisory Board, our International Advisory Panel, as well as other collaborators across the public and private sectors. Your partnership and support have been invaluable.

The energy transition is happening and the prospects are bright - let the sun shine and do its magic!

Highlights 2025

FEBRUARY

SERIS and TÜV Rheinland signed a strategic partnership agreement to advance solar energy testing and R&D in Asia-Pacific

SERIS and TÜV Rheinland signed a strategic partnership agreement to provide R&D, quality assurance and reliable testing services for PV modules and systems in the Asia-Pacific region. Following a rigorous due diligence, SERIS was also awarded the status of an official TÜV Rheinland "PV Module Testing Laboratory" (PTL). Both parties will work together to promote technological innovation, testing, certification and standardisation in the future. A brief report of the partnership can be found on page 9 of this Annual Report.

(Photo credit: TÜV Rheinland)

MARCH

SERIS hosted a scientific workshop with visitors from Helmholtz Centre Berlin and Humboldt University Berlin

A one-day workshop was held on 26 March 2025 at SERIS for visitors from HZB/HUB and colleagues from various departments in NUS (SERIS, Chemical Engineering, Chemistry, Materials Science). The aim was to determine possible research topics for future collaborative projects between NUS and HZB/HUB in the areas of multi-junction solar cells and PV module reliability testing (lab-based and outdoors).

APRIL

Official Launch of SERIS spin-off PV Doctor Pte Ltd

PV Doctor is the latest spin-off from SERIS. It commercialises 15 years of in-depth research on PV system performance with the aim to maximise energy yield in different climate zones. It offers a unique combination of cutting-edge data analytics using Artificial Intelligence (AI), daily routine checks and performance benchmarks. This ensures that PV assets under management (AUM) operate at optimum yield at any time, leading to higher revenues and ultimately higher returns on investment for PV system owners.

PV DOCTOR
Asset Management

MAY

SERIS received a Certificate of Appreciation from the Singapore Civil Defence Force (SCDF)

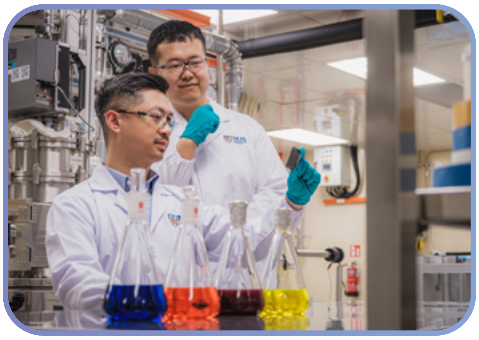
Dr Carlos Clement, Head of Building Integrated Photovoltaics at SERIS, has been awarded a Certificate of Appreciation by the Singapore Civil Defence Force (SCDF) in recognition of his significant contributions to the revision and enhancements of Singapore's Fire Code, supporting industry readiness. Dr Clement currently serves as a member of the Working Group on Roof-mounted Solar Photovoltaic (PV) Installations.

Highlights 2025

MAY

SERIS co-hosted the Spring Meetings of four IEC TC82 Workgroups in Singapore

The IEC TC82 spring meetings of workgroups WG 3, 6, 9, and JWG 1 were co-hosted by SERIS, the Singapore Standards Council (SSC) under Enterprise-SG and the Standards Development Organisation at NTU. About 50 global experts in solar PV standards (mostly from US, Europe, China, South Africa, Japan) came to Singapore for workgroup meetings, as well as to attend technical tours to SERIS labs and the 60-MW_p Floating PV system in Tengeh reservoir. SERIS also organised a Public Seminar on the topic "Status and Outlook for Standards for Solar PV" as part of the week-long program.



JUNE

NUS-SERIS researchers achieved a world record perovskite tandem solar cell with novel NIR-harvesting molecule

The NUS-SERIS research team developed a perovskite-organic tandem solar cell with a certified world-record power conversion efficiency of 26.4% over a 1-cm^2 active area - making it the highest-performing device of its kind to date. This research was led by Asst Prof HOU Yi from NUS' Chemical and Biomolecular Engineering Department, who is the Head of the Perovskite-based Multijunction Solar Cells Group at SERIS. This groundbreaking work was published in the prestigious scientific journal Nature.

JULY

High School Student team from Hwa Chong Institution (HCI) won two awards under SERIS' mentorship

SERIS' High School student project '*Advanced photoluminescence imaging for tandem solar cells*', by students Alvin Liu En Yu, Lemuel Tan and Chen Tingyu from Hwa Chong Institution (HCI), won the Gold Award at the Singapore Science and Engineering Fair 2025 (SSEF) in March 2025 and the "Innovative Award" at the Korean Science Academy Science Fair (KSASF) in July 2025.

AUGUST

SERIS and PV Doctor co-organised a public seminar "The future of Solar PV Performance and Asset Management"

SERIS and its latest spin-off PV Doctor brought together local and international experts from industry and academia for a public seminar to share their insights on PV performance and asset management: from field diagnostics and AI-driven performance analytics to best practices in asset monitoring, loss recovery, and how to safe-guard PV investment and ROI. The public seminar was well received with more than 120 attendees from the local & regional PV community (i.e. solar developers, EPC companies, O&M providers, equipment manufacturers, academia, government agencies, financiers, insurance companies).

Highlights 2025

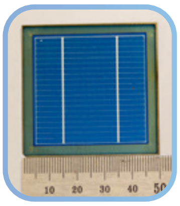
SEPTEMBER

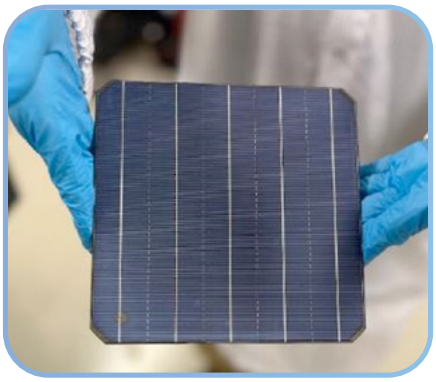
Assistant Prof HOU Yi wins the NUS Young Researcher Award 2025

At the NUS University Awards ceremony this year, Asst Prof HOU Yi from the Department of Chemical & Biomolecular Engineering and the Solar Energy Research Institute of Singapore received the NUS Young Researcher Award for conducting groundbreaking research in the field of renewable energy, particularly in perovskite solar cell technology. He has received global acknowledgement for his work, including his inclusion in the MIT Innovators Under 35 list for the Asia-Pacific region. His recognition as a Clarivate Highly Cited Researcher in the Cross-Field category from 2022 to 2024 further highlights his exceptional impact on his field.

In April this year, he also won the Young Researcher Award and the Design and Technology Innovation Award conferred by the NUS College of Design and Engineering (CDE). The CDE Young Researcher Award is conferred to researchers 40 years old and below, based on their impact and promise in research. The Design and Technology Innovation Award recognises faculty for their outstanding achievements in innovation and research translation.

(Photo credit: National University of Singapore)





OCTOBER

SERIS and collaboration partner Shanghai Geoharbour Group showcase several prototypes of flexible thin-film perovskite solar modules at the Asia Clean Energy Summit (ACES) 2025

Following the signing of a Memorandum of Understanding (MOU) in October, SERIS and Shanghai Geoharbour Group jointly showcased a high-efficiency, flexible thin-film perovskite solar technology at the SERIS booth at ACES 2025. The thin-film modules are like foil and hence ultra-lightweight. This opens fundamentally new possibilities of deployment (e.g., in large over-arching canopies). They can also be made in different levels of transparency for window applications.

NOVEMBER

Strong progress with efficiencies in SERIS' perovskite-silicon tandem solar cell flagship project

In 2025, SERIS continued to make good progress with improving the PV efficiencies of perovskite-silicon tandem solar cells with active areas of 16 and 244 cm^2, as shown in the photographs above (Tandem cell flagship project). Both the silicon bottom cells (heterojunction, Cz wafers) and the perovskite top cells were fully made in SERIS. The best efficiencies are > 28% for 16-cm^2 cells and > 24% for full-wafer cells (244 cm^2).

NOVEMBER

PV Doctor Pte Ltd surpasses 1 GW_p of assets under management (AUM)

SERIS spin-off PV Doctor, a Singapore-based solar asset performance management company, proudly announces a major milestone: over 1 GW_p of assets under management (AUM), across 1,300+ PV systems in 21 countries, now operating in 5 of the world's 7 continents, all within just eight months of its official launch.

SERIS' Participation in **SG60 key events**

SIEW Energy Showcase at Singapore International Energy Week (SIEW), 27-31 Oct 2025 and Asia Clean Energy Summit (ACES), 28-30 Oct 2025

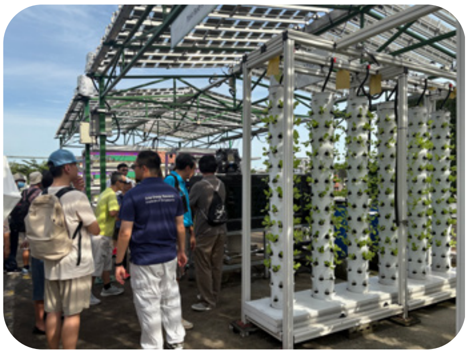
To celebrate Singapore's 60th year of independence, SERIS manufactured a special "SG60 edition" of the SIEW and ACES logos made of solar panels that were displayed at the SIEW and ACES 2025 events, respectively. Fabricated from solar cells and modules using SERIS-developed building-integrated photovoltaics (BIPV) technology, these prototypes demonstrate how solar panels can be both functional and visually appealing. Using architectural-grade printing, the designs seamlessly integrate aesthetics with energy generation and demonstrate the endless possibilities for applications in modern architecture.

Dr Thomas Reindl, Deputy CEO of SERIS, explaining the novelties and innovation of the BIPV panels to Dr Tan See Leng, Minister for Manpower and Minister in Charge of Energy, Science & Technology, Ministry of Trade and Industry, Singapore (right), at the SIEW Energy Showcase 2025.

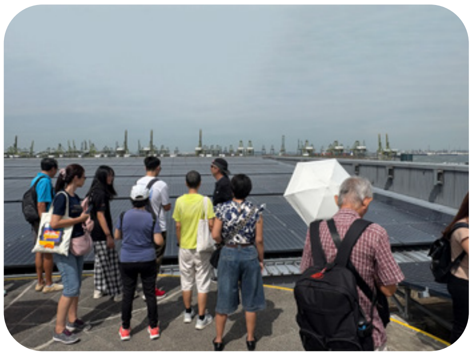
The special "SG60 edition" of the ACES logo

Go Green SG 2025 National Sustainability Movement, 16 May - 29 June 2025

Launched in 2023 and led by the Ministry of Sustainability and the Environment (MSE), the Go Green SG event is an annual national movement to rally for collective action towards a more environmentally sustainable and climate-resilient Singapore. To celebrate Singapore's 60th birthday, the 3rd edition of Go Green SG ran for 6 weeks and offered more than 900 activities by some 400 partners from the Public, Private and People sectors to the general public. To support the Go Green SG2025 event, SERIS - in collaboration with NUS' College of Design and Engineering and Sembcorp Industries - organised the following guided tours for the general public.



Yuhua Agritech Solar (YAS) Living Lab, 23 May 2025: Participants learned about SERIS' innovative urban farming concepts at the YAS Living Lab - an innovative hub striving to foster innovation and experimentation in solar PV and soil-less agritech.



NUS Zero-Energy Building, 23 May 2025: A great opportunity for the general public to learn about the innovative projects by SERIS and NUS and their contributions towards environmental sustainability. More than 60 rooftops at NUS are now equipped with solar panels.

Sembcorp Tengeh Floating Solar Farm, 6 June 2025

Safety briefing and information about the Sembcorp Tengeh Floating Solar farm for the tour participants.

Participants onboard a solar-powered boat enjoying a close-up tour of the 60-MW_p solar farm, with over 122,000 floating solar panels spanning 45 hectares.

SERIS and TÜV Rheinland Signed a **Strategic Partnership to Advance Solar Energy Testing and R&D in Asia-Pacific**

The signing ceremony of the strategic partnership between TÜV Rheinland and SERIS was held during PV EXPO 2025 in Japan, Feb 2025. The ceremony was attended by Mr Frank Piller, Senior Vice President of TÜV Rheinland (right in images above) and Dr Thomas Reindl, Deputy CEO of SERIS *(images credit: TÜV Rheinland)*

TÜV Rheinland and the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) have officially signed a strategic partnership aimed at driving innovation and excellence in the solar energy sector across the Asia-Pacific region. The signing ceremony, held during PV EXPO 2025 in Japan, was attended by Mr Frank Piller, Senior Vice President of TÜV Rheinland, and Dr Thomas Reindl, Deputy CEO of SERIS. The partnership is expected to enhance technological advancements in photovoltaic (PV) module testing, certification and research, supporting the industry's continued growth.

As part of the collaboration, TÜV Rheinland has certified **SERIS as a Partner Testing Laboratory (PTL)** after the institute successfully passed a rigorous audit process, demonstrating compliance with TÜV Rheinland's global standards for PV module testing. This recognition further strengthens SERIS' position as a key player in solar research and testing, contributing to higher quality and reliability in the industry.

The partnership between TÜV Rheinland and SERIS marks a significant step in advancing solar technology and accelerating the region's energy transition. By combining TÜV Rheinland's global expertise in certification with SERIS' cutting-edge research and testing capabilities, the collaboration aims to drive technological innovation and set new benchmarks in solar PV.

The agreement is expected to have a lasting impact on the development of high-performance solar solutions, reinforcing Asia-Pacific's position as a leader in renewable energy. Further initiatives and joint projects are anticipated as both organisations work towards advancing solar technology and industry standards.

TÜVRheinland®
Precisely Right.

Qualified
Laboratory

TÜV Rheinland Singapore Pte. Ltd.
hereby certifies that
SERIS
(Solar Energy Research Institute of Singapore)
1 CleanTech Loop,
#06-01, CleanTech One
Singapore 637141

PV Module Testing Laboratory

has been designated as a Qualified (PTL) Laboratory for testing of:

Standards: IEC 61215 & IEC 61730

Under the Partner Test Lab Program – PTL

An audit was conducted to assess compliance with the requirements of PTL MS-0004326, and the associated documentation was reviewed for adherence to these requirements.

Vilmos Sztaroveczki
Recognized Asia Pacific Manager

Valid until 19th February 2028

SERIS' PV Module Testing Laboratory in Singapore has been designated as a Qualified Laboratory for testing of standards IEC61215 & 61730 under this Partner Test Lab Program (PTL).

Contact person:
Dr Thomas REINDL, Deputy CEO of SERIS
(thomas.reindl@nus.edu.sg)

SERIS drives energy transition in ASEAN
Partnering with think tanks in the Southeast Asia Energy Transition Collaborative Network (SETC)

SERIS is an inaugural member of the Southeast Asia Energy Transition Collaborative Network (SETC), a collaborative effort among think tanks and civil society organisations across Southeast Asia. The coalition's objective is to support the region in establishing its leadership in the energy transition and fostering interdependence in Southeast Asia to reduce emissions.

SETC was initiated by the Institute for Essential Services Reform (IESR) and officially launched during the First SETC Strategic Meeting held in Bali in August 2024. The coalition partners formally agreed to collaborate under a unified framework, which developed strategies for research, policy advocacy, communication, and outreach, with a focus on energy and climate issues in Southeast Asia.

Apart from IESR and SERIS, other key collaborative members are:
- EnergyLab - Cambodia
- Institute of Energy Policy and Research (IEPRe), Universiti Tenaga Nasional (UNITEN) - Malaysia
- Solar Energy Research Institute (SERI), Universiti Kebangsaan Malaysia - Malaysia
- Institute for Climate and Sustainable Cities (ICSC) - The Philippines
- Institute for Environment and Sustainability (IES), National University of Singapore (NUS) - Singapore
- SDG Move, Thammasat University - Thailand

In 2025, SETC developed the Southeast Asia Energy Transformation Initiative (SEA-ETI), a regionally driven policy framework proposing a practical pathway for ASEAN to accelerate clean energy deployment, expand manufacturing capacity, and strengthen green finance.

SETC's analysis points to five priority actions that ASEAN Leaders can adopt to sustain the momentum and embed SEA-ETI into the region's economic and political architecture:
- ✓ Launch the ASEAN Green Investment Platform in 2026
- ✓ Establish a regionally-owned ASEAN Just Energy Transition Partnership (ASEAN-JETP)
- ✓ Accelerate the ASEAN Power Grid and Submarine Cable Framework
- ✓ Embed a clean energy workforce and industrial strategy
- ✓ Institutionalise policy continuity through a rolling Green Transition Flagship Agenda

Dr Thomas Reindl, Deputy CEO of SERIS, is a member of SETC's Expert Consortium, lending his expertise in the areas of Solar PV systems, PV module reliability, floating solar, techno-economic road-mapping, PV performance analysis, and solar forecasting.

Dr Thomas Reindl participated in the strategic meeting of SETC, August 2024, Bali. Image credit: IESR

Dr Thomas Reindl participated in a closed-door meeting with Dr Sufian Jusof, Vice Chancellor of UKM and High-Level Expert Member of ASEAN Chairmanship Malaysia. Image credit: IESR

Contact person:
Dr Thomas REINDL, Deputy CEO of SERIS
(thomas.reindl@nus.edu.sg)

SERIS' Key numbers in CY2025

(as of 30 Nov 2025, unless otherwise stated)

PEOPLE

109
Staff, Adjuncts & Students

65
With university degrees

RESEARCH HIGHLIGHTS

Two-junction perovskite-silicon PV:

33.3% efficiency for 1-cm^2 solar cell

> 25% efficiency for 244-cm^2 solar cell

28.2% efficiency for 16-cm^2 solar cell

> 21% efficiency for 244-cm^2 1-cell module

INDUSTRY INCOME

~ SGD 2 million
(FY 2025, projected)

PV PROJECTS

~ 150 locations (glare analysis) in Singapore assessed

~ 2.0 GW_p feasibility studies / design consultancies conducted on floating solar

> 1.0 GW_p of assets under management by PV Doctor, covering 1,300+ PV systems in 21 countries

 # cumulative since start of projects

PUBLICATIONS

21
Journals & conference papers published / in press

PV QUALITY INDEX

10 Golden modules* tested

SERIS' lab is accredited for the electrical characterisation of reference standard known as "Golden modules" according toIEC 60904-2.

SCIENTIFIC OUTREACH

> 45 talks & posters at conferences, symposia, workshops & webinars

3 seminars hosted at SERIS

LINK WITH ACADEMIA, INDUSTRY, GOVERNMENT BODIES

~ 30 memberships in technical and/or advisory committees

VISITS

Hosted
27
Visits from schools and companies

of which
> 10
VIP visits

MEDIA REPORTS*

> 25 in TV news, radio, newspaper & trade magazine

> 150 in social media platforms

** with SERIS mentioned*

SERIS' Spin-Offs – Status & Progress

Power Facade – Synergising PV Panels Through Prefabrication and Coloured BIPV Integration

Incubated by the National University of Singapore, and as a spin-off of SERIS, Power Facade develops and produces building-related photovoltaic products, e.g., prefabricated building-integrated photovoltaic (BIPV) systems and coloured BIPV panels for building facades. It aims to deliver sustainable solutions for the building industry in Singapore and Southeast Asia. With the drive towards the ESG (Environmental, Social, and Governance) framework, there is a growing demand for renewable energy generation and carbon emission reductions, especially in the building sector.

"All-in-one" prefab BIPV solutions

Building-integrated photovoltaic (BIPV) solutions enable the adoption of clean energy on site and promote low-energy buildings. In highly urbanised cities, BIPV applications on building façades can unlock additional deployment areas next to the traditional rooftop solar systems, especially on tall buildings with limited roof space. However, the lack of "plug-and-play" BIPV solutions in the market has hindered their deployment. To facilitate BIPV adoption in buildings, the spin-off has developed a design method for a unitised BIPV wall system based on light gauge steel prefabrication technology. The new BIPV wall system is characterised by an "all-in-one" design with multiple functional layers. Each unit can operate independently or interconnected through an interlocking design that enables fast installation and guarantees air and water tightness (see Fig. 1). The design approach has been constructed and demonstrated at full scale in Singapore, prior to the creation of the spin-off. Three workers without electrical experience can perform on-site installation from inside the building without the use of scaffolding, because each unit is pre-assembled and pre-wired at an off-site factory.

Coloured BIPV solutions

The colours of standard solar panels in the markets are typically limited to black and blue. As a result, architects and developers are hesitant to use them on building facades, due to the lack of visual appeal and design variability to blend seamlessly with the existing environment. To address this challenge, Power Facade offers coloured solar panels that can replicate the colours and textures of building materials such as marble, bricks, and concrete. Using SERIS-patented hybrid printing techniques, the efficiency of the modules is maximised while meeting the aesthetic demands (see Fig. 2).

Power Facade has completed the EMA-Shell Partnership Start-up Grant by the Energy Market Authority (EMA) to deliver solutions that promote and improve the clean energy sector in Singapore. SERIS was a collaborator of Power Facade in this grant.

Fig. 1: The patented applied design of a unitised BIPV wall system

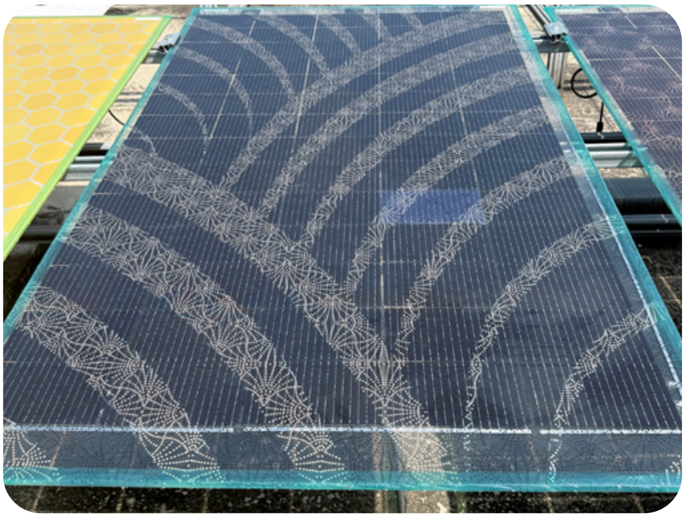


Fig. 2: Coloured BIPV modules with high design flexibility and "hot spot" free

For further information please contact:
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SERIS' Spin-Offs – Status & Progress

Quantified Energy

About Quantified Energy

Quantified Energy (QE) is a solar software company spun off from SERIS/NUS. QE specialises in AI-driven automation and analytics to support solar asset management. Its flagship solution is autonomous drone electroluminescence (EL) mapping. This in-situ, X-ray-style diagnostic tool provides cost-effective and comprehensive insights into the health of utility-scale solar farms. QE is dedicated to delivering high-quality services and cutting-edge technology to meet the evolving needs of the solar energy industry.

Key Innovations and Contributions

In 2025, QE reached a major milestone in commercial scalability by pioneering a novel approach to in-situ QA/QC testing for large-scale solar asset management. In collaboration with Spanish inverter manufacturer Ingeteam, QE successfully demonstrated fully automated, contactless drone-coupled EL inspections integrated with the INGECON SUN B and C Series® Inverter. This breakthrough enabled QE to inspect 40,000 PV modules in a single 8-hour night shift — a record-setting throughput that marks a 400% improvement over previous state-of-the-art methods. By eliminating the need for manual current injections by ground teams, QE dramatically reduces labour and operational costs. This achievement sets a new global benchmark for high-volume, cost-effective photovoltaic (PV) inspections, validating QE's readiness for industrial-scale deployment and reinforcing its leadership in solar diagnostics and risk intelligence.

In addition, QE's contribution to industry-wide excellence is exemplified by the company's work on the sixth edition of SolarPower Europe's Operation & Maintenance (O&M) Best Practice Guidelines, released in February 2025. Drawing on its extensive experience in solar diagnostics, QE defined the 6 main tests conducted at various maintenance intervals throughout the PV lifecycle to ensure the optimal performance and longevity of PV systems. This involvement underscores QE's role as a thought leader, helping to set new global benchmarks for PV asset management and quality assurance.

Our Growth and Achievements

In December 2025, QE successfully closed its Series A funding round, raising a total of $6 million. The final closing included new strategic investments from Asian Development Bank Ventures (ADBV) and Beacon Venture Capital, the venture capital arms of Asian Development Bank (ADB) and Thailand's KASIKORNBANK (KBank) respectively, joining initial lead investor Vertex Ventures Southeast Asia & India (VVSEAI). This expanded consortium underscores strong institutional confidence in QE's pivotal role in advancing the bankability and financial resilience of utility-scale solar power plants globally.

The capital accelerates the integration of QE's solution into existing quality assurance protocols, enabling operators to detect and address potential issues before they affect energy production. Solar asset owners, insurers and financiers can thereby make informed decisions about asset health early, protecting their investment returns across their 25-30 year lifecycles.

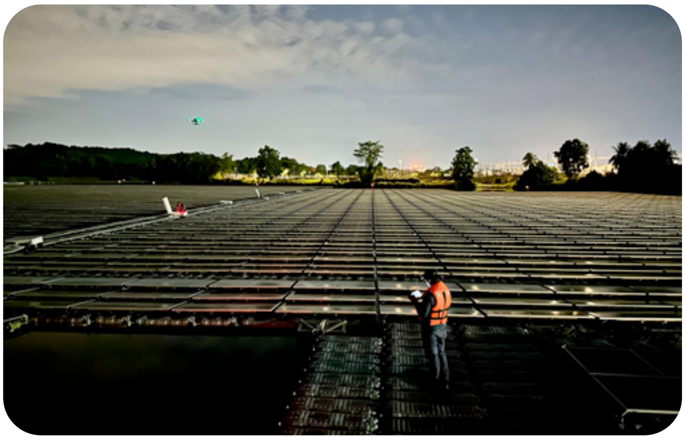
This integration is delivered by its second-generation drone EL inspection solution, which is built around a flexible pay-per-use model, allowing any partner operating a DJI Matrice drone to plug in QE's proprietary EL camera payload and subscribe to its Technical Asset Management (TAM) platform. This unlocks the ability to perform high-throughput, lab-quality inspections anywhere in the world - making scalable, data-driven solar diagnostics more accessible than ever.

QE also achieved a major milestone in September 2025 by signing a strategic MOU with Generali China Insurance (GCI), part of the global Generali Group. This agreement establishes a new industry standard by integrating QE's proprietary technology into GCI's insurance underwriting and claims processes. By providing high-resolution pre-incident data that diagnoses subtle, internal solar panel defects (like micro-cracks), it enables a critical shift from reactive claims handling to proactive asset protection, showcasing QE's role in shaping global renewable energy insurability and risk management.

Real-World Application: Asset Value Recovery

QE's technology and expertise deliver clear financial and operational benefits to utility clients worldwide. Global renewable energy provider Engie utilised QE's drone EL scanning to diagnose performance issues in their large-scale solar rooftop system. The EL imaging uncovered extensive microcracks and solder defects in the modules, which were contributing to a drop in performance. The data quantified a defect rate that was then used as the basis for financial recovery.

As a direct result of QE's solution, Engie was able to work with the module manufacturer to negotiate a prorated credit that covered 8% of the full site, as shared by Tan Bin Ming, Asset Manager of Engie South East Asia. This demonstrates how QE's solution translates directly into significant financial recovery, safeguarding the long-term value for solar asset owners globally.



A QE pilot operates a DJI Matrice drone carrying its proprietary EL camera payload. Image credit: Quantified Energy

For further information please contact:
Dr Yan WANG, CEO and Co-founder of Quantified Energy, yan.wang@quantified-energy.com

SERIS' Spin-Offs – Status & Progress

The PV DOCTOR

We listen, we analyse, we cure

PV Doctor provides an advanced and comprehensive range of asset management services for photovoltaic (PV) system owners across Asia. The company started full operation in April 2025 and now provides services directly to industry customers. In less than a year, the team has on-boarded more than 1 GW_p of PV assets across more than 1300 sites in 21 countries across the world (see map below).

PV Doctor Pte Ltd is a PV Asset Performance Management (APM) company which commercialises the know-how and services previously developed in the Smart O&M Group at SERIS. It also leverages the vast experiences with PV systems (design, implementation, operation, troubleshooting, maintenance) which SERIS has gathered over the past 15 years in Singapore and the region.

The importance of daily monitoring of solar PV systems (and ideally in real time) cannot be overstated, given the number of PV assets that are under-performing in the world (a global assessment by a consulting company estimates annual losses of USD 10 billion worldwide). Poorly operating PV systems can also pose safety and/or fire risks, which must be mitigated.

PV Doctor offers a broad range of services which aim at increasing PV system performance, energy yield and, in consequence, also revenue – to secure (or ideally even raise) the return of investment of the asset owners.

The various PV Doctor services are listed below:

i. Smart O&M:
Daily monitoring of assets under management (AUM) and real-time notifications of under-performance.

ii. Preventive O&M:
Analysing long-term patterns to derive preventive on-site actions.

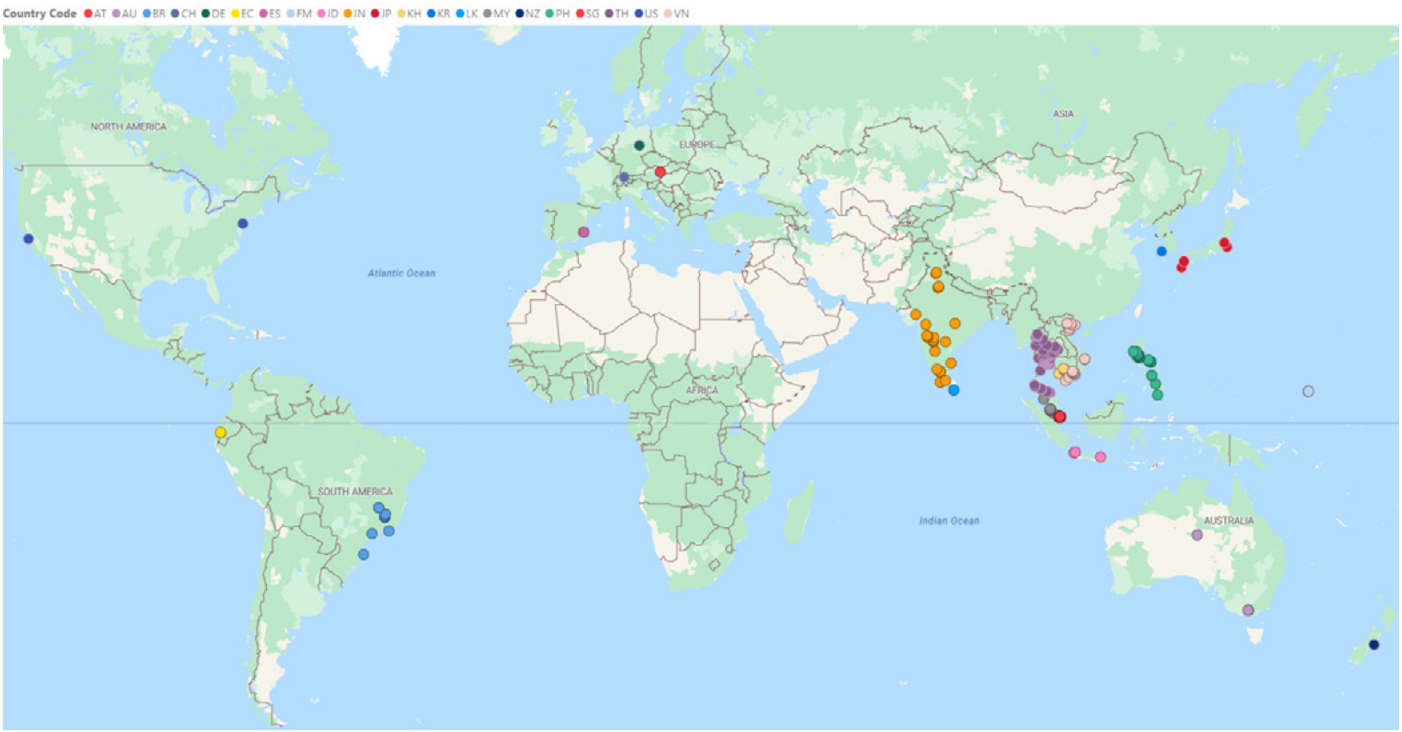
iii. Rectifications & Special Investigations:
Interventions to ensure that under-performing assets are rectified and energy yield is re-instated to expected levels.

iv. Repowering:
Partial or full re-powering of a PV site, in case rectification measures would not be sufficient to re-instate performance to expected levels.

v. Audits & Performance Assessments:
PV Doctor can act as 'independent third-party" for audits or as part of a technical due diligence process (e.g. at times of assets transactions)

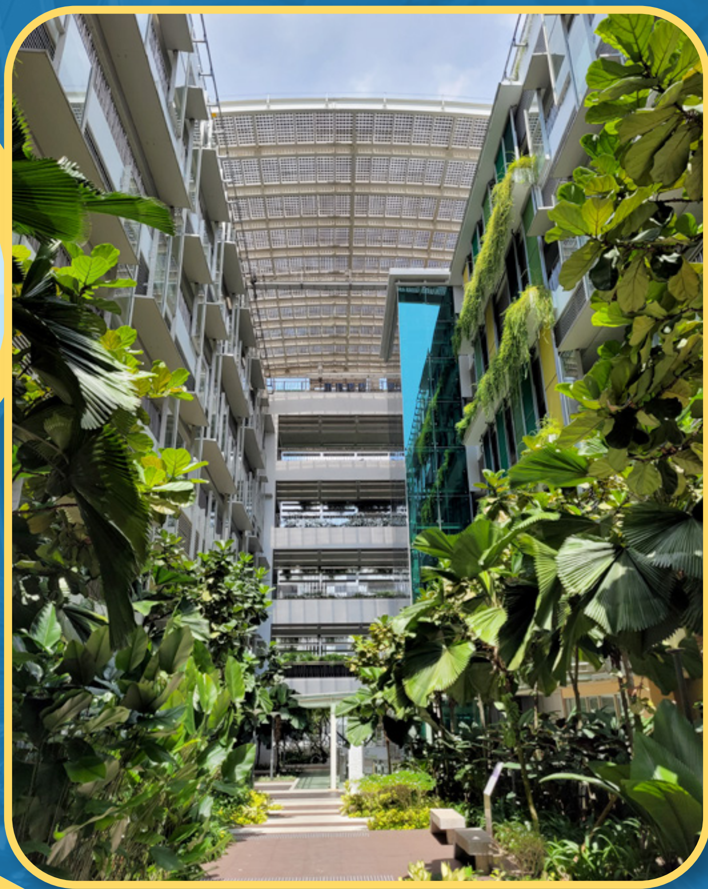
vi. General Technical Support:
This includes, for example, owner's engineer services, technical assistance on M&A deals, or the development of targeted O&M strategy for new market entrants

For further information please contact:
Dr André NOBRE
andre.nobre@pv.doctor



Map of the 1 GW_p of PV "assets under management" (AUM) by PV Doctor at the end of November 2025 across 1300 sites in 21 countries, demonstrating the global reach of the SERIS spin-off company. Image credit: PV Doctor Pte Ltd

INSTITUTE IN BRIEF



Introduction

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) is the nation's institute for solar energy research and a global leader in photovoltaic (PV) research and innovation. Established in 2008, the institute is supported by NUS, the National Research Foundation Singapore (NRF), the Energy Market Authority of Singapore (EMA) and the Singapore Economic Development Board (EDB).

SERIS actively advances solar adoption and PV industry development in Singapore and the region, supporting national decarbonisation goals. In recent years, the institute has been driving next-generation PV research, improving cell efficiency and reliability - through perovskite-silicon tandem technologies, aiming to translate lab-scale breakthroughs into bankable products and scalable deployments. To expand the solar deployment potential in land-scarce regions, SERIS has developed innovative solutions including building-integrated PV (BIPV), floating solar on water bodies, agrivoltaics, and solar canopies over existing infrastructures such as carparks. The institute also delivers advanced solar energy forecasting tools that mitigate intermittency and support power grid stability as solar penetration increases.

SERIS conducts research, development, deployment, testing and consulting on solar energy technologies and their integration into urban infrastructures, buildings and power systems. Its R&D spectrum covers industrially relevant materials, components, processes, systems and services, with an emphasis on solar PV cells, modules and systems. The focus of SERIS' core-funded work is on three Flagship projects and on research topics that address the specific deployment challenges of solar PV systems in mega-cities like Singapore (space constraints) and in tropical climate conditions (high temperature and humidity throughout the year).

The institute operates world-class laboratories and facilities for solar R&D and testing services, of which the electrical testing of PV modules (indoor characterisation and reliability) and grid-tied solar PV system measurement (for insulation resistance test voltages up to 1000 V) are accredited in accordance with the recognised International Standard ISO/IEC 17025:2017 by the Singapore Accreditation Council (SAC) under the Singapore Laboratory Accreditation Scheme (SINGLAS).

SERIS is globally active but focuses on technologies and services for tropical regions, in particular for Singapore and South-East Asia. The institute collaborates closely with universities, research organisations, government agencies and industry, both locally and globally. SERIS is a sponsor member of the IEA PVPS programme and is actively involved in PVPS Tasks 1 (Strategic PV Analysis and Outreach), 13 (PV Operations & Maintenance), 15 (Enabling Framework for the Development of BIPV) and 19 (Photovoltaic Integration in Electricity Networks and Markets), with the purpose of sharing its know-how with other experts and fulfilling its vision of contributing to global sustainable development. SERIS is also an inaugural member of the Southeast Asia Energy Transition Collaborative Network (SETC), a collaborative effort among think tanks and civil society organisations across Southeast Asia to support the region in establishing its leadership in the energy transition and fostering interdependence in Southeast Asia to reduce emissions. SERIS has established close links and R&D collaborations with more than 100 companies in Singapore, Asia Pacific and beyond. Its industrial partnerships have attracted many local and international solar companies to establish high-value operations in Singapore to serve Asia.

SERIS' multidisciplinary team of scientists, engineers, technicians, administrative staff and PhD students

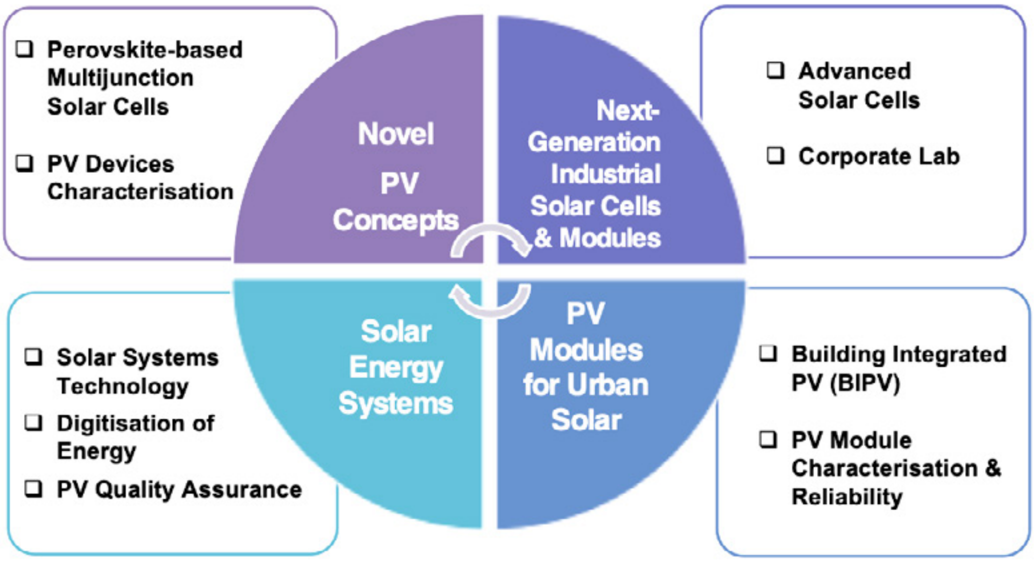
Business Areas

SERIS' research & development activities are conducted within four research clusters (or departments):

- Novel PV Concepts (NPVC)
- Next-Generation Industrial Solar Cells and Modules (NISCM)
- PV Modules for Urban Solar (PVM)
- Solar Energy Systems (SES)

Collectively, these 4 research clusters operate and support SERIS' three main business areas:

- Solar cells
- PV modules
- PV systems



SERIS' four Reseach Clusters and the associated R&D Groups supporting the three main research areas

In each business area, SERIS generates innovations for the solar industry ecosystem and the public sector. The institute's application-oriented research and development works are complemented by targeted fundamental research that forms the basis for a steady flow of scientific-technical innovations. A wide range of activities at SERIS are aiming at accelerating the deployment of solar PV systems in Singapore, South-East Asia, and beyond.

Selected R&D activities:

- Floating solar PV systems
- Agrivoltaics
- Smart O&M
- Building integrated photovoltaics (BIPV)
- Solar potential analysis
- Solar energy forecasting
- PV system technologies
- PV quality assurance
- PV grid integration
- PV module development
- Reliability of PV modules and systems
- PV waste management and circular economy
- PV modelling and simulation
- Characterisation of solar cells and PV modules
- Next-generation industrial solar cells
- Perovskite-silicon tandem solar cells
- Perovskite multi-junction thin-film solar cells

Finances

For Financial Year (FY) 2025, core funding from the National Research Foundation Singapore (NRF) - via the Energy Market Authority of Singapore (EMA) - and the National University of Singapore (NUS) is anticipated at SGD 13.9 million. The core funding is complemented by grants from public competitive R&D programmes and funds from industry contracts of approximately SGD 12.3 million and SGD 2.0 million, respectively. These are projected amounts, as FY 2025 will end on 31 March 2026. The breakdown of the projected SERIS funding of SGD 28.2 million for FY 2025 is displayed in Fig. 1.

Figure 2 shows the breakdown of the projected SERIS expenses of SGD 28.5 million in FY 2025: SGD 10.1 million for manpower, SGD 10.6 million for equipment, SGD 6.4 million for operating expenses, and SGD 1.4 million for other expenses, which include infrastructure, indirect research costs, and non-refundable GST (Goods and Services Tax).

The evolution of SERIS' industry income over the last 11 financial years is shown in Fig. 3.

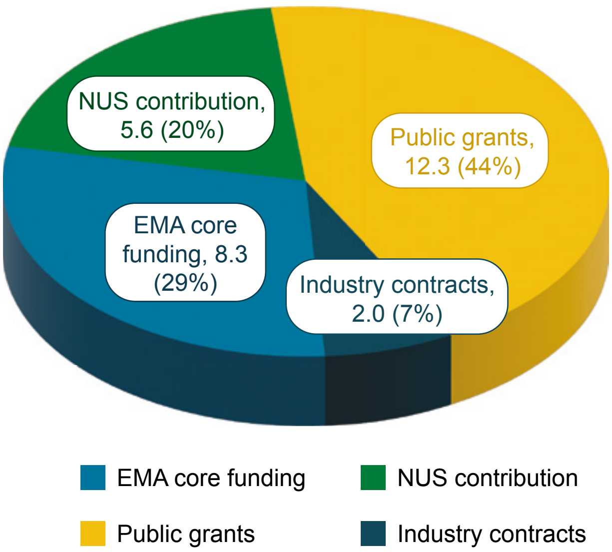


Fig. 1: Projected SERIS funding for FY 2025 (1 Apr 2025 to 31 Mar 2026, in SGD million)

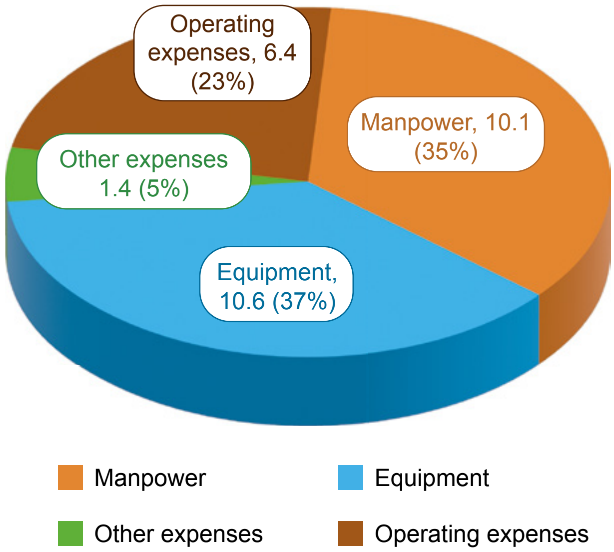


Fig. 2: Projected expenses for FY 2025 (1 Apr 2025 to 31 Mar 2026, in SGD million)

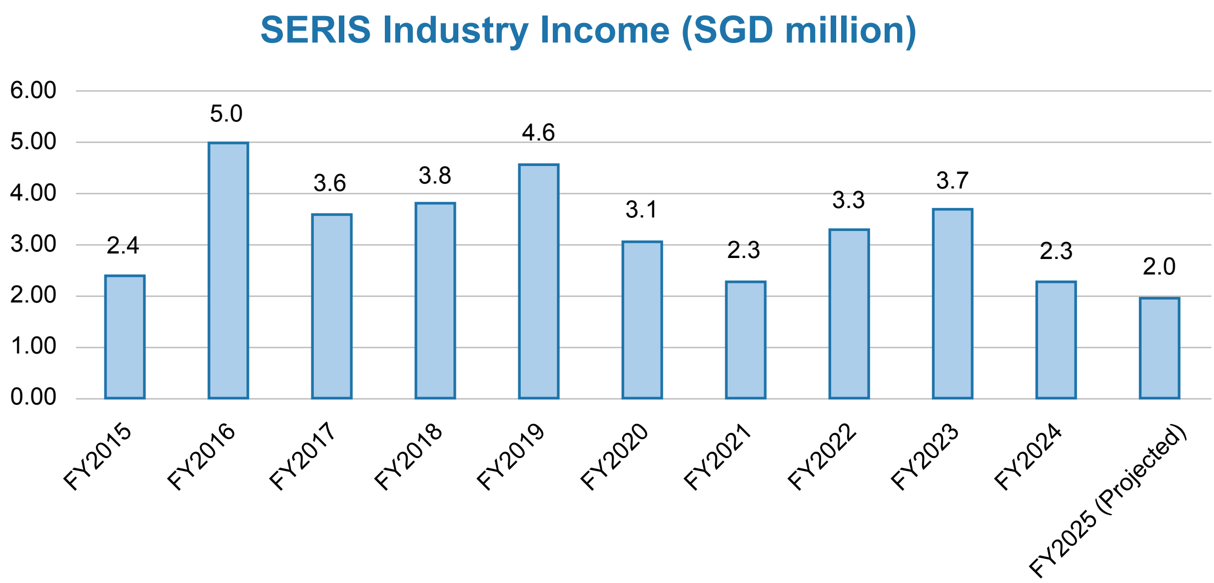
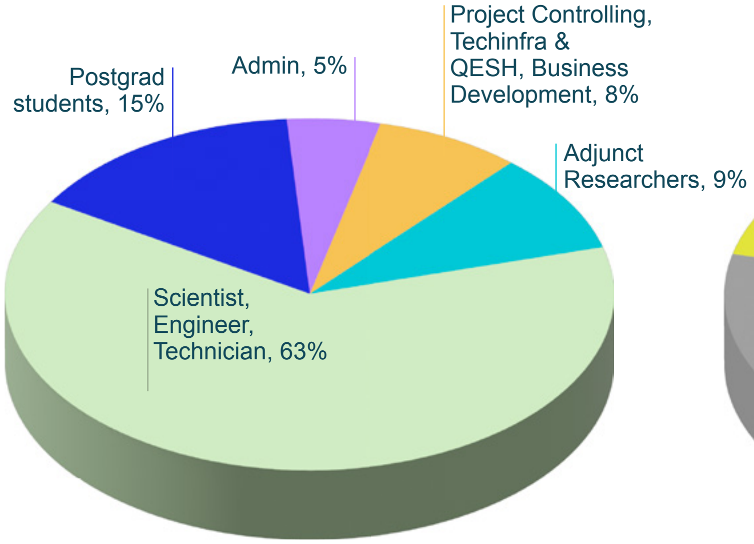


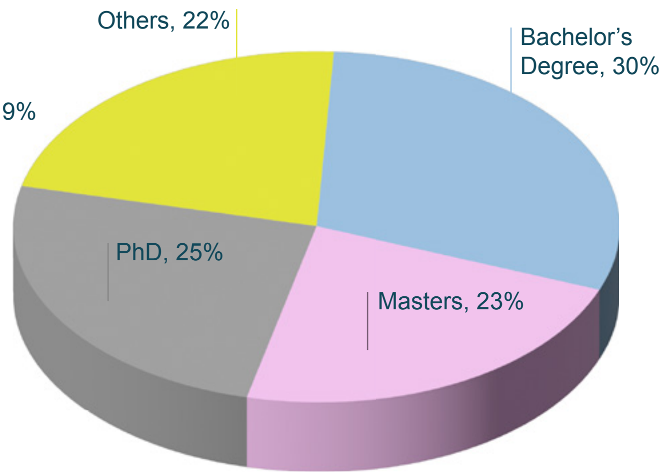
Fig. 3: Evolution of SERIS' annual industry income since FY 2015 (in SGD million)

Headcount

At the end of calendar year 2025, the SERIS headcount was 109, including NUS-funded postgraduate students and adjunct researchers ("faculty"). The figure on the left shows that research personnel - including scientists, engineers, technicians, postgraduate students and adjunct researchers – constitute 87% of the total SERIS headcount. Employees from Project Controlling, Technical Infrastructure & QESH and Business Development form 8% of the total headcount, while administrative staff represent 5% of the headcount.



Breakdown of SERIS headcount in December 2025



Highest educational qualification of SERIS staff

Laboratory, Office and Rooftop Space

SERIS occupies approximately 5160 m² of space within the E3A building on the main NUS campus, comprising offices, laboratories, and associated laboratory support facilities. It also rents approximately 1415 m² of laboratory and office space at its off-campus site in CleanTech Park, which houses the PV Module Development and Testing laboratories. In addition, SERIS utilises around 3330 m² of rooftop space at both NUS and CleanTech Park for experimental outdoor solar installations.

SERIS' rooftop facilities at CleanTech Park (left) and at NUS (right)

SERIS International Advisory Panel

The SERIS International Advisory Panel (IAP) advises SERIS on strategic directions with respect to research and development activities. The panel meets at least once every two years.

Chairman of the SERIS IAP

Prof Andrew BLAKERS
Professor
School of Engineering
Australian National University (ANU)
Australia

Members of the SERIS IAP (in alphabetical order of last name)

Dr Dan ARVIZU
Former member of President's Council of Advisors on S&T (PCAST), USA
Former Director of the National Renewable Energy Laboratory, USA
Former Chancellor of New Mexico State University (NMSU), USA

Dr Nancy HAEGEL
Senior Research Advisor
Director, National Centre for Photovoltaics
National Renewable Energy Laboratory
USA

Mr Steve O'NEIL
Board Chairman, REC Solar Americas
Director, Endurans Solar and Great Northern Bancshares
Executive Advisor, Solestial
USA

Mr Frank PHUAN
Founder, CEO, Managing Partner
Equator Renewables Asia
Vice-Chairman, Sustainable Energy Association of Singapore (SEAS)
Singapore

Dr SHI Zhengrong
Chairman & Founder
Sunman Energy Co. Ltd.
PR China

Prof Eicke WEBER
Prof. emeritus, University of California, Berkeley, USA
Former Director, Fraunhofer ISE, Freiburg, Germany
Member, German Academy of Science and Engineering ACATECH, Germany

SERIS Supervisory Board

The SERIS CEO reports to the SERIS Supervisory Board (SB). The Board monitors the institute's activities and corporate development. It meets at least three times a year.

Chair of the SERIS Supervisory Board

Prof Thorsten WOHLAND
Director, Research Governance and Enablement
Office of the Deputy President (Research and Technology)
National University of Singapore

Members of the SERIS Supervisory Board (in alphabetical order of last name)

Er Edwin T.F. KHEW PBM
Chairman of the Sustainable Energy Association of Singapore (SEAS)
Chairman & Co-Founder of AirCarbon (ACX) Exchange
Emeritus President, The Institution of Engineers (IES), Singapore

Dr KOH Shuwen
Director, Technology Transfer and Innovation, NUS Enterprise
National University of Singapore
Deputy Group Chief Technology Officer and Director of Innovation
National University Health System
(member of SERIS SB until Apr 2025)

Mr LIM Wey-Len
Executive Vice President
Member of EXCO, Green Economy
Singapore Economic Development Board (EDB)
(member of SERIS SB until Aug 2025)
Recipient of The Public Administration Medal (Silver), National Day Awards 2025

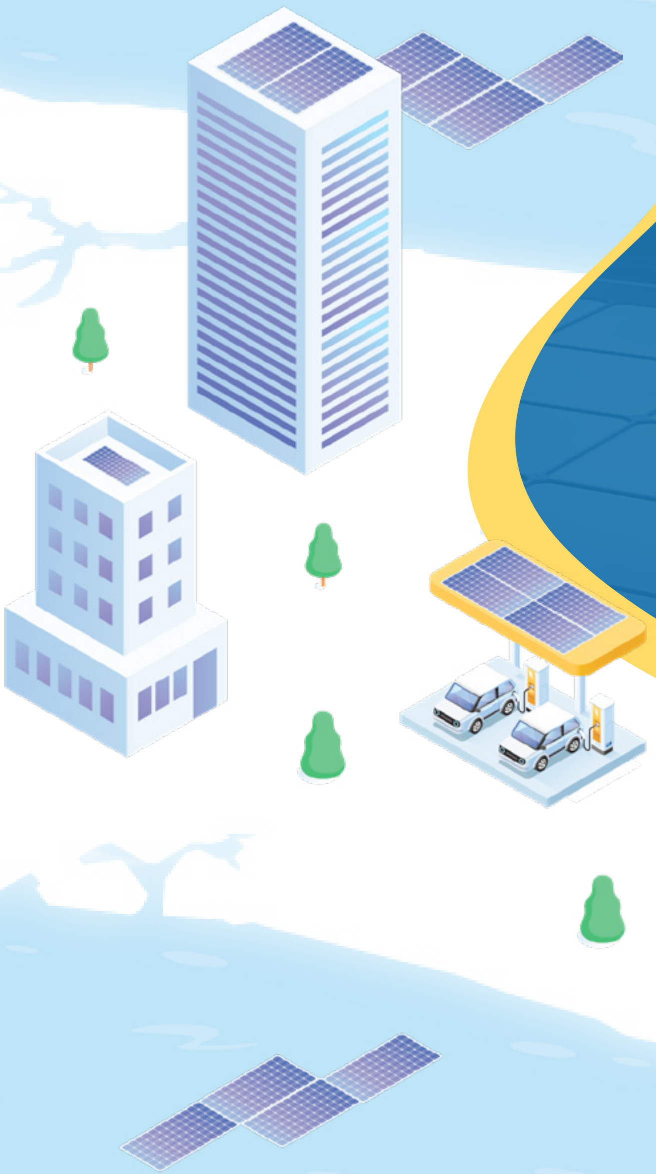
Mr LOW Xin Wei
Assistant Chief Executive
Energy Market Authority (EMA), Singapore

Ms MOH Yu Ying, Josephine
Senior Vice President and Head, Energy and Renewables
Singapore Economic Development Board (EDB)
(member of SERIS SB since Sep 2025)

Mr NI De En
Director, Urban Solutions & Sustainability
National Research Foundation Singapore (NRF)

Dr Shankar G. SRIDHARA
Chief Technology Officer
REC Solar Pte Ltd.
Singapore

ORGANISATION STRUCTURE



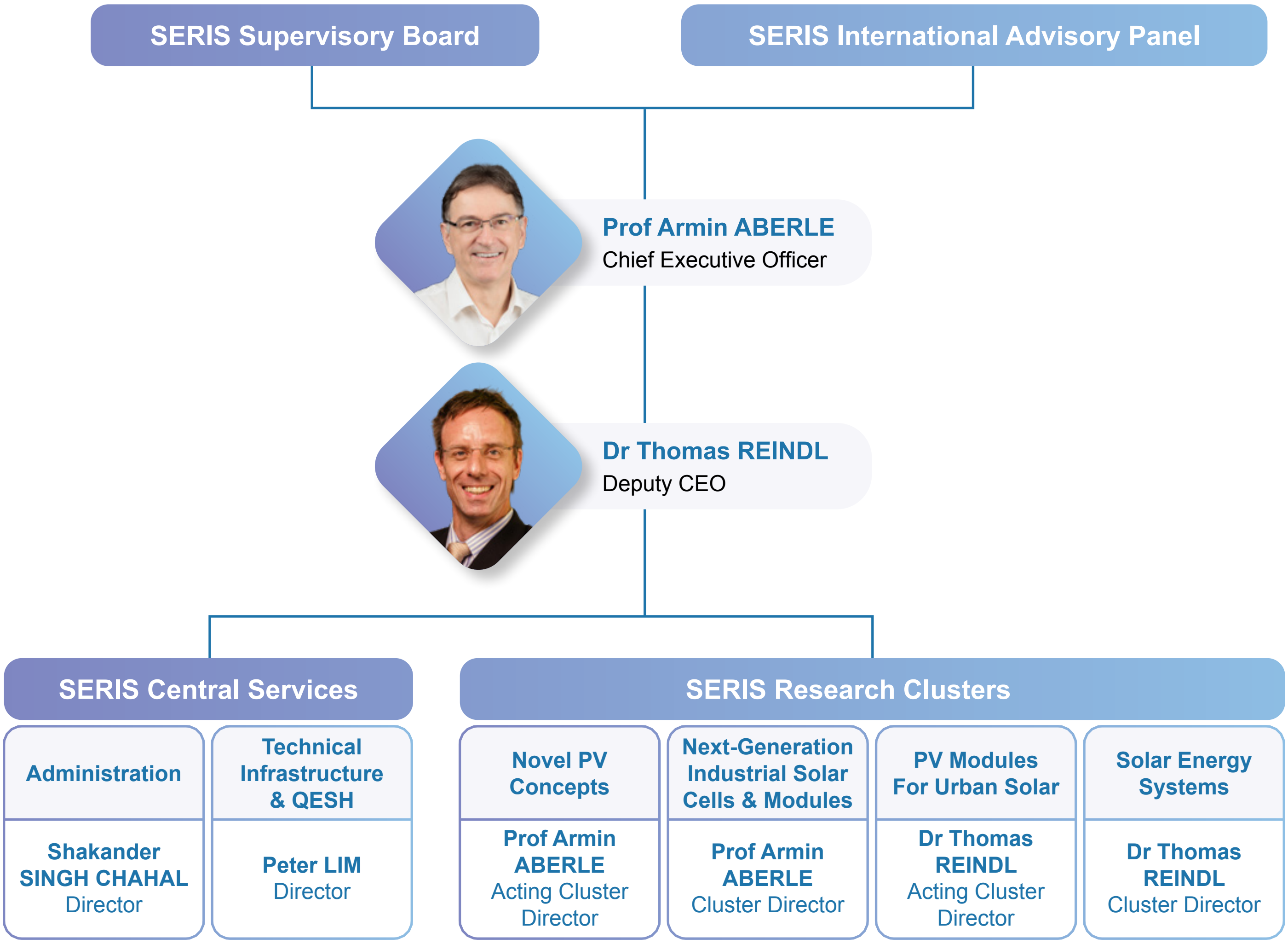
Organisational Chart

SERIS comprises four research clusters and two central service units. The research clusters conduct research, development, testing and consulting on solar energy technologies and their integration into buildings and power systems. The two service units provide central services such as administration, facility support and QESH (quality, environment, safety & health) management.

The directors of the research clusters and service units report to the SERIS Senior Management, consisting of the CEO and the Deputy CEO.

The SERIS CEO reports to the SERIS Supervisory Board. The Board monitors the institute's activities and corporate development. It meets at least three times a year.

The SERIS International Advisory Panel (IAP) advises SERIS on strategic directions with respect to research and development activities. The panel meets at least once every two years.



SERIS Senior Management:

- CEO
- Deputy CEO

Research Clusters:

- Novel PV Concepts (NPVC)
- Next-Generation Industrial Solar Cells & Modules (NISCM)
- PV Modules for Urban Solar (PVM)
- Solar Energy Systems (SES)

Central Service Units:

- Administration
- Technical Infrastructure and QESH (Quality, Environment, Safety and Health)

Management Team

SERIS Management Team (left to right):
Mr Peter LIM, Dr Thomas REINDL, Prof Armin ABERLE, Mr Shakander Singh CHAHAL

SERIS' Management Team consists of the CEO, the Deputy CEO, the Directors of the research clusters, the Director of Administration, and the Director of Technical Infrastructure and QESH. The team meets fortnightly to decide on the managerial, operational and strategic directions of the institute.

Management Team
Prof Armin ABERLE CEO Cluster Director, Next-Generation Industrial Solar Cells and Modules Acting Cluster Director, Novel PV Concepts armin.aberle@nus.edu.sg
Dr Thomas REINDL Deputy CEO Cluster Director, Solar Energy Systems Acting Cluster Director, PV Modules for Urban Solar thomas.reindl@nus.edu.sg
Mr Shakander Singh CHAHAL Director, Administration shakander.chahal@nus.edu.sg
Mr Peter LIM Director, Technical Infrastructure and QESH peter.lim@nus.edu.sg

Secretary to CEO

Ann Mythel ROBERTS
Secretary to CEO and Next-Generation Industrial Solar Cells & Modules Cluster

Corporate Relations

TAN Mui Koon
Senior Scientific Manager
Corporate Relations

Kesha Jane DRYSDALE
Senior Scientific Executive
Corporate Relations

Extended Management Team

SERIS Extended Management Team consists of the SERIS Management Team (see previous page), the Heads of the various research groups/teams, the Laboratory Managers, the Business Development Manager, the Scientific Manager (Corporate Relations), and the SERIS Business Partners for Finance and Human Resources from NUS. The team meets every 2-3 months to discuss managerial, operational and strategic matters of the institute.

Dr CHOI Kwan Bum
Head, PV Devices Characterisation Group
Team Leader, Solar Cell Testing
NPVC Cluster
serckb@nus.edu.sg

Assoc Prof Karl Erik BIRGERSSON
Team Leader, Thin-Film Device Modelling
PV Devices Characterisation Group
NPVC Cluster
mpebke@nus.edu.sg

Asst Prof HOU YI
Head, Perovskite-based Multijunction Solar Cells Group
NPVC Cluster
yi.hou@nus.edu.sg

Dr WANG Puqun
Team Leader, Advanced Characterisation
PV Devices Characterisation Group
NPVC Cluster
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Dr Selvaraj VENKATARAJ
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Dr Biplab GHOSH
Project Manager
Corporate Laboratory Project
NISCM Cluster
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Dr Jan HASCHKE
Senior Research Fellow
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Dr Krishna SINGH
Research Fellow
Corporate Laboratory Group
NISCM Cluster
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Dr JANG Yu Jin
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Dr Yong Ryun KIM
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Dr Jinhyun KIM
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Dr Romika SHARMA
Research Fellow
Advanced Solar Cells Group
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romika@nus.edu.sg

Dr Carlos Enrico Cobar CLEMENT
Head, BIPV Group
PVM Cluster
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Aziz NAIRI
Head, PV Module Characterisation & Reliability Group
PVM Cluster
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Dr LONG Jidong
Laboratory Manager
SERIS laboratory at CleanTech Park
PVM Cluster
jidonglong@nus.edu.sg

Dr Jaffar Moideen YACOB ALI
Head, Solar System Technology Group
SES Cluster
(until Feb 2025)

Dr Serena LIN Fen
Deputy Cluster Director and
Head, Solar System Technology Group
SES Cluster
lin.fen@nus.edu.sg
(since Mar 2025)

Dr André NOBRE
Deputy Cluster Director and Head of Smart O&M Group
SES Cluster
(until Mar 2025)

Eddy BLOKKEN
Business Development and
Co-Head, PV Quality Assurance Group
SES Cluster
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Kendrick LOH Chun Ming
Co-Head (since Oct 2025),
PV Quality Assurance Group
SES Cluster
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Rachel TAN Yek Wha
Head, PV Quality Assurance Group
SES Cluster
(until Sep 2025)

SOE Pyae
Team Leader, PV Monitoring,
Digitisation of Energy Group
SES Cluster
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Dr Firdaus Bin SUHAIMI
Laboratory Manager
Perovskite Solar Cells,
Technical Infrastructure & QESH Unit
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TAN Mui Koon
Senior Scientific Manager
Corporate Relations
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Janet GOH
SERIS Business Partner Human Resources, NUS
janetgoh@nus.edu.sg

Elsie ANG Xin Yi
SERIS Business Partner Finance, NUS
elsie.ang@nus.edu.sg
(since Apr 2025)

ZHUO Yuqing
SERIS Business Partner Finance, NUS
(until May 2025)

Adjunct Researchers

A number of NUS professors ("faculty") have official links with SERIS, as researchers and/or research managers. These "Adjunct researchers" supervise PhD and Master students at SERIS and perform joint R&D projects with one or more of the R&D clusters at SERIS. The research projects involving Adjunct researchers are partly or fully funded by SERIS. Adjunct researchers remain academic staff members of their respective NUS Departments and NUS continues to pay 100% of their salaries.

In 2025, the following Adjunct researchers from NUS have been working with SERIS:

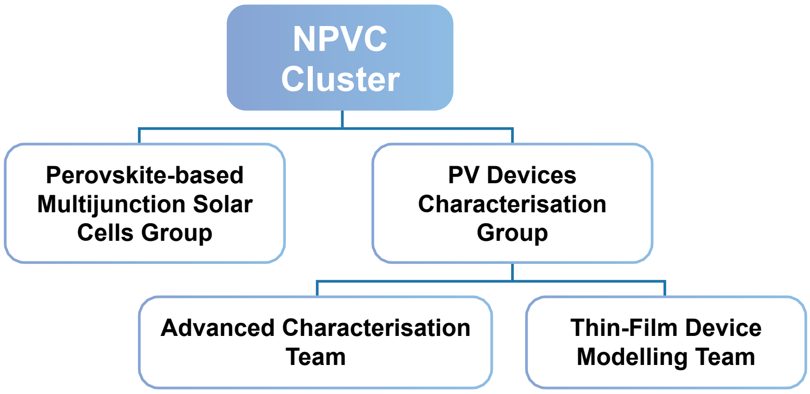
Name	NUS Department	Research area / role at SERIS
Prof Armin ABERLE	Electrical and Computer Engineering	Photovoltaic materials, devices and modules / CEO and Cluster Director
Assoc Prof Karl Erik BIRGERSSON	Mechanical Engineering	Modelling, optimisation and characterisation of solar cells; Modelling of PV modules / Team Leader, Thin-Film Devices Modelling
Assoc Prof Aaron DANNER	Electrical and Computer Engineering	Application of ultra-thin films to high-efficiency silicon wafer solar cells
Asst Prof HOU Yi	Chemical and Biomolecular Engineering	Perovskite-based multijunction solar cells
Assoc Prof Ashwin KHAMBADKONE	Electrical and Computer Engineering	Analysis and solutions for PV grid integration through energy system modelling and advanced power electronics & control for smart grids
Assoc Prof Sanjib Kumar PANDA	Electrical and Computer Engineering	High-performance control of power electronic converters
Prof Seeram RAMAKRISHNA	Mechanical Engineering	PV modules
Prof Dipti SRINIVASAN	Electrical and Computer Engineering	Analysis of impacts of solar PV integration into the medium- and low-voltage power distribution systems
Assoc Prof TAN Zhi Kuang (until March 2025)	Chemistry	Perovskite devices
Assoc Prof Stephen TAY En Rong	Built Environment	Glare studies, co-location of PV with greenery and PV and urban heat island (UHI) effect
Prof WONG Nyuk Hien	Built Environment	Solar and Energy Efficient Buildings, interaction of buildings and environment

RESEARCH & DEVELOPMENT CLUSTERS & GROUPS

1. Novel PV Concepts Cluster

This Cluster researches novel and emerging solar PV materials, devices and applications that have the potential to gain market entry within the next 5-10 years. The experimental work in the semiconductor laboratories focuses on novel thin-film solar cells such as perovskite devices (both single- and multi-junction) and on perovskite-silicon tandem solar cells (SERIS flagship project). The device fabrication work is supported by a well-equipped Characterisation Laboratory for PV materials and cells, as well as a Thin-Film Device Modelling Team that operates a state-of-the-art simulation infrastructure. In December 2025, the Cluster had 30 members (including 8 PhD students) spread over two R&D Groups.

Cluster Director's Office
Prof Armin ABERLE Acting Cluster Director
Ann Mythel ROBERTS Cluster Secretary
Laboratory Manager
Dr Firdaus Bin SUHAIMI



Organisation chart of the Novel PV Concepts Cluster (in Dec 2025)

Group Heads	Team Leaders
Asst Prof HOU Yi Perovskite-based Multijunction Solar Cells	**Assoc Prof Karl Erik BIRGERSSON** Thin-Film Device Modelling
Dr CHOI Kwan Bum PV Devices Characterisation	**Dr WANG Puqun** Advanced Characterisation

Adjunct Researchers, NUS
Prof Armin ABERLE Dept of Electrical and Computer Engineering (Photovoltaic materials, devices & modules)
Assoc Prof Karl Erik BIRGERSSON Dept of Mechanical Engineering (Modelling, optimisation and characterisation of solar cells; Modelling of PV modules)
Asst Prof HOU Yi Dept of Chemical and Biomolecular Engineering (Perovskite-based multijunction solar cells)
Assoc Prof TAN Zhi Kuang Dept of Chemistry (Perovskite devices), until March 2025

Perovskite-based Multijunction Solar Cells Group

The group's research is centred around bridging chemistry, physics, and materials engineering disciplines to advance perovskite multi-junction solar cells. Our work is organised into three main thrusts:

1. Materials Innovation: This thrust focuses on developing new materials to enhance device functionality. We are particularly interested in wide-bandgap perovskite absorbers, interfacial materials, flexible electrodes, self-assembled monolayers, and metal oxides that can efficiently convert solar energy into electricity.
2. New Device Structures and Assembly Processes: Here, we explore innovative methods to manipulate, process and assemble materials, aiming to create unique optical and electrical properties. Our objective is to establish reproducible, cost-effective and rapid processing techniques suitable for large-scale production in the solar industry.
3. Tandem Solar Cells: Building upon the knowledge gained from the previous thrusts, we concentrate on developing reliable, efficient and affordable perovskite-based tandem solar cells. To maximise solar energy harvesting, we are working on different tandem architectures, new recombination junctions, electrical contacts, transparent conductive oxides (TCOs), passivation layers, and encapsulants for dual- and triple-junction tandem solar cells.

Through these research endeavours, we aim to contribute to the advancement of sustainable and accessible energy generation solutions.

Group Head
Asst Prof HOU Yi

Research Scientists
- Dr HU Jingcong
- Dr JIA Zhenrong
- Dr JIANG Ershuai (since Nov 2025)
- Dr KAN Chenxia
- Dr LI Nengxu
- Dr LUO Chao
- Dr NIU Xiuxiu
- Dr PEI Fengtao (since Nov 2025)
- Dr WANG Tao
- Dr YAO Yuxin
- Dr ZHU Zihao

PhD Students
- Ezra ALVIANTO
- CHEN Jinxi
- DONG Zijing
- DU Xinyi
- GUO Xiao
- JIANG Yuhui
- LEE Ling Kai
- LUO Ran
- MENG Xin
- WANG Xi
- WANG Yuduan
- WEI Zhouyin
- ZHANG Xinyu
- ZHOU Qilin

PV Devices Characterisation Group

The group researches and develops innovative characterisation, analysis and modelling solutions for solar photovoltaic materials and devices. Its activities span multiple disciplines of science and engineering, with applications that cover the entire PV value chain. The group manages and operates the PV Devices Characterisation Laboratories at SERIS, which are equipped with a wide array of measurement, diagnostics and analysis tools. Selected R&D activities in 2025 include:

(i) Conducting optoelectronic characterisations to uncover and understand PV material and device properties.
(ii) Developing novel mathematical models for tandem PV devices.
(iii) Creating new characterisation and simulation methods for tandem PV devices to support both research and industry.

Group Head
Dr CHOI Kwan Bum

Team Leaders
- Assoc Prof Karl Erik BIRGERSSON (Thin-film Device Modelling)
- Dr WANG Puqun (Advanced Characterisation)

Research Scientists / Engineers
- Stella HADIWIDJAJA
- Elisaveta UNGUR
- YE Jiayi (until Mar 2025)

Adjunct Researcher
Assoc Prof TAN Zhi Kuang (until Mar 2025)

PhD Student
Sai Prashanth JOSYULA (until Aug 2025)

Internship Students
- KRISHNAPUR Praveen Kumar (until Jul 2025)
- NICOT-SENNEVILLE Zoltan (until Jul 2025)

2. Next-Generation Industrial Solar Cells and Modules Cluster (NISCM)

Solar photovoltaic (PV) power generation is booming and poised to become the world's largest source of electricity. To accelerate the manufacture and deployment of PV technologies in Singapore and abroad, and to support the decarbonisation of the global energy system, continuous improvements of the efficiency, manufacturing cost, and long-term stability of industrial solar cells and modules are required. This Cluster researches and develops next-generation industrial solar cells and modules featuring superior performance and cost-effectiveness. The experimental work in our solar cell laboratories focuses on (i) low-cost high-efficiency single-junction solar cells based on M2-size (244 cm^2) monocrystalline silicon substrates and (ii) low-cost large-area (M2) 30% efficient perovskite-silicon tandem solar cells and mini-modules (SERIS flagship project). The Cluster also hosts, manages and operates the REC@ NUS Corporate R&D Laboratory for Next Generation Photovoltaics targeting low-cost 30% tandem solar cells on ultra-large silicon substrates (440 cm^2, G12). In December 2025, the Cluster had 26 members (including 2 PhD students) spread over two R&D groups.

Cluster Director's Office
Prof Armin ABERLE Cluster Director
Ann Mythel ROBERTS Cluster Secretary
Laboratory Manager
Dr Selvaraj VENKATARAJ

NISCM Cluster

- Advanced Solar Cells Group
- Corporate Laboratory Group

Organisation chart of the Next-Generation Industrial Solar Cells and Modules Cluster (in Dec 2025)

Group Heads
Prof Armin ABERLE Advanced Solar Cells
Dr Selvaraj VENKATARAJ Corporate Laboratory
Adjunct Researchers, NUS
Prof Armin ABERLE Dept of Electrical and Computer Engineering (PV materials, devices and modules)
Associate Prof Aaron DANNER Dept of Electrical and Computer Engineering (Application of ultra-thin films to silicon solar cells)

Advanced Solar Cells Group

The Advanced Solar Cells Group focuses on the development and commercialisation of low-cost high-efficiency solar cells and modules. One focus area is the exploration of novel or advanced processes and technologies that enable to approach the practical 1-Sun efficiency limit of ~27% of single-junction silicon solar cells while maintaining low manufacturing costs ($/$W_p$) and excellent long-term stability. The other focus area is the development and upscaling of process technologies for low-cost large (> 200 cm^2) 30% efficient perovskite-silicon tandem solar cells and mini-modules (SERIS flagship project). A modern cleanroom laboratory (> 1200 m^2) enables single- and double-junction solar cell fabrication on n- and p-type industrial Cz silicon substrates. The group collaborates with numerous solar cell, equipment, automation and materials companies to jointly develop new processes and technologies. Selected research topics include development of novel or advanced functional layers or layer stacks (e.g. charge carrier transport layers, recombination junctions), upscaling of next-generation thin-film semiconductors (e.g. perovskites), tandem cell & mini-module fabrication, and related materials and equipment R&D.

Group Head
Prof Armin ABERLE

Research Scientists / Engineers
- Dr Yu Jin JANG
- Dr Jinhyun KIM
- Dr Romika SHARMA
- John Derek Dumaguin ARCEBAL (until Feb 2025)
- Gabby Alonzo DE LUNA

Adjunct Researcher
Assoc Prof Aaron DANNER

PhD students
- Varsha DAHIYA (until Sep 2025)
- LAN Yuchi (until Aug 2025)
- Erik Maurits SPAANS
- YAP Qi Jia

Academic Visitor
Assoc Prof CAI Jingyong

Corporate Laboratory Group

This group hosts, manages and operates the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics project that started at SERIS on 1st November 2022. The group focuses on the development and commercialisation of two-terminal (2T) perovskite-silicon tandem solar cell technologies. The key research areas are (1) high-throughput and ultra-fast deposition methods to enable > 30% efficiency for industrially relevant large-area (≥ 244 cm^2) 2T perovskite-silicon tandem solar cells with good long-term stability, (2) tackling process and equipment upscaling challenges to reduce the barriers to industrial manufacturing of perovskite-silicon tandem cells, and (3) establishing rapid metrology and monitoring techniques suitable for industrial production lines to enable reliable process control methods for 2T perovskite-silicon tandem solar cell manufacturing. The heart of the Corporate Laboratory project is a dedicated 200-m^2 zone at SERIS that houses a state-of-the-art R&D pilot line for ultra-fast deposition of perovskite top cells on large-area silicon bottom cells with sizes of up to G12 (210 mm x 210 mm). The group also utilises the Silicon cleanroom lab where heterojunction bottom cells are being made using large industrial Cz silicon wafers. The group works in close partnership with local solar cell & module manufacturer REC Solar, and collaborates with external research teams (e.g. at Nanyang Technological University, NTU) as well as several equipment, automation and materials companies to establish a leading ecosystem for tandem photovoltaics in the region.

Group Head and Project Manager
- Dr Selvaraj VENKATARAJ (Group Head)
- Dr Biplab GHOSH (Manager of Corp Lab project)

Principal Investigator
Prof Armin ABERLE

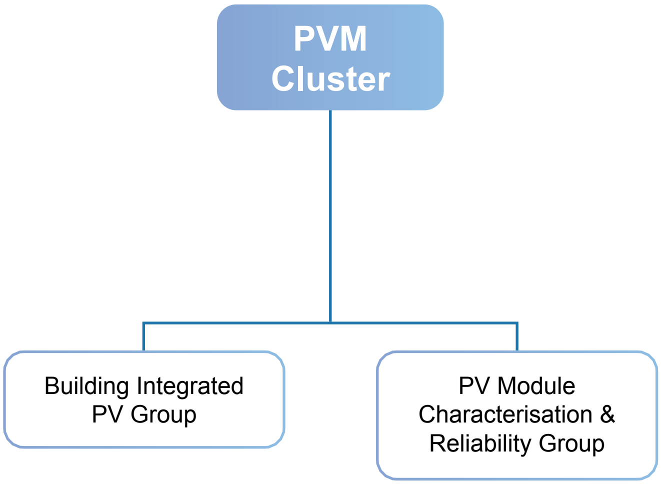
Research Scientists / Engineers
- Dr Jan HASCHKE
- Dr Yong Ryun KIM
- Dr Krishna SINGH
- Jammaal Kitz BUATIS
- Edwin Decena CARMONA
- Mohammed M. S. FARAJ
- Rosalie Cleofe GUERRA
- Mohd Asri Bin MOHD HAMDAN
- Jeffrey Garcia ISON
- Maria Luz Loria MANALO
- Delio Justiniani PEREZ
- Ashwath Narayan RAVICHANDRAN
- Louis Nicholas RETNAM
- Bobby Salinas UNGOS

Internship Students
- CHIA Ern Kang (since Jul 2025)
- LIANG Zhongchen (since Jul 2025)
- LEI Yanyang (since Jul 2025)

3. PV Modules for Urban Solar Cluster (PVM)

The PVM cluster develops and characterises novel and advanced PV module technologies suited for urban and tropical applications. It consists of two research groups - the Building Integrated Photovoltaics (BIPV) Group and the PV Module Characterisation and Reliability (PVMC&R) Group. The cluster is located in the CleanTech One (CTO) building at Singapore's CleanTech Park, hosting the PV module technology R&D laboratory and SERIS' ISO/IEC 17025 accredited laboratory for PV module testing. The cluster's main R&D activities are: development of building-integrated PV technologies (for SERIS' BIPV flagship project) and for various urban solar applications; advanced and pre-normative characterisation methods for PV modules; reliability studies for the three flagship projects of SERIS (tandem solar cells, BIPV modules & systems, floating PV); studies of degradation mechanisms that are particularly relevant for tropical climates, including potential-induced degradation (PID); and novel methods for PV module recycling.

Cluster Director's Office
Dr Thomas REINDL Acting Cluster Director
Dr LONG Jidong Laboratory Manager
Mabel LEOW Cluster Secretary



Organisation chart of the PV Modules for Urban Solar Cluster (in Dec 2025)

Group Heads
Dr Carlos Enrico Cobar CLEMENT BIPV
Aziz NAIRI PV Module Characterisation and Reliability
Adjunct Researchers, NUS
Prof Seeram RAMAKRISHNA Dept of Mechanical Engineering (PV modules)
Assoc Prof Karl Erik BIRGERSSON Dept of Mechanical Engineering (Modelling of PV modules)

Building Integrated Photovoltaics (BIPV) Group

The Building Integrated Photovoltaics (BIPV) Group drives innovation in PV solutions tailored for urban environments, spanning curtain walls, façades, balustrades, sunshades, noise barriers, and other non-traditional surfaces. Our work combines technical performance with architectural and urban design by creating IP that enables colourful, patterned PV modules with minimal efficiency loss – offering architects and city planners new tools to realise sustainable and visually striking PV surfaces. Key research areas include PV fire safety, the unique shading challenges faced by BIPV systems, and the development of multi-functional, aesthetic PV technologies for façades and other urban surfaces (e.g. noise barriers, fences). The group also explores the integration of BIPV into Building Information Modelling (BIM) workflows, ensuring seamless adoption across the building lifecycle.

Group Head

Dr Carlos Enrico Cobar CLEMENT

Research Scientists / Engineers

- Rupendra ARYAL
- Dr CHEN Tianyi
- Srinath NALLURI (50%)

PhD Students

- YUE Jiaming
- Vundrala Sumedha REDDY (until Sep 2025)

Internship Students

- HUANG Zitao (until July 2025)
- Priscille KOEHL (until Aug 2025)
- Wilson Bolton MOYER (until Aug 2025)
- Chanet RUANGRIT (until Oct 2025)
- XIONG Suwen (until Nov 2025)

PV Module Characterisation & Reliability Group

The group operates SERIS' ISO/IEC 17025 accredited laboratory for PV module testing. Its research activities focus on two main topics: (i) Electrical characterisation of PV modules and (ii) PV module reliability. High-efficiency PV modules and innovative architectures - such as bifacial, floating, curved, coloured and multi-junction modules - are the subject of research on new and innovative measurement methods for which standardisation is required. Reliability studies are conducted via investigating the theoretical basis and the kinetics of important PV module degradation mechanisms such as PID (potential-induced degradation) and LeTID (light and elevated temperature induced degradation). Studies of the module degradation modes in high-humidity and high-UV conditions are performed based on the data and evidence from the field. Reliability stress testing of modules designed for floating PV is a new research topic that is attracting attention from the PV industry. Furthermore, pre-normative PV module metrology activities are routinely conducted in liaison with the International Electrotechnical Commission (IEC) and research partners worldwide.

Group Head

Aziz NAIRI

Research Scientists/Engineers

- Maryknol Estrada DELOS SANTOS (Quality & Safety)
- Henry LIM Kian Meng (Head of Metrology)
- Srinath NALLURI (50%)
- John Arcebal Derek DUMAGUIN (since Apr 2025)

R&D Project Executive

Zuraidah Binte JA'AFAR

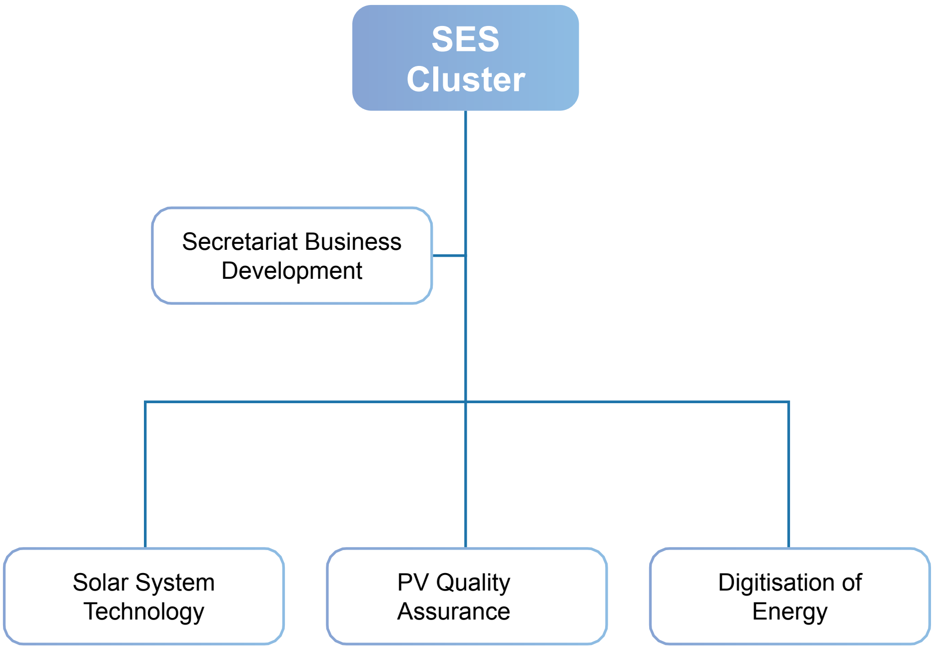
Technicians

- CHOY Woon Loong
- CHUAH Tuang Heok
- LOH Joon Ann (until Jul 2025)
- Abdul RAZAK BIN SAMAN

4. Solar Energy Systems Cluster (SES)

The Solar Energy Systems (SES) Cluster focuses on making solar power a cost-effective and trusted source of electricity. The SES activities have a wide variety and span from remote monitoring to novel PV system deployments such as Agrivoltaics (= combining agriculture + PV) and forecasting of irradiance for better grid integration management. The cluster also addresses the specific challenges when deploying solar technologies in urban environments like Singapore and other megacities. SES is driving the SERIS flagship project on Floating Solar and focuses on important aspects to increase solar adoption, such as solar potential analysis, quality assurance, technical standards, long-term reliability, smart operation and maintenance (O&M) of PV assets, and the economics of PV installations.

Cluster Director's Office
Dr Thomas REINDL Cluster Director
Eddy BLOKKEN Senior Business Development Manager
Dr Xiaoqi XU Research Fellow, Smart O&M
Marinel DUNGCA Cluster Secretary



Organisation chart of the Solar Energy Systems Cluster (in Dec 2025)

Group Heads
Dr Serena LIN Fen Solar System Technology (since Mar 2025)
Dr Jaffar Moideen YACOB ALI Solar System Technology (until Feb 2025)
Dr Thomas REINDL Digitisation of Energy (acting)
Kendrick LOH Chun Ming PV Quality Assurance (Co-Head) (since Oct 2025)
Eddy BLOKKEN PV Quality Assurance (Co-Head) (since Oct 2025)
Rachel TAN Yek Wha PV Quality Assurance (until Sep 2025)
Team Leader
SOE Pyae PV Monitoring
Adjunct Researchers, NUS
Assoc Prof Ashwin KHAMBADKONE Dept of Electrical and Computer Engineering (Analysis and solutions for PV grid integration through energy system modelling and advanced power electronics & control for smart grids)
Assoc Prof Sanjib Kumar PANDA Dept of Electrical and Computer Engineering (High-performance control of power electronic converters)
Prof Dipti SRINAVASAN Dept of Electrical and Computer Engineering (Analysis of impacts of solar PV integration into the medium- and low-voltage power distribution systems)
Assoc Prof Stephen TAY En Rong Dept of the Built Environment (Glare studies, co-location of PV with greenery and PV and urban heat island (UHI) effect)

Solar System Technology Group

The group runs extensive research programmes that are the scientific base to analyse and optimise the performance of solar PV systems in the tropics. They include outdoor energy yield evaluation on both module and system levels to better understand the performance and degradation of various PV module technologies in Singapore's tropical climate conditions. Beyond the tropics, the team also carries out comparative research on PV module and system performance across different climate zones (within the "TruePower" project). A major emphasis of the group is on integrated PV applications, such as "Floating Solar", "Urban Solar" and "Agrivoltaics", with the goal of developing technologies and solutions that maximise solar deployment in Singapore while addressing challenges such as high urbanisation and space constraints. A special focus is "Floating Solar". The group has established international leadership in this field by building deep technical expertise in system design, implementation, operation and maintenance, as well as energy-yield assessment through the MW-scale floating PV testbed at the Tengeh Reservoir and a wide range of technical consultancy projects. Current research is expanding toward near-shore and offshore floating solar to evaluate its potential for co-location with applications such as aquaculture and desalination. The "Urban Solar" activities include the design, test-bedding and optimisation of innovative concepts that integrate PV into existing infrastructures, such as carparks, roadways, flood canals and rooftop spaces with high utilisation. Under "Agrivoltaics", the group operates both soil-based and soil-less agrivoltaic testbeds in Singapore, covering the full process from concept development to implementation, testing and optimisation. These efforts aim to develop practical urban-farming solutions that balance energy generation, energy consumption and crop yield.

Group Head

- Dr Serena LIN Fen (since Mar 2025)
- Dr Jaffar Moideen YACOB ALI (until Feb 2025)

Research Scientists / Engineers

- Myint Khaing AUNG
- Dr Oktoviano GANDHI
- LIU Tianyuan
- Lokesh VINAYAGAM
- ZHAO Shengnan

Technicians

- David KHUP
- Jamil Bin ZAINAL

Internship Student

YIN Kaili (until Sep 2025)

PV Quality Assurance Group

The perceived quality of a photovoltaic (PV) system is determined by multiple dimensions, ranging from the reliability of individual components to the robustness of system design, to long-term aspects such as operation and maintenance (O&M) practices and overall economic viability. Ensuring that these elements meet the highest standards is essential for building trust among investors, developers, and end-users. In its role as a Lender's Technical Advisor (LTA), the group delivers comprehensive support through both economic analyses and an extensive portfolio of technical services. This includes conducting independent third-party reviews of system design, engineering, and project execution, as well as preparing feasibility studies and carrying out detailed technical due diligence assessments. These evaluations help financial institutions and stakeholders to make informed decisions with confidence, reducing project risks while strengthening bankability. Equally important are the group's Owner's Engineer (OE) services, which focus on safeguarding project quality and long-term performance. These services typically encompass on-site inspections of PV installations, system performance evaluations and energy audits, and the testing and commissioning (T&C) of PV systems. All activities are carried out in alignment with local regulatory requirements and international best practices and standards, ensuring that projects not only comply with statutory obligations but also achieve optimal efficiency and reliability. By combining technical expertise with an independent and objective perspective, the group's services provide system owners, lenders, and government authorities with assurance that their PV investments are designed, built, and operated to deliver sustainable, high-quality outcomes throughout the system's lifecycle.

Group Head

- Eddy BLOKKEN (Co-Head, since Oct 2025)
- Kendrick LOH Chun Ming (Co-Head, since Oct 2025, T&C Lead)
- Rachel TAN Yek Wha (until Sep 2025)

Research Scientists / Engineers

- Nicholas Hong ALAMSYAH
- Lutfi Irawan Bin RAWAN
- SEAH Zhan Qi, Eugene
- Dexter TONG Yong Hong

Technicians

- Norhisham Bin HABDIN
- Muhammad Fahmie Bin IDRUS
- KOH Jun Yong
- Muhamad Firdaus Bin YUSOF

Digitisation of Energy Group

The group develops proprietary software tools and also applies commercially available solutions to address challenges of solar PV deployment which can be solved by information technology (IT) and artificial intelligence (AI). One of the challenges is the high variability of the solar resource, particularly in tropical regions such as Singapore. This is being addressed by “solar forecasting”, for which the group has developed a fully operational forecasting system that has been successfully implemented inside the Power System Operation Division (PSOD) of Singapore’s grid operator EMA (Energy Market Authority). It combines several data streams from ground sensors, satellite imagery and numerical weather prediction models with advanced machine learning blending approaches to generate the best-possible combination of forecasting techniques over time horizons ranging from 5 minutes to 24 hours ahead. Beyond Singapore, the group has also developed a regional solar forecasting model based on high-resolution satellite data. Another challenge is the highly distributed nature of solar PV deployment (particularly in urban areas) and the need for remote monitoring and control. SERIS has developed a proprietary “live” monitoring system that lets asset owners know their PV power generation in real time, which greatly assists trouble shooting, energy flow optimisations for self-consumption, and reporting to the authorities (e.g. to the grid operator). The group also has in-depth knowledge in solar potential assessment (on building, neighbourhood and city-scale), complex glare studies, and various types of feasibility studies.

Group Head
Dr Thomas REINDL (acting)

Team Leader
SOE Pyae, PV Monitoring

Research Scientists / Engineers
- Erik AUNG Naing Thu
- KYAW Zin Win
- David LEE Soon Kiat
- Sholihin Bin SANI (until Oct 2025)
- Hrishikesh Nitin SATARKAR
- Dr SUN Huixuan
- Dr Gokhan Mert YAGLI

Internship Students
- ANG Wei Xiang Anson (until Aug 2025)
- CHIA Yu Hong (until Jan 2025)
- Joan LOH Yee Li (since Mar 2025)
- Ethan LEE Jie (until Feb 2025)
- ONN Zhi Kang Jacky (until Feb 2025)
- SEOW Qian Yun (since Aug 2025)

SERIS CENTRAL SERVICES UNITS

Administration

SERIS' Administration Unit works closely with NUS' centralised administration team to jointly provide a spectrum of administrative support services (contract management, finance, human resources, information technology, intellectual property, legal and procurement) to the institute's research and development activities. The unit also works closely with SERIS' funding agencies - the National Research Foundation Singapore (NRF), the Energy Market Authority (EMA) and the Singapore Economic Development Board (EDB) - as well as other grantors and various stakeholders within NUS to ensure close collaboration on administrative issues.

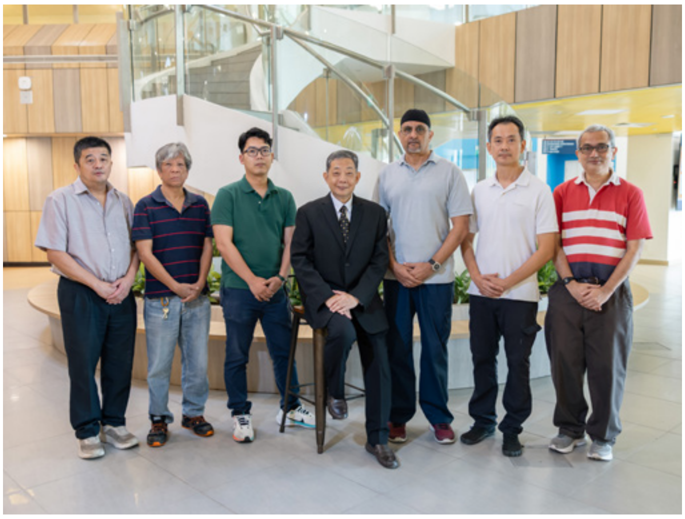
Director

Shakander Singh CHAHAL

Team

- CHUA Ai Leng
- Noor A'ishah Bte MOHAMAD
- Grace SIA De La Cruz (from Feb 2025)

Technical Infrastructure & QESH



The unit consists of the Technical Infrastructure Team and the Quality, Environment, Safety & Health (QESH) Team. The Technical Infrastructure Team oversees all facilities and provides infrastructure support to all SERIS laboratories and offices. The QESH Team oversees all QESH matters, including the ISO 9001 Quality Management System, the ISO 17025 Laboratory Accreditation, and the NUS Safety & Health Management System Certification.

Director

Peter LIM Young Leng

Team Leaders

- Peter LIM Young Leng (QESH)
- LOI Teck Shiun (Technical Infrastructure)

Laboratory Manager

Dr Firdaus Bin SUHAIMI (Perovskite Solar Cell Lab)

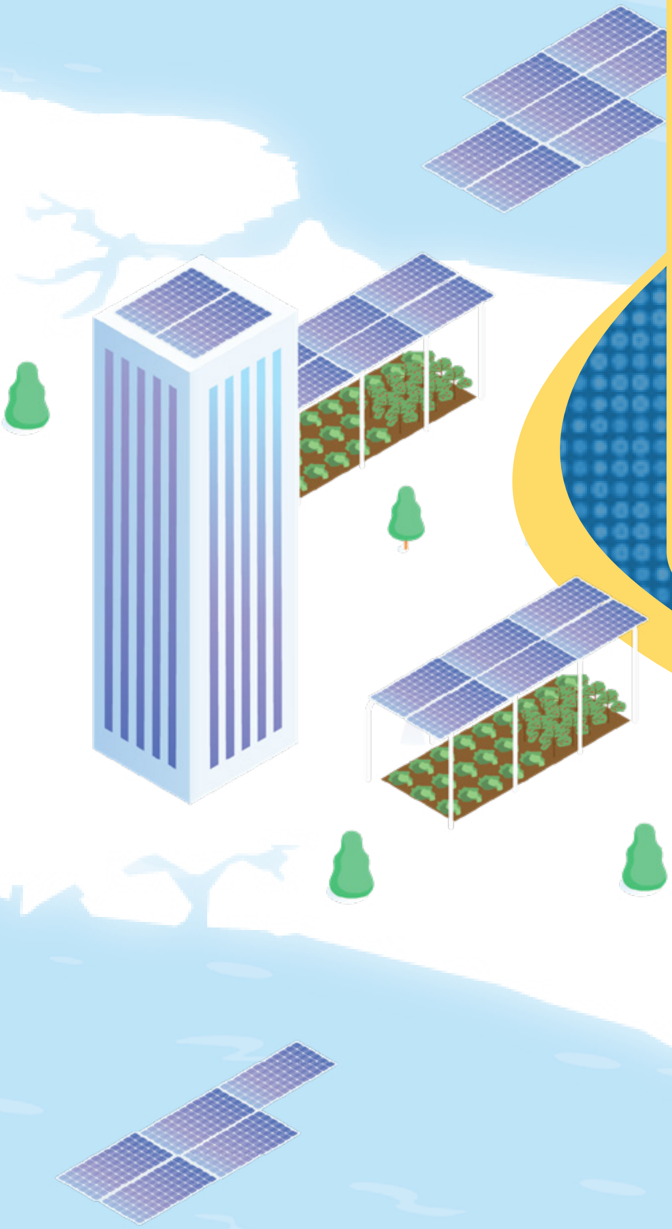
Staff, Technical Infrastructure Team

- CHEANG Kong Heng
- CHEW Siow Choen
- Muhammad Shaheer HARDIP
- WONG Wei Lung

Staff, QESH Team

Syed Nasser Bin ABDUL QUDDOOS

RESEARCH & DEVELOPMENT



NPVC Acting Cluster Director's Foreword

Prof Armin ABERLE
Acting Director, Novel PV Concept Cluster

> *We are developing double- and triple-junction perovskite-silicon tandem solar cells with 1-Sun efficiencies of well above 30% and good potential for long-term stability and low manufacturing costs.*

Research Focus / R&D portfolio of NPVC Cluster

In 2025, the Cluster's research continued to focus on the development and improvement of single-junction perovskite cells and small-area (up to 1 cm^2) double- and triple-junction perovskite-silicon tandem cells (SERIS Flagship project). We are using low-cost coating methods for high-quality wide-bandgap perovskite semiconductors, making them an excellent choice for the top sub-cells in tandem applications paired with silicon bottom sub-cells. We are exploring innovative perovskite compositions, passivation strategies, thin-film fabrication methods and device architectures, all aimed at improving wide-bandgap perovskites in multi-junction solar cells. In parallel, we have been working on the enhancement of our characterisation, modelling, simulation and reliability study capabilities for tandem solar cells.

1. Major activities/achievements in 2025

Perovskite-based Multijunction Solar Cells Group

This multi-disciplinary group is dedicated to advancing hybrid perovskite materials for next-generation tandem photovoltaic technologies with the potential to positively impact future energy and environmental sustainability. To overcome the limitations of single-junction photovoltaics, we are synergistically stacking solar cells with decreasing bandgaps to effectively overcome the Shockley-Queisser limit. We are accelerating the development of perovskite-based solar cells by using low-cost coating methods for high-quality, wide-bandgap semiconductors, making them an excellent choice for top sub-cells in tandem applications paired with lower-bandgap bottom subcells.

Two-junction perovskite-Si tandem cells

In 2025, SERIS' Perovskite-based Multijunction Solar Cells Group achieved 33.3% efficiency for a perovskite-silicon tandem solar cell using an industrially fabricated Cz heterojunction silicon bottom cell with cell area of 1 cm^2, see Fig. 1. The measurement was performed at SERIS. This was accomplished by successfully forming high-quality 1.66-eV perovskite films on textured silicon surfaces using the spin-coating method. A key challenge in this work was improving the perovskite crystal quality on silicon architectures. We introduced a ligand that effectively controls the principal organic cations to regulate crystallisation. Our organic control approach supplements previous strategies mainly focused on strong coordination with inorganic lead halides (inorganic control), enabling refined crystal growth and improved film quality of perovskite films on thin Si wafers. We effectively minimised the quality gap between perovskite films grown on glass and those grown on thin Si substrates, thereby enabling high-quality wide-bandgap perovskite films being integrated with industrially fabricated Cz silicon bottom cells.

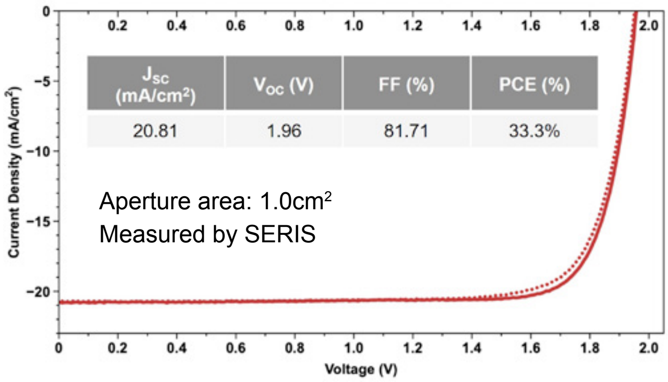


Fig. 1: Measured J-V curves of a 33.3% efficient perovskite-silicon tandem solar cell (1.0 cm^2 aperture area) made at SERIS using a Cz heterojunction silicon bottom cell. The silicon cell has pyramid-textured front and rear surfaces. The perovskite absorber was made by spin coating.

The group's ongoing efforts are focused on closing the gap to the current world-record 1-cm^2 perovskite-silicon tandem solar cell (34.8%, LONGi, China).

Triple-junction perovskite-perovskite-Si tandem cells

The Multijunction Group also made very good progress in 2025 with its high-efficiency triple-junction solar cells. This innovation combines a 1.53-eV perovskite middle cell with a 1.9-eV wide-bandgap perovskite top cell (both developed by SERIS) and a heterojunction silicon bottom cell supplied by an external collaborator. These cells employ double-side textured n-type Cz-Si wafers for the bottom cell. Meticulous process optimisation enabled the deposition of a high-quality 1.53-eV perovskite middle cell onto the textured Si bottom cell, achieving a smooth upper surface. A thin 1.9-eV perovskite top cell was then deposited onto this smooth middle cell. As shown in Fig. 2, one of these triple-junction solar cells made in 2025 has a 1-Sun efficiency of 29.6%, measured at SERIS using a shadow mask with an aperture area of 1.0 cm^2.

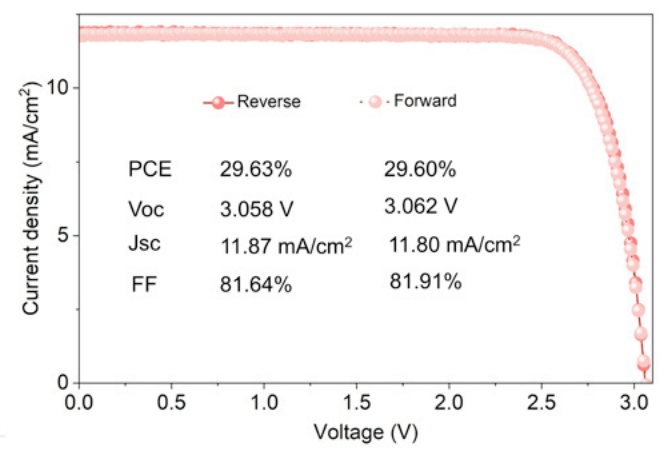


Fig. 2. Measured 1-Sun J-V curves (forward, reverse) of a 29.6% efficient perovskite-perovskite-silicon triple-junction solar cell (1.0 cm² aperture area) made in 2025 in SERIS on a textured Cz silicon bottom cell.

Selected publications:

- Surpassing 90% Shockley-Queisser V_{oc} limit in 1.79 eV wide-bandgap perovskite solar cells using bromine-substituted self-assembled monolayers, Z. Wei, Q. Zhou, X. Niu, S. Liu, Z. Dong, H. Liang, J. Chen, Z. Shi, X. Wang, Z. Jia, X. Guo, R. Guo, X. Meng, Y.-D. Wang, N. Li, Z. Xu, Z. Li, A.G. Aberle, X. Yin and Y. Hou, Energy Environ. Sci. 2025, 18, 1847-1855.
- Determining the bonding-degradation trade-off at heterointerfaces for increased efficiency and stability of perovskite solar cells, J. Chen, X. Wang, T. Wang, J. Li, H.Y. Chia, H. Liang, S. Xi, S. Liu, X. Guo, R. Guo, Z. Jia, X. Yin, Q. Zhou, Y. Wang, Z. Shi, H. Zhou, D. Lai, M. Zhang, Z. Xing, W.R. Leow, W. Yan and Y. Hou, Nature Energy 2025, 10(2), 181-190.
- Perovskite tandems: the next big leap in photovoltaic technology, C. Luo, H. Gu, B. Zhang, S.M. Park, M. Wei and Y. Hou, Adv. Mater. 2025, e08331.

PV Devices Characterisation Group

Understanding and measuring the properties of materials related to tandem solar cells is crucial for enhancing solar cell device performance and reliability. SERIS is equipped with several advanced characterisation tools and continues to develop new measurement and analysis techniques to provide deeper insights for device optimisation and process control. In 2025, our efforts focused on further developing our effective carrier lifetime imaging method for perovskite solar cells using modulated optical excitation. This technique is fast and provides spatial and quantitative information on the effective carrier lifetime of the perovskite samples, as shown in Fig. 3.

Furthermore, we have initiated outdoor monitoring of tandem solar cells, in collaboration with several groups in SERIS. This cross-cluster activity has provided information on the performance ratio of the short-circuit current I_{sc} of tandem cell mini-modules in Singapore outdoor conditions, over a period of 5 months. This was demonstrated for mini-modules with and without edge sealant as can be seen in Fig. 4. The works on effective carrier lifetime imaging and outdoor monitoring were both presented at the SNEC 2025 conference in China.

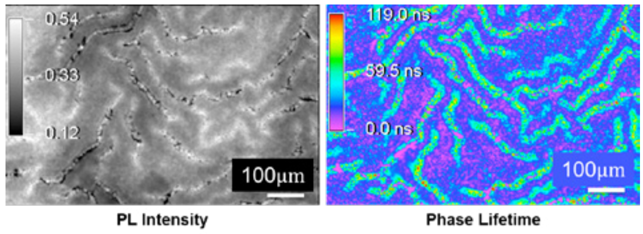


Fig. 3. Modulated optical excitation imaging of a small region (< 1 mm²) of a perovskite film with (left) photoluminescence intensity information and (right) phase-derived effective carrier lifetime. The effective carrier lifetime map hints at laterally non-homogeneous crystallisation of the perovskite film.

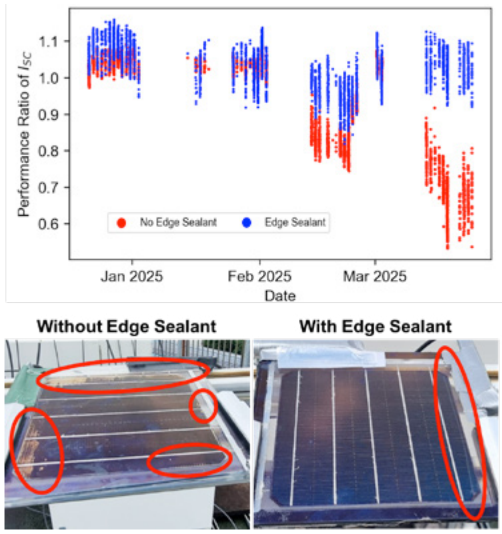


Fig. 4. (Top) Performance ratio of I_{SC} of tandem cell mini-modules with and without edge sealant, in outdoor conditions at a NUS rooftop, over a 5-month period. (Bottom) Photographs of mini-modules with and without edge sealant after 5 months. Multiple defects are visible for the one without edge sealant, likely due to moisture penetration.

Modelling of perovskite-based tandem solar cells

We are developing neural networks to support the fabrication and characterisation of tandem solar cells, with a focus on the perovskite top cell layers. In 2025, we expanded our datasets using a physics-based optoelectronic model to train multiple neural network architectures for predicting device performance. The new 200k-entry dataset strengthens the networks by integrating analytical solutions and relevant constraints. Our earlier work with a 100k dataset, led by X. Zhao, was published in Applied Energy in 2025.

Selected publications:

- X. Zhao, C. Huang, E. Birgersson, N. Suprun, H.Q. Tan, Y. Zhang, Y. Jiang, C. Shou, J. Sun, J. Peng and H. Xue. Accelerating device characterisation in perovskite solar cells via neural network approach, Applied Energy, vol 392 (2025).

2. Plans of NPVC Cluster for 2026

- Achieve > 34% efficiency for a 2-junction perovskite-silicon tandem solar cell with active area of at least 1 cm²
- Achieve > 30% efficiency for a 2-junction perovskite-silicon tandem mini-module with active area of at least 150 cm²
- Further enhance the fabrication and characterisation capabilities for perovskite-silicon tandem solar cells and mini-modules
- Conduct reliability studies for perovskite-silicon tandem solar cells
- Develop advanced or novel mathematical models for perovskite solar cells and perovskite-silicon tandems
- Develop in-depth loss analysis of perovskite solar cells and perovskite-silicon tandems

NISCM Cluster Director's Foreword

Prof Armin ABERLE

Director, Next-Generation Industrial Solar Cells and Modules Cluster

We are developing and upscaling technological processes for the next generation of industrial solar cells and PV modules.

Research Focus / R&D portfolio of NPVC Cluster

In 2025, the focus of the NISCM Cluster's two R&D groups remained on next-generation industrial solar cells and modules providing improved PV efficiency and cost effectiveness (LCOE, \$/kWh). The Advanced Solar Cells Group continued its research on medium-to-large (16 - 244 cm^2) perovskite-silicon tandem solar cells and mini-modules with targeted efficiencies of > 30% (SERIS flagship project), while the Corporate Laboratory Group focused on establishing a new R&D pilot line for ultra-large (440 cm^2, G12 size) 30% perovskite-silicon tandem solar cells using an ultra-fast perovskite deposition process ("REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics").

1. Major activities / achievements in 2025

Advanced Solar Cells Group

In 2025, the ASC Group continued to make good progress with improving the PV efficiencies of perovskite-silicon tandem solar cells with active areas of 16 and 244 cm^2, as shown in the photographs of Fig. 1 (Tandem cell flagship project). Both the silicon bottom cells (heterojunction, Cz wafers) and the perovskite top cells were fully made in SERIS. A low-temperature screen-printed silver metallisation was utilised on both sides of the 2-terminal (2T) tandem solar cells.

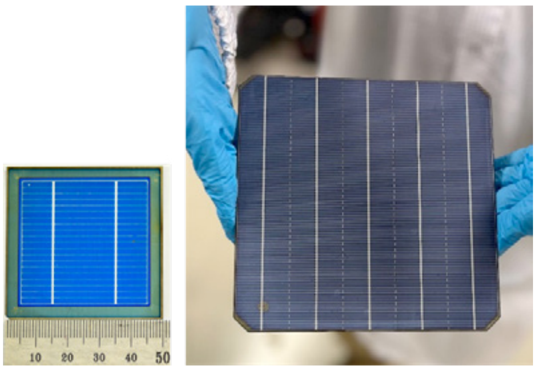


Fig. 1: Photographs of SERIS-made perovskite-silicon 2T tandem solar cells for the Tandem cell flagship project. (Left) 16-cm^2 (active area) device on a 25-cm^2 smooth silicon substrate; (Right) M2-size (244 cm^2) full-wafer tandem cell with textured silicon surface

The current-voltage curves of a 16-cm^2 tandem cell measured at SERIS and a schematic of the cross-sectional device structure are shown in Fig. 2. The cell has an efficiency of 28.2%, which is a very good result considering that the top surface of the silicon bottom cell is smooth (i.e., not textured), which limits the current that can be generated by the silicon cell. The top cell's perovskite absorber layer has a bandgap of ~1.68 eV and was deposited using the spin-coating method.

During spinning the wet precursor film spreads uniformly across the surface and undergoes rapid and controlled crystallisation, leading to large well-formed crystal grains with few defects. This results in a high electronic quality of the absorber layer and enabled the group to achieve more than 28% tandem cell efficiency on 16 cm^2, up from 25% a year earlier.

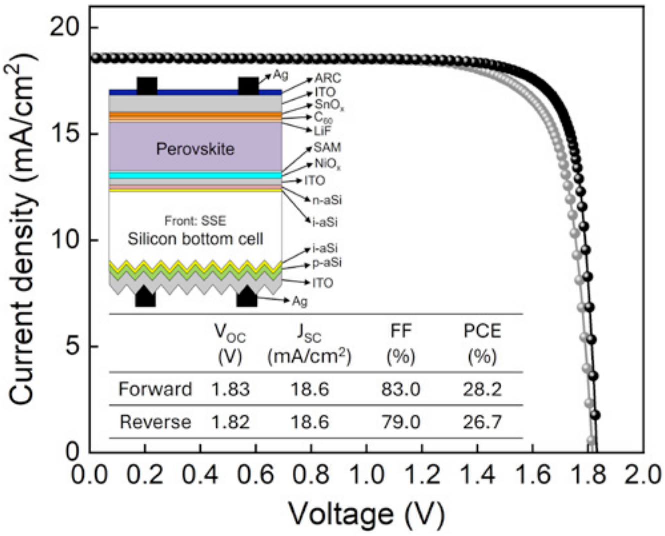


Fig. 2: Measured 1-Sun J-V curves of a 28.2% efficient perovskite-silicon 2T tandem solar cell with active area of 16 cm^2. The inset shows a schematic cross section of the device structure. The heterojunction Cz silicon bottom cell has a smooth front surface and a pyramid-textured rear surface. The perovskite absorber was made by spin coating.

Using SERIS-made heterojunction silicon bottom cells on M2-size (244 cm^2) Cz wafers with pyramid texture on both surfaces, the group achieved 24.1% tandem cell efficiency in 2025. The M2-size perovskite absorber layer of the top cell was produced via a 2-step hybrid dry-wet processing sequence, providing compatibility with upscaling to industrial wafer sizes and mass production workflows. The current-voltage curve of the 24.1% tandem cell and a schematic of its cross-sectional device structure are shown in Fig. 3. As can be seen, the open-circuit voltage (1.80 V) is good, but the fill factor is still rather low (~68%) due to a shunting issue. The group's ongoing efforts are focused on eliminating this cell shunting issue and improving the tandem cell efficiency to more than 30%.

These achievements make SERIS the only facility in Singapore, and one of only a few labs in the world, capable of producing fully in-house fabricated high-efficiency perovskite-silicon 2T tandem solar cells on industrial-size silicon wafer substrates (M2 size). In terms of power conversion efficiencies, SERIS maintained its position in 2025 as one of the top labs in the world for medium (~20 cm^2) and large-area (> 200 cm^2) 2-junction perovskite-silicon tandem solar cells.

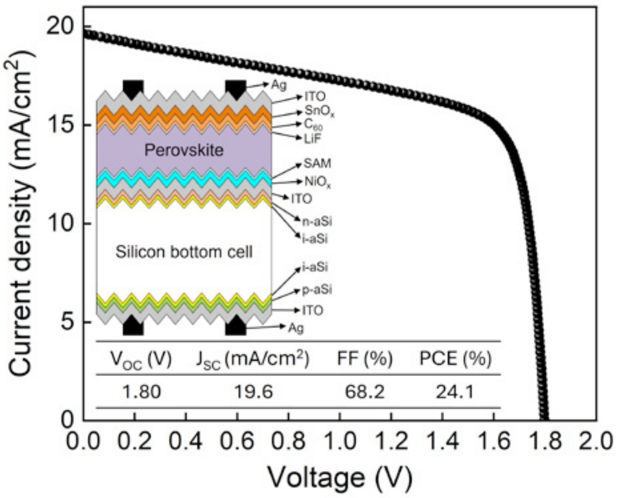


Fig. 3: Measured 1-Sun J-V curve of a 24.1% efficient perovskite-silicon 2T tandem solar cell with an area of 244 cm^2 (M2 size wafer). The heterojunction Cz silicon bottom cell has pyramid-textured front and rear surfaces. The perovskite absorber was made by a 2-step hybrid dry-wet processing sequence.

Development and upscaling of perovskite-silicon tandem cell mini-modules

In 2025, the project's module team continued its work on the scaling of perovskite-silicon tandem cell mini-modules from lab-scale devices to M2-size (244 cm²) prototypes. This process requires significant adaptation of our fabrication methods to meet the low thermal budget requirements imposed by the perovskite top cells. The Bill of Materials (BOM) was optimised to ensure compatibility with low-temperature processes below 120°C, without sacrificing efficiency. The main achievement in 2025 was the fabrication and testing of M2-size perovskite-silicon 1-cell tandem mini-modules with efficiencies of more than 21%, up from 16% a year earlier. Figure 4 shows a photograph of one of these fully in-house fabricated 244-cm² tandem mini-modules featuring low-temperature encapsulation and interconnections. This efficiency result was obtained through significant improvements in low-temperature encapsulation and interconnection technologies, specifically designed to meet the stringent temperature requirements of perovskite layers while reducing thermal stress and protecting structural integrity. The team screened and evaluated thermoplastic polyolefin (TPO) encapsulants for compatibility with perovskite layers, demonstrating high optical transmittance and minimal degradation after damp-heat testing, which is comparable to or better than that of conventional encapsulants. Stencil-printed electrically conductive adhesives (ECAs) were optimised for low-temperature interconnections, enabling strong adhesion while minimising cell-to-module (CTM) losses.

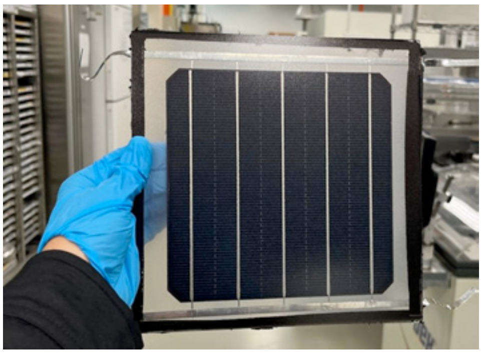


Fig. 4: Photograph of a fully in-house fabricated 244-cm² (M2-size) perovskite-silicon 1-cell tandem mini-module featuring low-temperature encapsulation and interconnections.

In 2025, the module team achieved the following technical milestones:

- Over 21% efficiency (with CTM losses of ~5%) for M2-size 244-cm² 1-cell tandem mini-modules. Using advanced materials (BOM) and encapsulation methods, we maintained the structural integrity and performance of these mini-modules, marking an important step forward on the path to commercialisation of perovskite-silicon PV technology.
- Outdoor testing of tandem cell mini-modules: We started our outdoor tandem-cell mini-module testing activities at the NUS Rooftop Testbed in tropical Singapore in December 2024, using in-house fabricated tandem mini-modules. The initial tests highlighted the need for a stricter Bill of Materials in hot-humid conditions. In September 2025, the second batch of tandem mini-modules with optimised BOM for the tropics was deployed for continuous J_{sc} logging, temperature/irradiance monitoring, and monthly indoor stabilised I-V and spectral response measurements. Initial results show no significant degradation, with continuous monitoring ongoing to validate long-term stability.
- Indoor stability testing of tandem mini-modules: In June 2025, we initiated indoor testing of tandem modules under accelerated stress conditions. This includes damp-heat exposure, thermal cycling, and continuous maximum power point tracking (MPPT) under controlled irradiance and temperature conditions. We use in-house fabricated perovskite-silicon 1-cell tandem mini-modules for these tests. The primary aim is to identify possible degradation pathways and failure modes. We also aim to correlate these findings with outdoor data to provide accurate module lifetime predictions.

Path Forward: Towards a 60-cell perovskite-silicon tandem module

The R&D roadmap of this flagship project involves the scaling up of 1-cell perovskite-silicon tandem mini-modules to 60-cell (~1.7 m²) tandem modules by March 2027. Current efforts are focused on improving the durability of the low-temperature encapsulants and ECAs while adapting the processes to industry-compatible methods. We are conducting climate chamber testing and MPPT testing under controlled illumination and temperature conditions to refine our processes and improve the PV efficiency and durability of these novel tandem modules. This is complemented by ongoing outdoor testing of the prototype modules in Singapore's hot and humid tropical climate, with emphasis on correlating indoor (damp heat, thermal cycling, and MPPT) and outdoor field data to predict degradation rates and guide BOM choices. Overall, this tandem flagship project is progressing well and is making major contributions to bringing the perovskite-silicon tandem PV technology closer to commercial viability, with the potential to deliver very-high-efficiency (30%) PV modules optimised for space-constrained environments like Singapore.

Corporate Laboratory Group

The group's main focus in 2025 was on establishing an R&D pilot line for ultra-large (up to 440 cm^2, G12 size) 30% perovskite-silicon tandem solar cells using an ultra-fast perovskite deposition process ("REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics"). The facilities for the new Corporate Lab zone at SERIS were completed in March 2025, followed by the installation of the perovskite deposition tools by Q4 2025. This R&D pilot line is expected to be ready for research in Q1 2026, and is believed to be the largest in South-East Asia and one of the very few globally in public research institutes.

In parallel to establishing the new pilot line, the group continued to make good progress in tandem solar cell development using the existing equipment infrastructure for perovskite top cells on M2-size silicon substrates. The group achieved tandem cell efficiencies of more than 25% on full-area M2 wafers in 2025, confirming the robustness and potential of our perovskite technology.

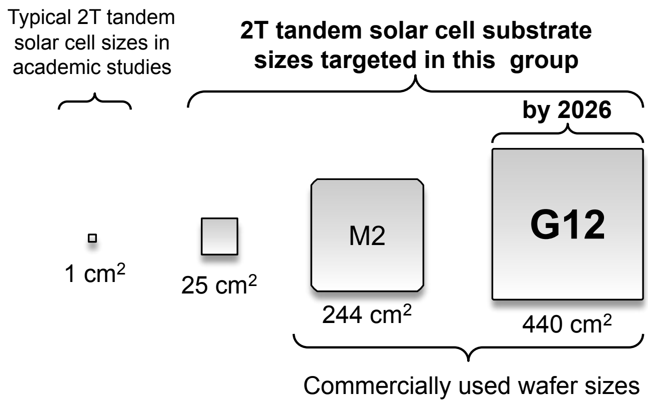


Fig. 5: Typical sizes of 2T perovskite-silicon tandem solar cells in academic studies (left) and in SERIS' Corporate Lab Group (right)

Building on the progress in 2025, the group has developed a realistic roadmap to achieve > 28% tandem cell efficiency in 2026. Furthermore, with the new R&D pilot line in place, significant efforts will be dedicated to up-scaling the technology towards the wafer sizes used in modern PV factories. The group will be transitioning from M2-size wafers to half-cut G12 wafers as well as full-size G12 wafers (440 cm^2), addressing key challenges in lateral thin-film uniformity, process stability and process yield. This work will be a crucial step towards demonstration of the technology's industrial viability, and will put the group in a strong position for future technology transfer to industry.

2. Plans of NISCM Cluster for 2026

- Enhance the fabrication and characterisation capabilities for perovskite-silicon tandem solar cells and mini-modules
- Develop know-how and intellectual properties (IP) on processing steps for industrial 2T perovskite-silicon tandem solar cells
- Achieve > 31% efficiency for perovskite-silicon tandem solar cells with area > 10 cm^2 and > 30% for tandem cells with area > 200 cm^2
- Achieve > 30% efficiency for perovskite-silicon mini-modules with active area of at least 150 cm^2
- Develop a 60-cell (~1.7 m^2) perovskite-silicon tandem module with power output of at least 400 W
- Conduct indoor & outdoor reliability studies for perovskite-silicon tandem solar cells and mini-modules
- Corporate Lab Group: Successfully commission the R&D pilot line for ultra-large perovskite-silicon tandem solar cells (up to 440 cm^2, G12 wafers)
- Corporate Lab Group: Achieve > 28% efficiency for tandem cells with area > 200 cm^2 and demonstrate tandem solar cells on both half-cut and full-size G12 wafers

PVM Cluster Director's Foreword

Dr Thomas REINDL
Acting Director, PV Modules for Urban Solar Cluster

> *The PVM Cluster hosts a world-class PV module testing laboratory, driving standardisation and the development of test methods for new stressors such as UVID or off-shore Floating PV. To enable more Building-integrated PV deployment, the Cluster is integrating BIPV into the BIM workflow and is creating fundamentally new design options using pixels, colours and timber structures.*

Research Focus / R&D portfolio of the PVM Cluster

In 2025, the Cluster's research focused on two main topics: (i) Reliability of PV modules, and (ii) Building Integrated Photovoltaics (BIPV). The Cluster also carries out research on recycling of PV modules, which makes SERIS one of the few research institutes in the world able to carry out holistic PV research, from solar cell & module development via PV module reliability studies & stress tests to PV module recycling. The Cluster consists of two groups: the PV Module Characterisation & Reliability Group, which also operates SERIS' ISO/IEC 17025 accredited laboratory for PV module testing, and the BIPV Group, which focuses on PV module development and PV recycling.

1. Major activities / achievements in 2025

PV Module Characterisation & Reliability Group

The group strongly supports industrial development in Singapore and the region through its leading PV module characterisation and testing services. The laboratory is accredited since 2012 to ISO/IEC 17025 for the electrical testing of PV modules, including the measurement of bifacial modules according to IEC TS 60904-1-2 Edition 1.0. SERIS also provides "Golden module" measurements to PV manufacturers in Singapore, Southeast Asia and Australia, based on our world-class uncertainty of ± 1.4% for the module's measured maximum power and the associated certificate from the Singapore Accreditation Council (SAC).

SERIS' PV Module testing laboratory (see Fig. 1) is considered a trusted reference lab by the PV industry in Asia. It successfully passed a comprehensive audit and round robin testing conducted by leading certification body TÜV Rheinland. In consequence, SERIS has been awarded the status of an official TÜV Rheinland "PV Module Testing Laboratory" (PTL). Both parties will work together to promote technological innovation, testing, certification and standardisation in the future. This achievement further validates our testing methodologies against international benchmarks.

To address evolving industry needs, the group is expanding its testing capabilities to include advanced imaging techniques such as photoluminescence (PL), electroluminescence (EL), and UV fluorescence. These methods enhance defect detection and enable more detailed diagnostics of module performance and degradation, supplementing traditional electrical testing.

In the area of pre-normative and reliability testing, the group built upon its expertise in floating PV (FPV) by actively participating in the development of new testing methods for FPV modules, in collaboration with IEC TC82 WG2.

Through these achievements the group further consolidated its role as a regional hub for high-quality PV module assessment, and contributed technical expertise to the international community in the development and testing methods for new standards.

Fig. 1: UV chamber at SERIS' ISO/IEC 17025-certified PV module testing laboratory for quantifying the impact of UV-induced degradation (UVID)

BIPV Group

Pixel PV

SERIS has advanced its patented Pixel PV concept (see Fig. 2), which reimagines conventional large-format panels (> 2 m^2) as modular "pixels." These smaller units can be mass-produced in uniform colours or tile-inspired designs, enabling mosaic-style façades that combine cost efficiency with creative freedom for architects. Beyond aesthetics, the modular approach improves adaptability to diverse façade dimensions and complex architectural forms, minimising unused space and enhancing design flexibility. In 2025, the BIPV team developed and tested multiple prototypes under indoor and outdoor conditions, focusing on electrical and mechanical interconnection strategies to validate durability and performance.

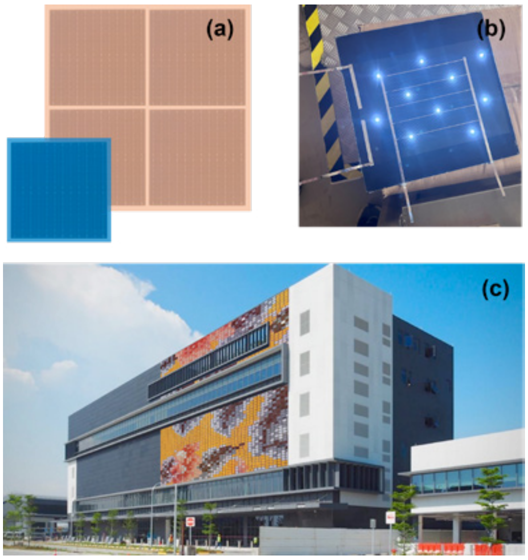


Fig. 2: (a) PV pixels of various colours for mass producibility. (b) LED lights integrated onto the pixels for potential PV displays. (c) Rendered image of the PV pixel concept as mosaic art applied on the Maintenance Base Admin Building at Tuas Port BAPV installation in Singapore

Building information modelling (BIM)

To accelerate BIPV adoption, the team created a digitalised component library within Autodesk Revit and embedded BIPV products directly into BIM workflows. This enables architects and planners to integrate PV façades at the conceptual design stage, run annual energy yield simulations, and link outputs to life cycle assessment (LCA) and cost models. These capabilities provide early insights into performance, environmental impact, and economic feasibility, reducing barriers to the wider adoption and improving feasibility compared to late-stage retrofits. This initiative supports Singapore's Green Plan 2030 by promoting low-carbon, energy-efficient buildings through seamless digital integration.

Collaboration with local government agencies

SERIS continued its collaboration with the Singapore Civil Defence Force (SCDF), contributing to working groups that use data-driven and rigorous scientific approaches towards refining the Fire Code for PV systems. This effort led to a circular amendment issued in March 2025 for rooftop PV installations, where SERIS was formally recognised for its technical input (see Fig. 3). Such partnerships ensure that evolving regulations reflect best practices, reinforcing safety and reliability in Singapore's solar infrastructure.

Fig. 3: Recognition of SERIS' continued contributions to working groups by SCDF on Solar PV systems

BIPV displays

Beyond energy generation, BIPV enhances architectural aesthetics. In 2025, the team showcased innovative designs at major events (see Fig. 4), including the Art and Sustainability: A Shared Canvas exhibition and the Boloni Experience Center, featuring Peranakan-inspired panels that blend cultural heritage with modern technology. At the Singapore International Energy Week (SIEW) and the Asia Clean Energy Summit (ACES), our in-house rasterisation technology was used to create pointillist logos, demonstrating the creative potential of PV façades.

Fig. 4: SERIS displayed BIPV modules with enhanced architectural aesthetics at various occasions and exhibitions. "Art and Sustainability, a Shared Canvas" event (upper left), Boloni Experience Center (lower left), Singapore International Energy Week 2025 (upper right), and Asia Clean Energy Summit 2025 (lower right)

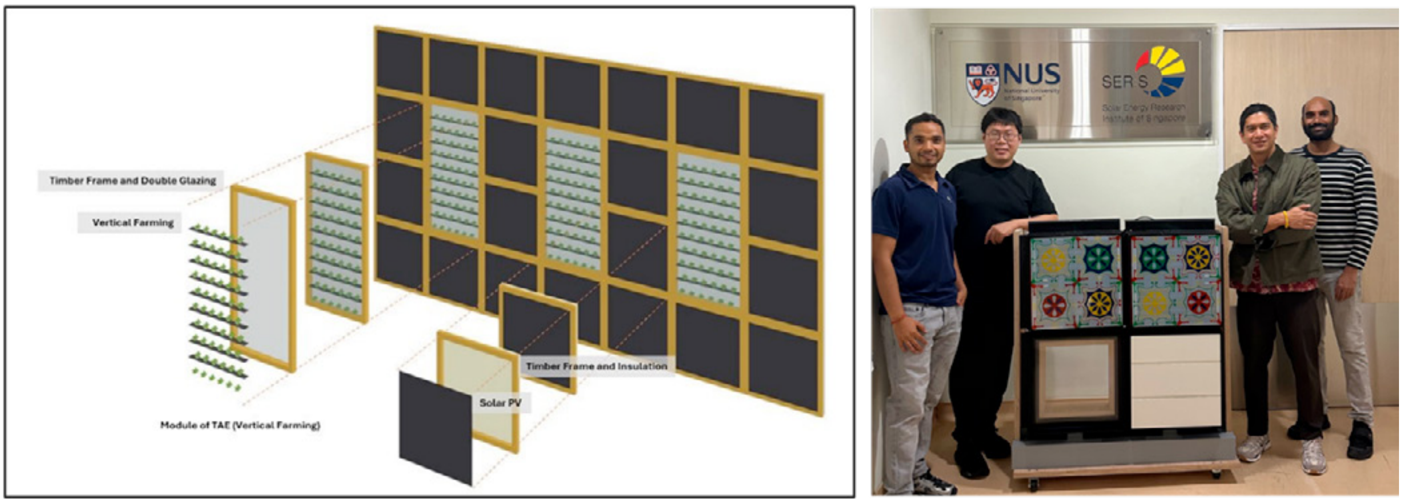


Fig. 5: Timber active envelopes that can seamlessly integrate multiple façade elements such as PV and vertical farming (left). A small-scale prototype was fabricated (right) where mating and interconnection between unitised elements was studied.

Timber active envelopes

In collaboration with the University of Sydney, the BIPV Group pushed the boundaries of sustainable design by prototyping unitised timber walls that integrate PV and vertical farming. These hybrid façades combine renewable energy generation with biophilic elements, creating multifunctional building skins. Hygrothermal simulations under Australian and Singaporean climates validated durability and resilience, while life cycle analyses quantified embodied carbon and circularity benefits. This work positions timber active envelopes as a game changer for low-carbon architecture, merging aesthetics, energy performance, and urban agriculture in one integrated solution.

2. R&D plans of PVM Cluster for 2026

- Further establish SERIS as the regional reference Testing Laboratory for PV modules in Southeast Asia
- Expand SERIS' advanced testing capabilities through seamless integration of various imagery technologies
- Develop combined stress and new reliability protocols, in collaboration with international partners and certification bodies
- Drive pre-normative testing methods for Floating PV application through data provision, technical know-how, and direct participation in the international FPV standards development
- Accelerate the Pixel PV concept towards market readiness, working closely with industry partners to scale production and enable bold, customisable façades across Singapore
- Further evolve the activities on Infrastructure-Integrated PV (IIPV), with pilot testbeds for PV fencing and noise barriers that transform everyday urban elements into clean energy generators
- Commission a next-generation solar cell stringer with advanced interconnection capabilities, unlocking new possibilities for ultra-high-efficiency PV modules (including those using tandem solar cells)
- Embark on studies of PV installations on the urban heat island (UHI) effect in dense city environments such as Singapore, for a better understanding of how the microclimates around PV systems affect thermal comfort, and if this could also reduce the energy consumption of buildings

SES Cluster Director's Foreword

Dr Thomas REINDL
Director, Solar Energy Systems Cluster (SES)

The aim of the research in the SES cluster is to develop and introduce novel technologies that have the potential to re-define the industry. One example are ultra-lightweight solar foils (using single-junction perovskites) which open fundamentally new deployment options such as overarching solar canopies. Another one are AI-driven algorithms for predictive maintenance of solar assets and solar forecasting over different time horizons. Innovation never stops."

Research Focus / R&D portfolio of SES Cluster

The SES Cluster focuses on making solar power a cost-effective and trusted source of electricity. Its activities have a wide variety and span from remote monitoring and smart operation & maintenance (O&M) to novel PV system deployments such as Agrivoltaics (i.e., combining agriculture & PV) and forecasting of solar irradiance for better grid integration management. The cluster also addresses the specific challenges when deploying solar technologies in urban environments like Singapore and other megacities.

1. Major activities / achievements in 2025

Solar System Technology (SST) Group

Floating Solar Systems

In 2025, the SST Group advanced R&D in floating PV, focusing on inland, near-shore, and offshore applications. Leveraging SERIS' decade-long expertise in floating PV systems, its authorship of Singapore's TR100:2022 Floating PV standard, and in-house studies on Failure Mode and Effect Analysis (FMEA), the group leads the drafting of the international floating PV standard (IEC TS 62548-3). It also assessed the potential of offshore floating PV, by integrating geographic, climatic and economic data, modelling energy output, and estimating system costs and levelised cost of electricity (LCOE) for global territories and exclusive economic zones. The group is also exploring near-shore floating PV test-bedding opportunities in Singapore, with Jurong Island identified as a potential site for screening and testing various technologies in tropical sea conditions.

Urban Solar Integration

In the area of Urban PV, the group has been actively pursuing innovations that enable new forms of solar canopy deployment. Prefabricated PV supporting structures - the UrbanBox™ and UrbanRoof™ - have been co-developed with European collaborators. Both systems offer reduced fabrication costs, shorter installation times, and lower on-site labour requirements, while UrbanBox™ additionally features a retractable design that allows occasional clearance or multi-functional use of spaces. A feasibility study is being planned for deploying the prefabricated UrbanRoof™ system at one of the NUS Kent Ridge Carparks, which could become Singapore's first test-bedding of prefabricated PV supporting structures. Figure 1 shows the wooden UrbanRoof™ prototype tested in Europe and the proposed steel version for Singapore.

The group is also evaluating ultra-lightweight perovskite PV foils that can achieve power conversion efficiencies of ~20% with operational lifetimes exceeding 15 years. These properties enable novel applications such as ultra-long-span and ultra-high-clearance solar canopies with minimal structural costs. Figure 2 illustrates potential concepts for such overarching canopies powered by ultralight perovskite PV foils.

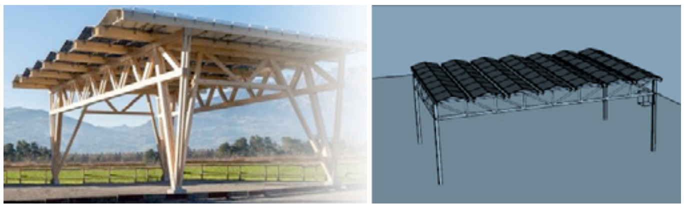


Fig. 1: UrbanRoof™ prefabricated PV supporting systems made with wood (left) and steel (right)

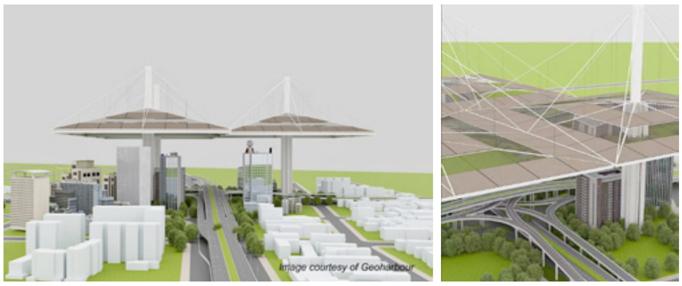


Fig. 2: Visions of ultra-long-span overarching solar canopies enabled by ultra-lightweight perovskite PV foils (Image credit: Shanghai Geoharbour Group)

Agrivoltaics

In the area of Agrivoltaics, the group completed the second year of test-bedding at the Yuhua Agri-tech Solar (YAS) Living Lab. Experiments were carried out on common leafy vegetables in Singapore, including lettuce, bok choy, nai bai, chye sim, kang kong, and bayam (spinach). Based on the data collected, the group conducted a financial scenario analysis to evaluate how different farming types could benefit from agrivoltaics (more details can be found in the R&D section). An upgrade of the testbed is also underway to enclose one of the greenhouses with transparent, electricity-generating windows enabled by innovative PV technology, advancing the vision of a fully energy-sustained rooftop greenhouse.

Beyond research, the YAS Solar Living Lab continues to serve as a strong outreach platform. In 2025, the SST group conducted numerous tours to showcase the agrivoltaics testbeds and innovations to community residents, students, companies, and government agencies.

Outdoor Module Testing (OMT)

The group continued operating SERIS' Outdoor Module Testing (OMT) facility, which has been supporting numerous industry R&D collaborations since 2010. The facility consistently provides clients with high-quality, precise outdoor energy yield data in tropical conditions, covering all major PV technologies including TOPCon, heterojunction, PERC, p-mono, p-multi, n-PERT, and various thin-film options. The group also continued leading the TruePower Alliance, which combines extended indoor and outdoor PV module and system testing across diverse climate zones such as Singapore, Germany, and Australia. This work has generated significant insights and rich datasets on the effects of different environmental conditions on PV modules and systems.

PV Quality Assurance (PVQA) Group

The PVQA Group provides a comprehensive suite of services that underpin the successful planning, development, and operation of PV projects in Singapore and the wider region. Its core expertise spans feasibility studies, lender's technical due diligence, and testing and commissioning (T&C) services, all aimed at ensuring that PV systems achieve the highest standards of safety, reliability, and long-term performance.

In 2025, the group played a pivotal role as the representative of the Housing and Development Board (HDB) during the construction phase of large-scale PV installations in public residential estates. This involvement included multiple phases of the flagship SolarNova programme - notably Phases 4, 6 and 8 (SN4, SN6, SN8) - where the group provided quality assurance oversight and safeguarded compliance with both project timelines and technical requirements.

Beyond HDB, the group has also delivered T&C services for other major government projects, including high-profile PV installations at Changi Airport, the Singapore EXPO, and facilities managed by the Defence Science and Technology Agency (DSTA). These engagements further reinforce PVQA's reputation as a trusted technical partner for critical public sector projects.

Expanding into the broader market, the PVQA Group has secured Owner's Engineering and T&C contracts for a number of landmark installations across both the public and private sectors. These successes reflect the team's ability to address diverse stakeholder needs and ensure project outcomes that are bankable, efficient, and future-ready.

Beyond project delivery, the group is actively involved in cross-group initiatives within the SES Cluster, such as the "Smart O&M" project, which leverages digitalisation and advanced analytics to enhance PV system lifecycle performance.

Through these efforts, the PVQA Group continues to establish itself as a center of excellence for PV system quality assurance, combining technical expertise with independent oversight to advance Singapore's clean energy transition while contributing to the growth of the regional solar industry.

Digitisation of Energy (DoE) Group

The DoE Group develops proprietary software tools and also applies commercially available solutions to address challenges of solar PV deployment which can be solved by information technology (IT) and artificial intelligence (AI).

Solar Asset Management

In 2025, the PV Monitoring Team achieved a major milestone, surpassing 130 commercial sites under its monitoring portfolio. Notable advancements this year include the introduction of portfolio-level visualisation tools, enabling advanced performance ratio calculations and comprehensive fleet-wide analysis for clients (see Fig. 3).

The upgraded SERIS platform enables real-time reporting to power grid operators such as the Singapore's Energy Market Authority (EMA) or the equivalent Data Collection System (DCS) in Malaysia. It now supports simultaneous multi-client onboarding and management, significantly boosting scalability and operational efficiency across diverse portfolios.

A major innovation was the implementation of bi-directional energy metering with refined 30-minute load profiling. This capability enables optimised storage designs and superior returns, meeting the demands of complex PV installations. Automated monthly energy report generation further streamlines client reporting, improving operational transparency.

The Monitoring Team continues to push boundaries in predictive and preventive maintenance for PV assets, in line with SERIS' goals in Smart O&M. Early detection of shading and underperforming strings is now powered by machine learning algorithms, which minimise losses and maximise energy yield. Advanced classification and clustering models are deployed to detect shading and segment underperforming strings, maximising yield and operational impact.

Solar Forecasting

The Solar Forecasting team continued to ensure the robust operation and continuous optimisation of the live forecasting system deployed at EMA. Further improvements are underway through a multi-faceted enhancement strategy designed to address the unique meteorological challenges of the tropical climate zone. Key initiatives include the integration of aerosol optical depth predictions to mitigate forecast volatility during haze events and the assimilation of infrared satellite bands to refine morning irradiance profiles. Furthermore, the team has rigorously benchmarked multiple numerical weather prediction (NWP) models to isolate the most accurate configuration for local climatic conditions.

Expanding beyond domestic applications, the team has successfully deployed a high-fidelity regional solar forecasting model covering the entire Asia-Pacific. This system delivers a spatial resolution of 4 km with rapid 5-minute update cycles, achieved through the seamless fusion of advanced NWP data and satellite imagery. The model's proven efficacy has garnered significant interest from regional stakeholders, initiating high-level dialogues with counterparts in Malaysia, Thailand, and Brunei. Additionally, the system's proprietary satellite image-to-irradiance conversion framework was presented to the scientific community at the 36th International Photovoltaic Science and Engineering Conference (PVSEC-36) in Bangkok in November 2025.

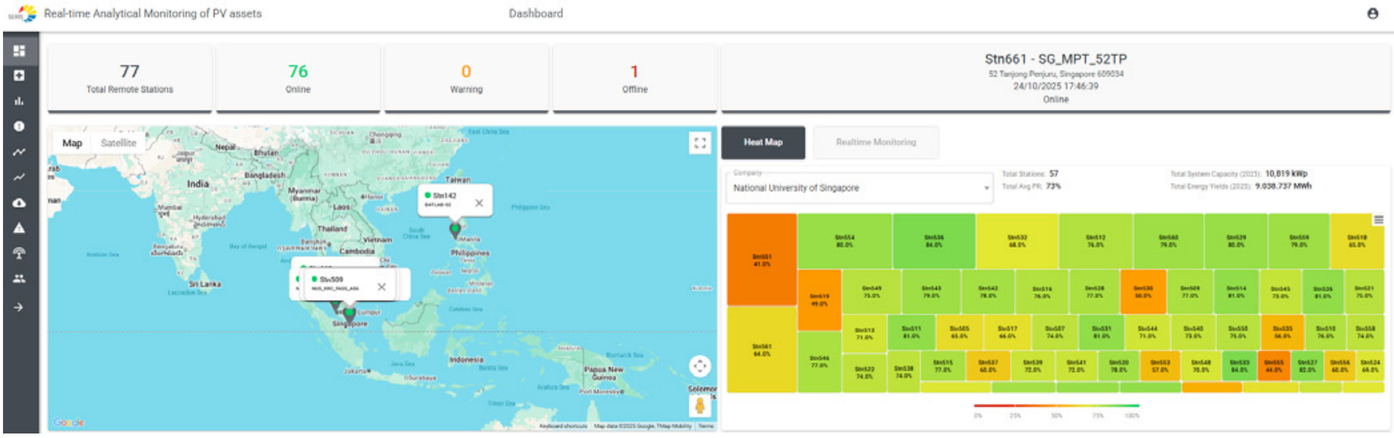


Fig. 3: SERIS PV Asset Management Platform, showcasing portfolio-level visualisation tools, enabling advanced performance ratio calculations and comprehensive fleet-wide analysis for clients

Glare studies

In 2025, the team advanced the glare assessment capabilities through the in-house development of an advanced 3D Glare Analysis Tool, designed to quantitatively evaluate visual glare impacts from solar PV and other reflective surfaces in complex urban environments and airport contexts. The tool integrates 3D geometric computation, sun-path modelling, and 3D ray-tracing simulation, enabling scenario-based glare assessment for buildings, infrastructure, and aviation-related viewpoints (see Fig. 4). The methodology and results were validated against field measurements, demonstrating good agreement between simulated and observed glare conditions. Following validation, the tool was presented and discussed with relevant Singapore government agencies to support regulatory review and deployment use cases. In parallel, SERIS engaged in technical discussions with industry stakeholders to explore potential collaboration pathways, such as tool integration, joint validation, and adoption in project certification and solar feasibility workflows.

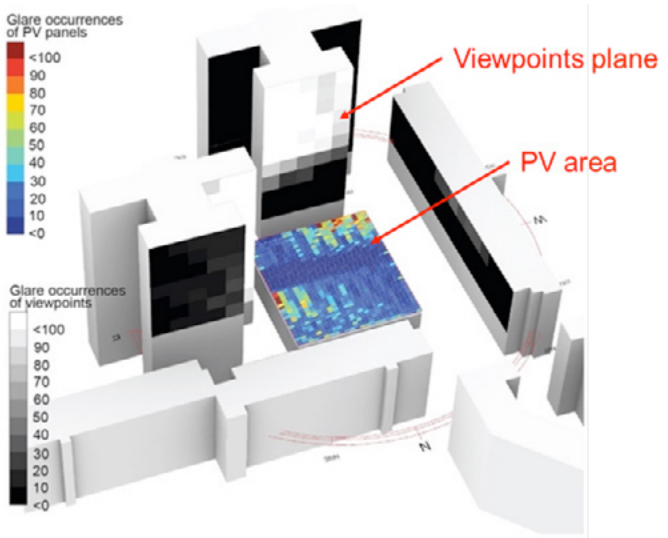


Fig. 4: Glare assessment using SERIS' proprietary 3D glare Assessment Tool on a proposed PV installation on a carpark surrounded by HDB buildings

The group also strongly supported the solarisation of Singapore, by carrying out pre-feasibility studies for hundreds of government-owned buildings under the SolarNova programme and for solar developers.

Smart O&M Group

The activities of the previous "Smart O&M" Group have been transferred to the PV Doctor spin-off, which aims to commercialise the 10+ years of SERIS' experience in this field and to offer professional services to PV asset owners around the world (see also the separate write-up in this Annual Report).

2. Plans of SES Cluster for 2026

- Further expand the activities in the Floating Solar flagship project, with a strong emphasis on near-shore floating PV R&D aiming towards the potential real-world test-bedding in Singapore
- A key milestone for the year will be the publication of a draft version of the international floating PV standard IEC TS 62548-3
- Develop the first test-bedding project of a prefabricated PV supporting structure in Singapore
- Evolve design concepts for the potential deployment of solar canopies, featuring ultra-lightweight perovskite PV foils
- Expand the research activities on agrivoltaics in the YAS Living Lab by adding semi-transparent PV walls, to make one of the testbeds a fully enclosed greenhouse
- Strengthen SERIS' leadership in testing and commissioning (T&C), ensuring that solar PV projects in Singapore and the region meet the highest standards of performance, safety, and reliability
- Further expand the scope of the PV monitoring platform towards real-time energy management
- Enhance the predictive precision of both domestic and regional solar forecasting models
- Commercialise the self-developed 3D Glare Analysis Tool, in collaboration with industry partners
- Support government agencies and the private sector in solarising Singapore, by providing technical expertise and by sharing knowledge through technical standards, workshops and relevant reports

UPDATE ON R&D PROJECTS 2025

SERIS Flagship Projects

SERIS has embarked on three flagship research projects to strengthen and deepen its solar capabilities.

1. Perovskite-silicon tandem solar cells and modules
2. Building-integrated Photovoltaics (BIPV)
3. Floating solar systems

Selected R&D Projects

1. Ligand-mediated surface reaction for achieving pure 2D phase passivation in high-efficiency perovskite solar cells
2. Machine learning driven insights for phase stable $FA_xCs_{1-x}Pb(I_yBr_{1-y})_3$ perovskites in tandem solar cells
3. Oxygen-dependent sputtered NiO_x for high-performance perovskite solar cells and minimodules
4. Optical losses in silicon heterojunction solar cells: analysis of record efficiency devices and practical limits based on ray tracing simulations
5. Reliability of floating photovoltaics (FPV): evaluating the effects of hydrodynamic mechanical loads on photovoltaic modules
6. BIM for BIPV simulation and cost model development
7. Performance evaluation of day-ahead solar irradiance forecasts from numerical weather prediction models in Singapore
8. Global floating PV potential in inland reservoirs: a comparison of different technologies
9. Economic analysis for agrivoltaics farms in Singapore

SERIS Flagship Project

Perovskite-silicon tandem solar cells and modules

Prof Armin ABERLE (Project Leader), Assoc Prof Erik BIRGERSSON, Asst Prof HOU Yi, Dr Firdaus BIN SUHAIMI, Dr CHOI Kwan Bum, Dr JANG Yu Jin, Dr KIM Jinhyun, Dr LUO Chao, Dr Romika SHARMA, Dr WANG Puqun, Mohd Asri BIN MOHD HAMDAN, Gabby Alonzo DE LUNA, Elisaveta UNGUR
PhD students: Varsha DAHIYA, DU Xinyi, Stella HADIWIDJAJA, LEE Ling Kai, Erik SPAANS, YAP Qi Jia, ZHOU Qilin

Introduction

Singapore's space constraints necessitate the installation of solar PV systems with very high efficiencies to maximise PV power generation. While single-junction crystalline silicon (Si) solar cells have a theoretical efficiency limit of about 30% under the standard 1-Sun solar spectrum (AM1.5G), stacking a second solar cell with a larger electronic bandgap onto a silicon cell to create a two-junction (or "tandem") solar cell offers the potential for much higher power conversion efficiencies while maintaining low manufacturing costs ($/W). For 2-junction Si-based tandem solar cells the theoretical 1-Sun efficiency limit is about 44%, whereby a practical cell efficiency limit of around 35% seems possible in future mass production (beyond 2030). Due to this excellent PV efficiency potential, Si-based tandem solar cells are of very high importance to Singapore's solar sector, for both manufacturing and deployment. This flagship project focuses on exploring low-cost wide-bandgap thin-film materials, in particular metal halide perovskites, as the absorber layer of the top cell on a silicon bottom cell. In 2025 our research efforts focused on the improvement of perovskite-Si tandem cells with small (1 cm^2), medium (16 cm^2) and large (244 cm^2) areas, the improvement of the efficiencies of our 1-cell mini-modules with active areas of up to 244 cm^2, and outdoor monitoring of encapsulated tandem mini-modules to study their long-term reliability in Singapore's tropical climate.

Small (1 cm^2) perovskite-Si tandem solar cells on textured Si bottom cells

In 2025, SERIS' Perovskite-based Multijunction Solar Cells Group achieved 33.3% efficiency for a perovskite-silicon tandem solar cell using an industrially fabricated Cz heterojunction silicon bottom cell with cell area of 1 cm^2, see Fig. 1. The measurement was performed at SERIS. This was accomplished by successfully forming high-quality 1.66-eV perovskite films on textured silicon surfaces using the spin-coating method. A key challenge in this work was improving the perovskite crystal quality on silicon architectures. We introduced a ligand that effectively controls the principal organic cations to regulate crystallisation. Our organic control approach supplements previous strategies mainly focused on strong coordination with inorganic lead halides, enabling refined crystal growth and improved film quality of perovskite films on thin Si wafers. We effectively minimised the quality gap between perovskite films grown on glass and those grown on thin Si substrates, thereby enabling high-quality wide-bandgap perovskite films being integrated with industrially fabricated Cz silicon bottom cells.

The group's ongoing efforts are focused on closing the gap to the current world-record 1cm² perovskite-silicon tandem solar cell (34.8%, LONGi, China).

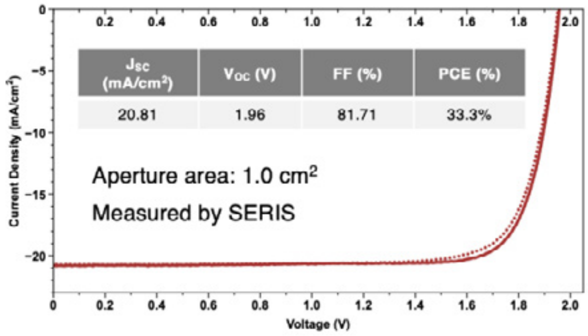


Fig. 1: Measured J-V curves of a 33.3% efficient perovskite-silicon tandem solar cell (1.0 cm² aperture area) made at SERIS using a Cz heterojunction silicon bottom cell. The silicon cell has pyramid-textured front and rear surfaces. The perovskite absorber was made by spin coating.

Upscaling of perovskite-silicon tandem solar cells to medium and large areas (16 and 244 cm^2)

In 2025, SERIS' NISCM Cluster continued to make good progress with improving the PV efficiencies of perovskite-silicon tandem solar cells with active areas of 16 and 244 cm^2, as shown in the photographs of Fig. 2. Both the silicon bottom cells (heterojunction, Cz wafers) and the perovskite top cells were fully made in SERIS. A low-temperature screen-printed silver metallisation was utilised on both sides of the 2-terminal (2T) tandem solar cells.

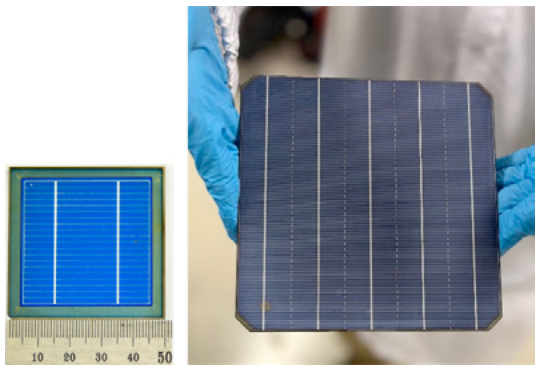


Fig. 2: Photographs of SERIS-made perovskite-silicon 2T tandem solar cells. Left: 16-cm² (active area) device on a 25-cm² smooth silicon substrate. Right: M2-size (244 cm²) full-wafer tandem cell with textured silicon surface.

The current-voltage curves of a 16-cm² tandem cell measured at SERIS and a schematic of the cross-sectional device structure are shown in Fig. 3. The cell has an efficiency of 28.2%, which is a very good result considering that the top surface of the silicon bottom cell is smooth (i.e., not textured), which limits the current that can be generated by the silicon cell. The top cell's perovskite absorber layer has a bandgap of 1.68 eV and was deposited using the spin-coating method. During spinning the wet precursor film spreads uniformly across the surface and undergoes rapid and controlled crystallisation, leading to large well-formed crystal grains with few defects. This results in a high electronic quality of the absorber layer and enabled the NISCM team to achieve more than 28% tandem cell efficiency on 16 cm², up from 25% a year earlier.

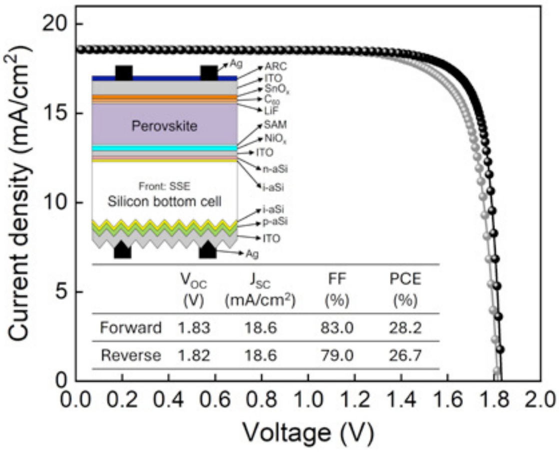


Fig. 3: Measured 1-Sun J-V curves of a 28.2% efficient perovskite-silicon 2T tandem solar cell with active area of 16 cm². The inset shows a schematic cross section of the device structure. The heterojunction Cz silicon bottom cell has a smooth front surface and a pyramid-textured rear surface. The perovskite absorber was made by spin coating.

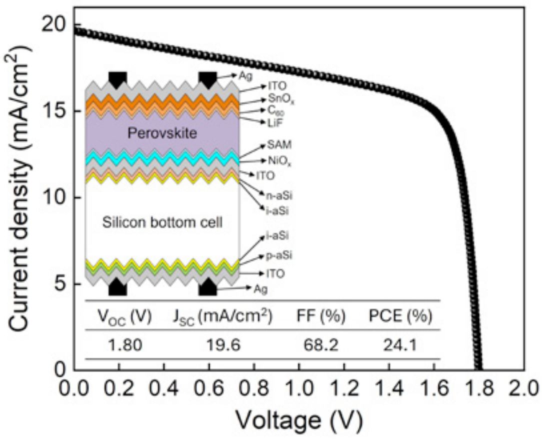


Fig. 4: Measured 1-Sun J-V curve of a 24.1% efficient perovskite-silicon 2T tandem solar cell with an area of 244 cm² (M2 size wafer). The heterojunction Cz silicon bottom cell has pyramid-textured front and rear surfaces. The perovskite absorber was made by a 2-step hybrid dry-wet processing sequence.

Using SERIS-made heterojunction silicon bottom cells on M2-size (244 cm²) Cz wafers with pyramid texture on both surfaces, the NISCM Cluster achieved 24.1% tandem cell efficiency in 2025, up from 20% a year earlier. The M2-size perovskite absorber layer of the top cell was produced via a 2-step hybrid dry-wet processing sequence, providing compatibility with upscaling to industrial wafer sizes and mass production workflows. The current-voltage curve of the 24.1% tandem cell and a schematic of its cross-sectional device structure are shown in Fig. 4. As can be seen, the open-circuit voltage (1.80 V) is good, but the fill factor is still rather low (~68%) due to a shunting issue. The NISCM Cluster's ongoing efforts are focused on eliminating this top cell shunting issue and improving the tandem cell efficiency to more than 30%.

These achievements make SERIS the only facility in Singapore, and one of only a few labs in the world, capable of producing fully in-house fabricated high-efficiency perovskite-silicon 2T tandem solar cells on industrial-size silicon wafer substrates. In terms of power conversion efficiencies, SERIS maintained its position in 2025 as one of the top labs in the world for small (1 cm²), medium (~20 cm²) and large-area (> 200 cm²) 2-junction perovskite-silicon tandem solar cells.

Development and upscaling of perovskite-silicon tandem cell mini-modules

In 2025, the project's module team continued its work on the scaling of perovskite-silicon tandem cell mini-modules from lab-scale devices (1 cm²) to M2-size (244 cm²) prototypes. This process requires significant adaptation of our fabrication methods to meet the low thermal budget requirements imposed by the perovskite top cells. The Bill of Materials (BOM, see Fig. 5) was optimised to ensure compatibility with low-temperature processes below 120°C, without sacrificing efficiency.

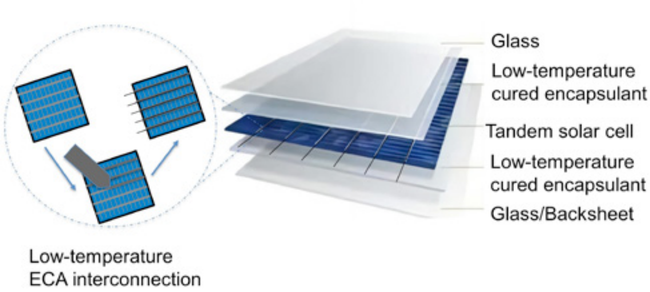


Fig. 5: Bill of Materials (BOM) for low-temperature fabrication of perovskite-silicon tandem cell modules.

The main achievement in 2025 was the fabrication and testing of M2-size perovskite-silicon 1-cell tandem mini-modules with efficiencies of more than 21%, up from 16% a year earlier. Figure 6 shows a photograph of one of these fully in-house fabricated 244-cm² tandem mini-modules featuring low-temperature encapsulation and interconnections. This efficiency result was obtained through significant improvements in low-temperature encapsulation and interconnection technologies, specifically designed to meet the stringent temperature requirements of perovskite layers while reducing thermal stress and protecting structural integrity. The team screened and evaluated thermoplastic polyolefin (TPO) encapsulants for compatibility with perovskite layers, demonstrating high optical transmittance and minimal degradation after damp-heat testing, which is comparable to or better than that of conventional encapsulants. Stencil-printed electrically conductive adhesives (ECAs) were optimised for low-temperature interconnections, enabling strong adhesion while minimising cell-to-module (CTM) losses.

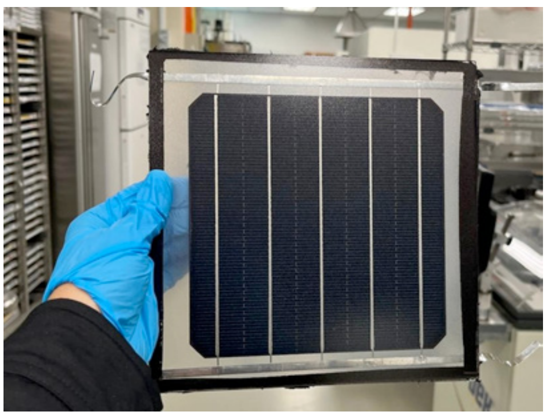


Fig. 6: Photograph of a fully in-house fabricated 244-cm² (M2-size) perovskite-silicon 1-cell tandem mini-module featuring low-temperature encapsulation and interconnections.

In 2025, the module team achieved the following technical milestones:

- Over 21% efficiency (with CTM losses of ~5%) for M2-size 244-cm² 1-cell tandem mini-modules. Using advanced materials (BOM) and encapsulation methods, we maintained the structural integrity and performance of these mini-modules, marking an important step forward on the path to commercialisation of perovskite-silicon PV technology.
- Outdoor testing of tandem cell mini-modules (see Fig. 7): We started our outdoor tandem-cell mini-module testing activities at the NUS Rooftop Testbed in tropical Singapore in December 2024, using in-house fabricated tandem mini-modules. The initial tests highlighted the need for a stricter Bill of Materials in hot-humid conditions. In September 2025, the second batch of tandem mini-modules with optimised BOM for the tropics was deployed for continuous J_{sc} logging, temperature/irradiance monitoring, and monthly indoor stabilised I-V and spectral response measurements. Initial results show no significant degradation, with continuous monitoring ongoing to validate long-term stability.
- Indoor stability testing of tandem mini-modules: In June 2025, we initiated indoor testing of tandem modules under accelerated stress conditions. This includes damp-heat exposure, thermal cycling, and continuous maximum power point tracking (MPPT) under controlled irradiance and temperature conditions. We use in-house fabricated perovskite-silicon 1-cell tandem mini-modules for these tests. The primary aim is to identify possible degradation pathways and failure modes. We also aim to correlate these findings with outdoor data to provide accurate module lifetime predictions.

Fig. 7: Perovskite-silicon tandem mini-modules deployed at the NUS Rooftop Testbed for outdoor testing in Singapore's hot-humid tropical climate.

Path Forward: Towards a 60-cell perovskite-silicon tandem module

The R&D roadmap of this flagship project involves the scaling up of 1-cell perovskite-silicon tandem mini-modules to 60-cell (~1.7 m²) tandem modules by March 2027. Current efforts are focused on improving the durability of the low-temperature encapsulants and ECAs while adapting the processes to industry-compatible methods. We are conducting climate chamber testing and MPPT testing under controlled illumination and temperature conditions to refine our processes and improve the PV efficiency and durability of these novel tandem modules. This is complemented by ongoing outdoor testing of the prototype modules in Singapore's hot and humid tropical climate, with emphasis on correlating indoor (damp heat, thermal cycling, and MPPT) and outdoor field data to predict degradation rates and guide BOM choices. Overall, this tandem flagship project is progressing well and is making major contributions to bringing the perovskite-silicon tandem PV technology closer to commercial viability, with the potential to deliver very-high-efficiency (30%) PV modules optimised for space-constrained environments like Singapore.

SERIS Flagship Project

Building-integrated Photovoltaics (BIPV)

Dr Carlos CLEMENT, Dr CHEN Tianyi, Srinath NALLURI, Rupendra ARYAL

Introduction

Solar deployment in Singapore has grown strongly, from an installed DC capacity of 429 MW_p (Megawatt-peak) of photovoltaic (PV) panels in 2020 to 1.64 GW_p in Q2-2025. At the current rate, the nation is projected to exceed its target of at least 2 GW_p (Gigawatt-peak) installed DC capacity by 2030. However, this translates to only about 3% of Singapore's annual electricity consumption, and there remains a need to further expand PV deployment. Singapore has an estimated PV installation capacity of 8.6 GW_p (DC) within its territorial boundaries. Of this, approximately one third is attributed to rooftop PV (see Fig. 1), which is also the predominant form of PV deployment here.

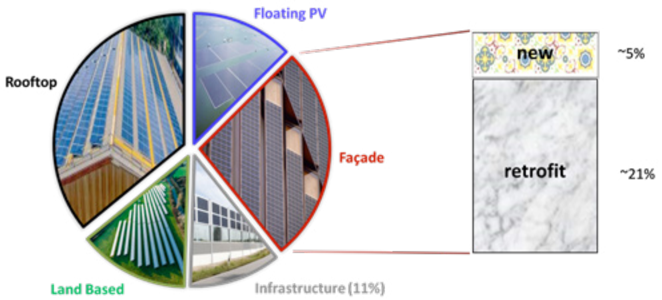


Fig. 1: Distribution of Singapore's techno-economic potential for PV deployment based on the Solar PV Roadmap of Singapore 2020

While there still remain significant unexploited rooftop spaces in Singapore, several challenges could hinder the full uptake of its potential, for example competing uses with building utilities (M&E equipment, chillers, antennas) or an increasing trend towards green roofs. Therefore it is ever more important and timely to address the second-largest solar potential shown in Fig. 1, which are façade areas by means of Building-integrated PV (BIPV) or Building-added PV (BAPV), collectively termed BIPV here. The techno-economic potential for facades entails an estimated 13.98 km^2 of deployable area (~38% of total PV potential), however there are major barriers for the adoption of BIPV, including reluctance from architects due to concerns about aesthetics, higher costs, fire safety and integration complexity.

Pixel PV

To further advance aesthetics and adaptability in BIPV, SERIS has developed and patented the Pixel PV concept, which reimagines conventional large-format panels (>2 m²) as smaller modular "pixels." These pixels can be mass-produced in uniform colours or tile-inspired designs and then assembled into mosaic-style façades, providing both cost efficiency and creative freedom for architects (see Fig. 2). Beyond aesthetics, the smaller unit size also allows the system to adapt seamlessly to diverse façade dimensions and architectural form factors, reducing unutilised space and improving overall design flexibility. In 2025, the team continued product development of Pixel PV modules and has begun engaging industry partners to refine the technology toward commercialisation.

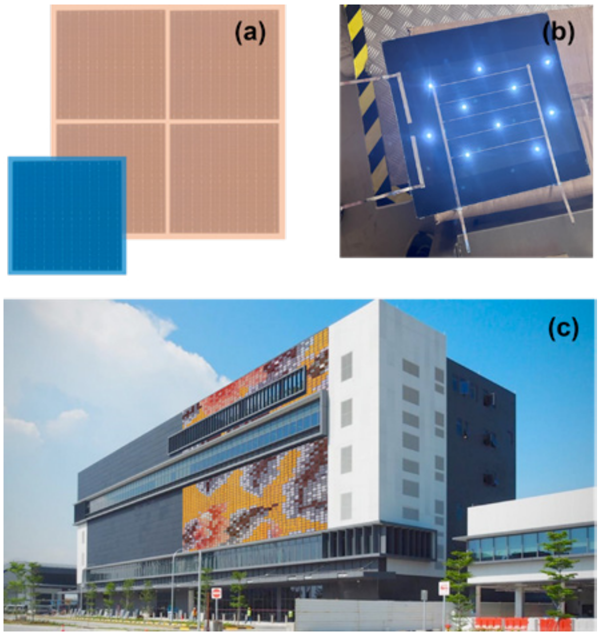


Fig. 2: (a) PV pixels of various colours for mass producibility. (b) LED lights integrated onto the pixels for potential PV displays. (c) Rendered image of the PV pixel concept as mosaic art applied on the Maintenance Base Admin Building at Tuas Port BAPV installation in Singapore

BIPV test-bedding

SERIS has built a dedicated outdoor BIPV testbed at the CleanTech One rooftop (see Fig. 3). The facility consists of two vertical walls, each measuring 5 m by 2 m, oriented to cover all four principal directions. Designed with versatile attachment points and a modular, swappable façade system, the testbed enables flexible installation and evaluation of diverse BIPV technologies and mounting strategies. An advanced monitoring system has also been deployed, capturing high-resolution meteorological and irradiance data, alongside real-time electrical performance and sensing measurements. This platform is now fully operational and will support the systematic testing and validation of next-generation BIPV solutions under real-world conditions.

Fig. 3: BIPV outdoor testbed at the Cleantech One rooftop. The testbed will be used to evaluate various technologies as well as mounting and interconnection strategies.

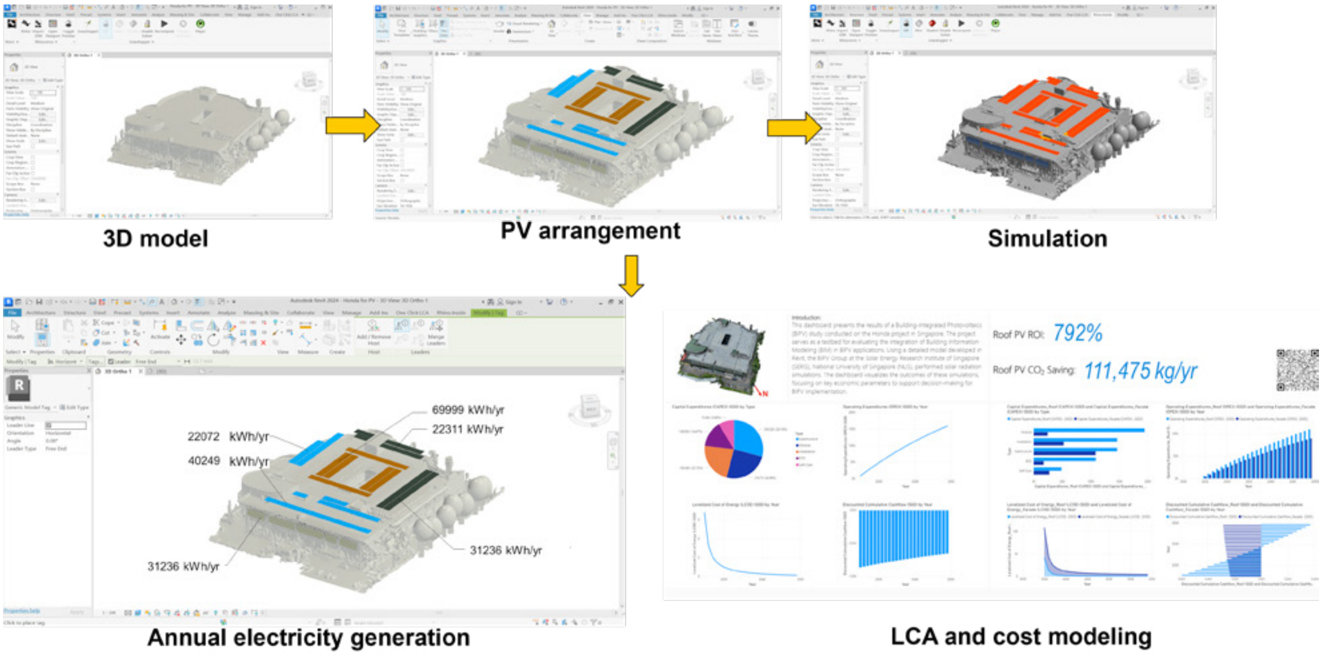


Fig. 4: Integration of BIPV components within BIM workflows. Modules are drawn from a digital component library and placed onto building surfaces in Revit alongside conventional PV. Embedded scripts couple these objects to annual energy yield simulations, life cycle assessments and cost models, providing architects and planners with rapid insights for informed decision-making at the early design stage.

Building information modelling (BIM)

Another key challenge for BIPV adoption is the lack of a digital workflow within the standard BIM (Building Information Modelling) framework to streamline design and execution processes across project stages. The BIM system entails creating and managing digital representations of a building's physical and functional characteristics ("digital twin"). This includes geometric models, time scheduling, cost and energy estimates and building operations.

In 2025, the team advanced this work by creating a digitalised BIPV component library within Revit, enabling direct integration of BIPV products into BIM workflows (see Fig. 4). The library allows architects and planners to populate 3D building models with PV elements, including façade-integrated systems, and run annual electricity generation simulations. These outputs are further linked to life cycle assessment (LCA) and cost models, providing early-stage insights into the performance, environmental impact, and economic feasibility of BIPV installations. By embedding BIPV elements at the conceptual design phase, this work lowers barriers to adoption, improves cost competitiveness compared to late-stage retrofits, thereby supporting Singapore's Green Plan 2030 target of driving low-carbon, energy-efficient buildings.

BIPV as Art

As part of our efforts to promote BIPV as both an attractive and practical solution for façades in Singapore, the team has been actively showcasing innovative displays at major events. In May, during the Art and Sustainability: A Shared Canvas exhibition, our Peranakan-inspired PV panels were presented alongside contemporary pieces of art at The Artworks Gallery (Fig. 5). In addition, our modules were featured at the Boloni Experience Center through a collaboration with Sunollo, interior design firm KAPA, and Porsche, highlighting the seamless integration of BIPV into modern design and lifestyle contexts (Fig. 6).

Fig. 5: Peranakan-inspired BIPV panels displayed at Art and Sustainability: A Shared Canvas, The Artworks Gallery

Fig. 6: BIPV modules showcased at the Boloni Experience Center in collaboration with Sunollo, KAPA, and Porsche

SERIS Flagship Project

Floating Solar Systems

Dr Serena LIN Fen, Dr Oktoviano GANDHI, Lokesh VINAYAGAM, Dr Thomas REINDL

Floating photovoltaics (FPV) offers great opportunities for renewable energy generation, particularly for countries with land constraints and available water bodies, such as Singapore, South Korea, Japan and the Netherlands. SERIS has been leading the Floating Solar research in Singapore and worldwide since 2016, and has created and maintained a FPV system database of around 1600 installations to date.

At the end of 2024, the cumulative installed global FPV capacity had reached around 9.5 GW_p (see Fig. 1). Despite the rapid deployment of FPV systems in the last 10 years, the current global installed capacity is still far below its potential. By covering just 10% of the > 250000 inland water bodies worldwide, FPV could reach an installed capacity of ~23 TW_p and a potential energy yield of around 25000 TWh/year, which is equivalent to the total global electricity demand in a year (2023 data). This demonstrates the huge potential of reservoir-based FPV in the future.

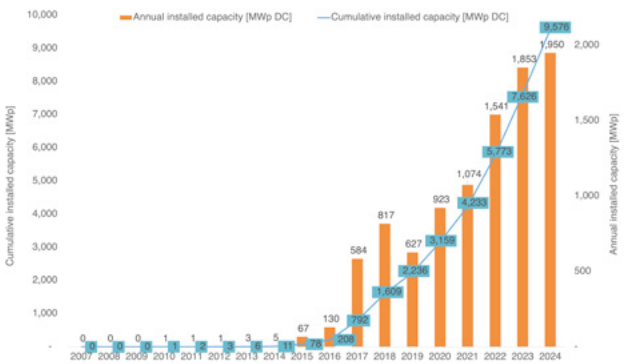


Fig. 1: Globally installed FPV capacity (Source: SERIS FPV database)

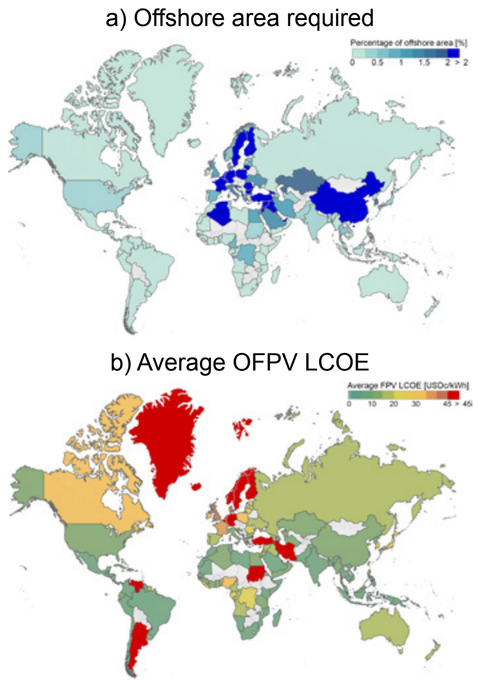


Fig. 2: Global potential of offshore FPV systems: a) offshore area required to fulfil the region's electricity demand; b) average LCOE from OFPV in water spaces considered in a)

In comparison with reservoir-based FPV, the potential for offshore FPV (OFPV) is even larger. A SERIS assessment showed that - even when limiting the ocean regions to conditions that can be withstood by current commercial floater capabilities, excluding protected areas and dense shipping routes - a 10% coverage would already provide about 686 TW_p of FPV capacity. Due to this enormous potential, less than 2% of the available offshore water surfaces are sufficient to meet the current electricity demands of 84% of the analysed regions. Moreover, in 53% of the analysed regions (see Fig. 2), the required FPV water area to satisfy their electricity demand corresponds to an OFPV LCOE of below 15 USDc/kWh, underscoring OFPV's potential cost competitiveness.

Even though the presently installed FPV capacity is concentrated in only a handful of regions (see Fig. 3), FPV is a global phenomenon, with 66 countries hosting FPV installations at the end of 2024, and many more with projects under development.

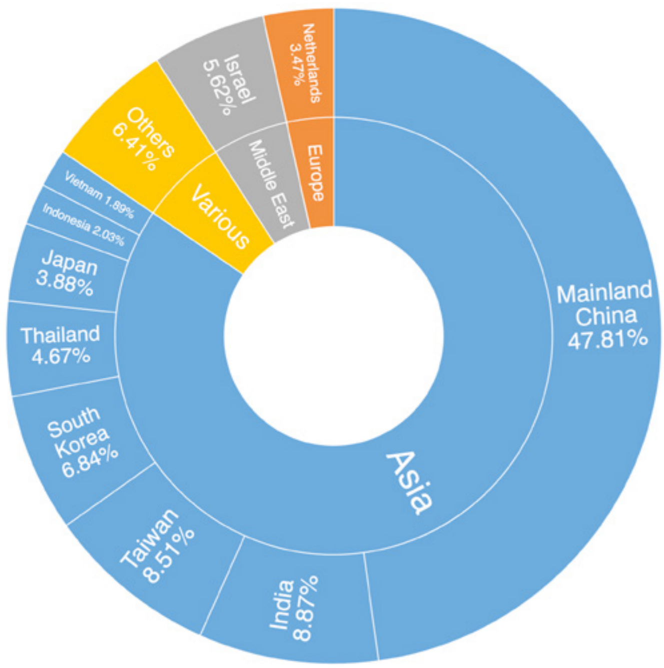


Fig. 3: Shares of cumulative installed FPV capacity by 2024 by region (Source: SERIS FPV database)

The increase in FPV installations, along with the advancements in technology, has brought down FPV cost from a median of 2.41 USD/W_p in 2015 to 1.25 USD/W_p in 2024 (see Fig. 4), which enabled even wider FPV adoption. The median CAPEX in 2024 experienced an increase from 2023 despite a drop in module prices, partly due to inflation.

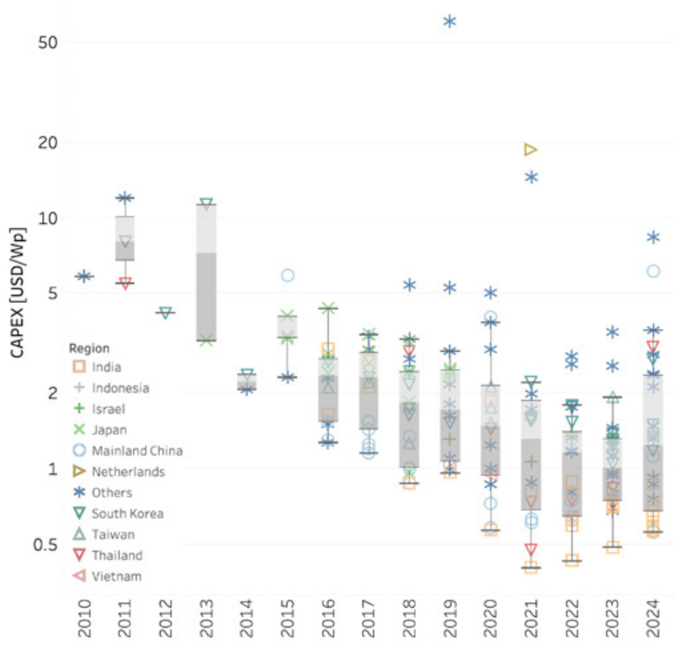


Fig. 4: Reported capital expenditure (CAPEX) for existing FPV installations. The values are not adjusted for inflation (Source: SERIS FPV database).

At the same time, the increase in module efficiency has allowed higher power density for FPV installations (from a median of 88 W_p/m^2 in 2015 to 139 W_p/m^2 in 2024, as illustrated in Fig. 5). Incremental increases in module efficiency and FPV deployment experience will increase FPV potential further in the coming years.

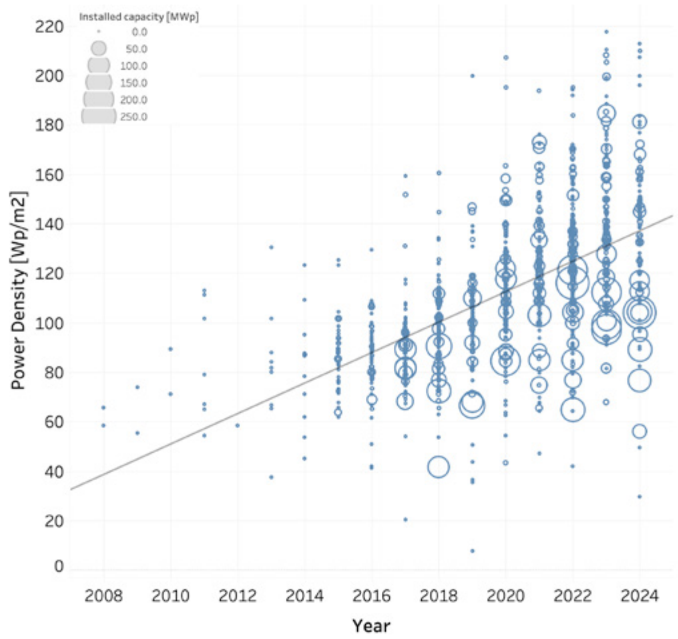


Fig. 5: Power density for existing FPV installations (Source: SERIS FPV database)

Such insights from our FPV database are regularly presented by SERIS in conferences and exhibitions and are highly valued by the industry. To share its knowledge, SERIS has published the "Where Sun meets Water" report series, together with the World Bank Group. By October 2025, downloads of these reports from the World Bank sharing website (ESMAP) had surpassed 160,000, underlining the high relevance of these reports for the solar industry.

SERIS' Floating Solar flagship project has adopted a holistic approach towards driving various aspects of the FPV industry, which is summarised in Fig. 6 and explained in more detail in the following sections.

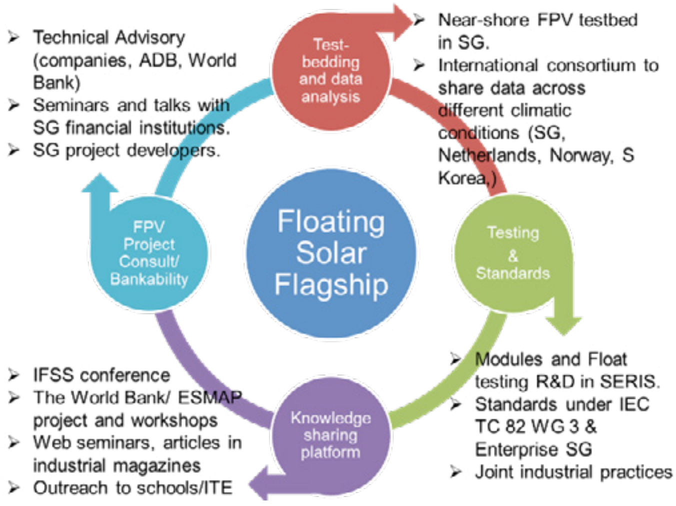


Fig. 6: Key thrusts of the Floating Solar flagship project

FPV test-bedding and data analysis

Floating PV systems deployed in sea water (either near-shore or off-shore) are the next frontier in scientific PV systems research at SERIS, following a growing interest in Singapore and around the world to utilise marine areas for Floating Solar. This could lead to a virtually unlimited availability of space, provided that there are cost-effective and reliable technologies for deployment as well as for the interconnection to shore. However, this market segment is at a very nascent stage and there is limited information about technical designs, component selection, feasibility, and field data available today to estimate the economic viability of marine-based floating PV systems. Sea conditions pose additional challenges - such as higher wind and wave forces (and their combined effects), salinity of seawater, and biofouling - that will affect the mechanical stability of the floating structures. Moreover, depending on the distance from the shore and the water depth, the anchoring and mooring engineering becomes more complex and thus expensive. There are solutions available in the marine industry to overcome certain technical challenges, but they need to match the cost levels required by the PV industry to ensure that FPV power is competitive with other forms of renewable energy generation.

FPV testing & standards

SERIS previously led the development of Singapore's national FPV standard, TR100:2022 – Floating photovoltaic power plants: Design guidelines and recommendations, in collaboration with Enterprise Singapore (E-SG). With this national guideline now established and widely adopted by the local industry, SERIS has shifted its focus towards international standardisation to support the global FPV market.

In 2025, SERIS continued to play a key role in the development of the first international FPV standard through IEC TC82 Working Group 3. SERIS presented the initial draft of IEC 62548-3: Floating Photovoltaic (FPV) Arrays – Design Requirements at the Spring 2025 WG3 meeting in Singapore, and is working closely with international partners toward its finalisation. The IEC work is being coordinated with ongoing standardisation efforts across the industry, including contributions from marine engineering, materials, and component-level technical domains, as well as parallel activities within IEC TC82 WG2 on FPV-specific PV module requirements. Together, these initiatives aim to establish a harmonised and comprehensive framework for FPV system design, strengthening the overall quality, durability, and bankability of FPV installations worldwide.

Knowledge sharing platform

As one of the leading research institutes in floating solar, SERIS' knowledge and expertise are highly sought after in the international PV community. In 2025, SERIS has been invited to major international PV conferences held in various countries, such as China, Germany, Spain, Thailand, South Korea and Singapore, to share the latest trends in Floating Solar, as well as the results of its research on topics such as FPV potential, reliability, and operation.

SERIS has shared its experiences not only with academia and industry, but also with the wider solar community, by giving lectures on Floating PV, such as in the "Sun Powered Future" webinar organised by Asian Development Bank and the two "Renewable Energy Futures" webinars organised by the Society of Floating Solutions (Singapore) on "Floating Solar PV Potentials in Malaysia and Operators' Experience" and "Floating Solar PV Systems in Indonesia".

FPV technical advisory

Although many FPV projects are now in operation or under construction globally, there is still a lack of technical knowledge in the industry. SERIS has been working with major developers and multi-national lenders such as the World Bank Group (World Bank, IFC), the Asian Development Bank (ADB), the Inter-American Development Bank (IADB) and the United States Agency for International Development (USAID) on projects in Singapore, Pakistan, India, Sri Lanka, Vietnam, the Philippines, Suriname, Tuvalu, Micronesia and Mexico to transfer its knowledge to their real-world projects, be it as part of feasibility studies, the engineering design work, or preparation of technical documents for tender specifications. As of 2025, SERIS was involved in the feasibility studies and the design of ~3.0 GW_p of FPV system.

Ligand-mediated surface reaction for achieving pure 2D phase passivation in high-efficiency perovskite solar cells

Dr SHI Zhuojie, Dr LIU Shunchang, Asst Prof HOU Yi

1. Background

Perovskite solar cells (PSCs) have achieved power conversion efficiencies above 26% through cost-effective solution processing, highlighting their strong prospects for large-scale industrial adoption [1, 2]. The device interface plays a pivotal role in enabling efficient charge transport and extraction, which is essential to unlock the full potential of the perovskite absorber layer. Defect passivation at the polycrystalline perovskite surface effectively boosts the charge transport and suppresses nonradiative recombination in PSCs [3]. Heterostructures of 2D/3D passivation layers by alkylammonium ligands have emerged as effective passivation methods for interfacial engineering of PSCs [4]. However, despite the significant progress in device efficiency achieved through 2D passivation, the high reaction reactivity induced wide quantum well distribution and disordered energy landscape impact the passivation effectiveness and duration [5, 6].

2. Scope of project & objectives

This project focused on advancing interfacial engineering strategies to address the critical bottlenecks of 2D passivation in PSCs. Conventional 2D passivation often suffers from the coexistence of multiple phases, which introduces energetic disorder and weakens device stability. To overcome this challenge, we introduced a ligand-mediated surface reaction approach that enables the controlled formation of phase-pure 2D passivation layers. This strategy improves the surface energy landscape and strengthens the rigidity of the 2D lattice, thereby facilitating more efficient charge extraction and suppressing interfacial recombination. The objectives were to establish a reliable method for eliminating phase inhomogeneity in surface passivation layers, enhance both device efficiency and operational durability, and provide a generalisable framework for tailoring ligand-perovskite interactions with direct relevance to scalable and industrially compatible manufacturing.

3. Significance & impact of project

This project demonstrates a new strategy to overcome the problem of uncontrolled phase formation in 2D passivation of PSCs. By employing a ligand-mediated surface reaction, we achieved phase-pure 2D passivation that provides both energetic uniformity and reduced ligand penetration at the interface. A dual-ligand approach was adopted, where both ligands were co-deposited onto the perovskite surface to guide the formation of a stable and phase-pure 2D layer. This advancement directly translates into higher device efficiency and greatly improved operational stability under continuous illumination. Beyond performance improvements, this work establishes a broadly applicable interface design concept that can accelerate the development of reliable perovskite devices and strengthen the prospects of their industrial deployment.

4. Methodology & Results

To address the issue of uncontrolled multi-phase formation in conventional 2D passivation, we designed a dual-ligand passivation (DLP) strategy. In this approach, a bulky carbazole-based ligand (MeCZEAI) was introduced to mediate the surface reaction of mFPEAI with the perovskite surface. Compared to mFPEAI, MeCZEAI possesses a stronger electron-withdrawing ammonium group as confirmed by Fig. 1a. The calculated adsorption energy difference enables MeCZEAI to preferentially be adsorbed on the perovskite surface, as shown in Fig. 1b. This characteristic allows MeCZEAI to regulate the reaction kinetics when co-deposited on perovskite surface.

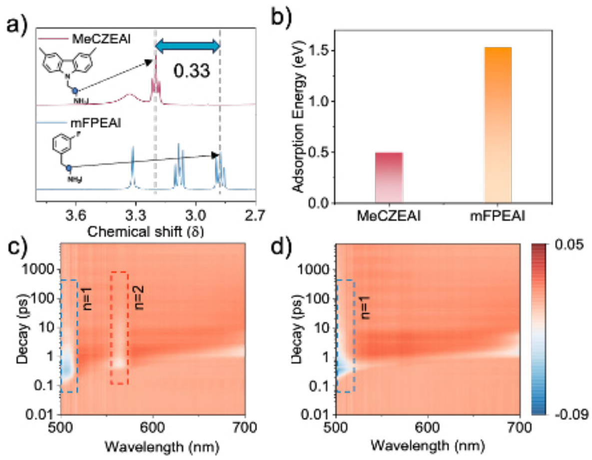


Fig. 1: a) HNMR chemical shift of CH_2 connected with ammonium group in MeCZEAI and mFPEAI. b) Adsorption energy calculation of MeCZEA and mFPEA on perovskite surface. Transit absorption spectrum of $Cs_{0.1}FA_{0.9}PbI_3$ surface treatment by c) single ligand mFPEAI and d) DLP

A comprehensive set of spectroscopic and structural characterisations validated the effectiveness of this approach. Transient absorption (TA) spectroscopy provided direct evidence for phase selectivity: while single-ligand passivation produced both n = 1 and n = 2 bleaching peaks (Fig. 1c), the DLP treatment resulted in only the n = 1 feature (Fig. 1d), demonstrating pure-phase formation.

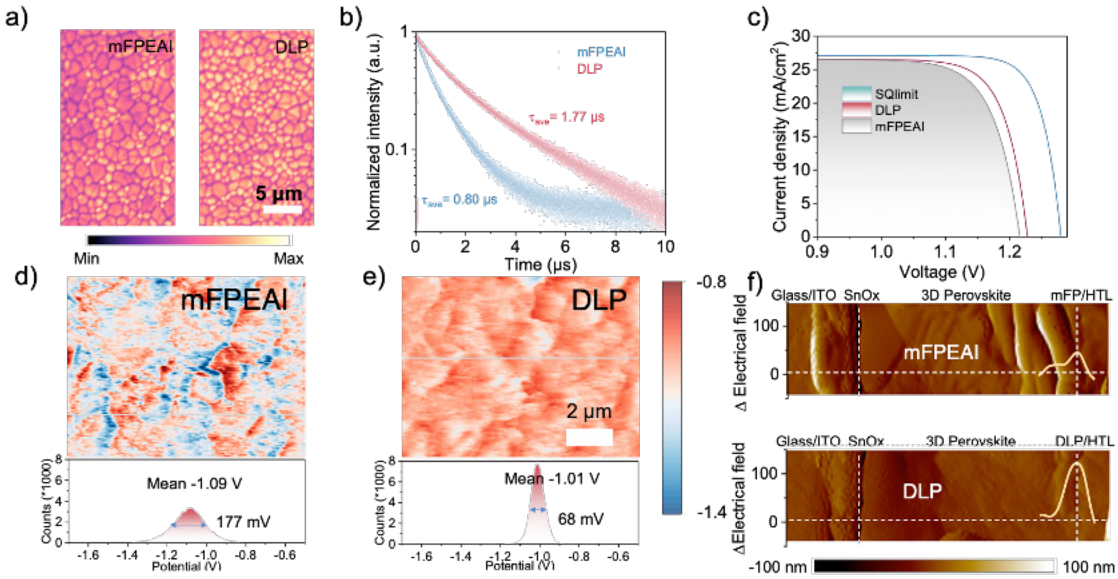


Fig. 2: a) Confocal PL images of perovskite surface passivation by mFPEAI and DLP. b) TRPL decay and calculated average carrier lifetime of mFPEAI and DLP modulation. c) Pseudo J-V curves of perovskite surface treated by mFPEAI and DLP. Surface KPFM images and corresponding potential distribution counts of perovskite passivated by d) mFPEAI and e) DLP. Cross-sectional KPFM of electrical field difference profiles by f) mFPEAI treatment and DLP treatment across perovskite to HTL

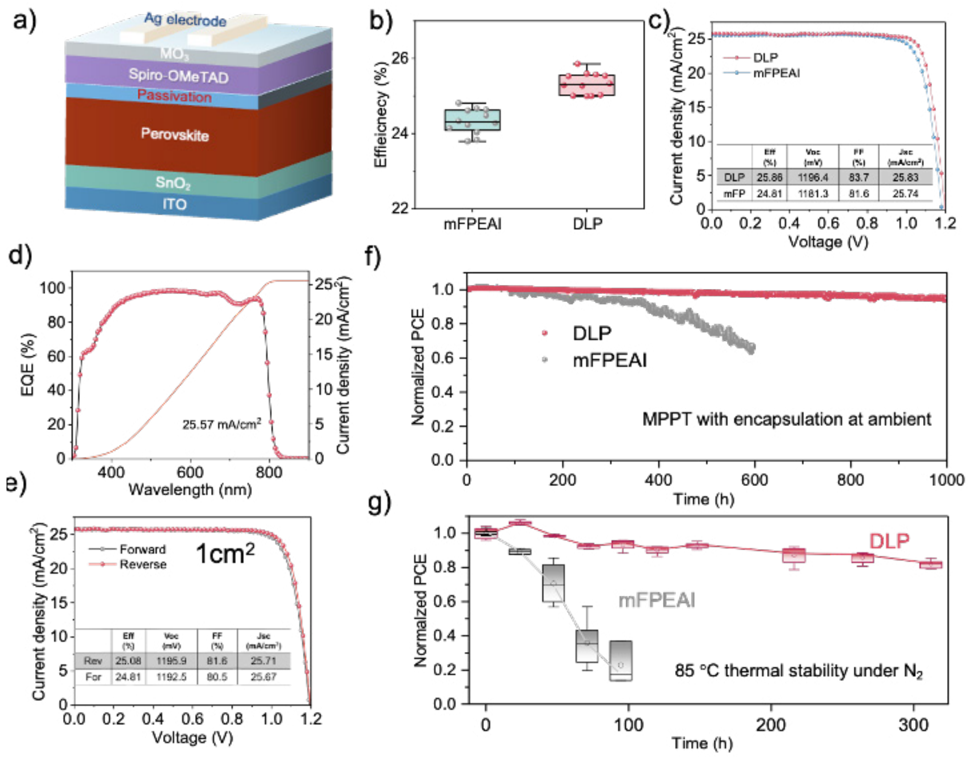


Fig. 3: a) Illustration of device configurations of perovskite solar cells. b) Measured efficiencies of the devices by mFPEAI and dual-ligand passivation. c) Champion J-V curves and corresponding parameters of surface passivation using mFPEAI and dual ligands. d) The EQE of champion device and corresponding integrated current density. e) The forward and reverse scan of champion 1-cm[2] device using dual ligands passivation. f) MPPT of encapsulated device with mFPEAI and dual ligand treatment at ambient under 60% humidity. g) Thermal stability test of device with mFPEAI and dual ligand under N_2 atmosphere in glovebox

Then, the impact on electronic properties was evaluated. The confocal PL showed that the perovskite surfaces treated by the DLP method exhibit stronger and more uniform photoluminescence intensity, see Fig. 2a. Time-resolved photoluminescence (TRPL) revealed significantly enhanced emission intensity and a doubled carrier lifetime from 0.8 µs to 1.77 µs after DLP treatment (Fig. 2b). Moreover, the obtained Pseudo J-V curves showed better V_{oc} and FF of DLP treated surface compared single-ligand treated sample, see Fig. 2c. To further probe the interfacial electrical properties, Kelvin probe force microscopy (KPFM) was employed. Compared to single-ligand passivation, the DLP-treated surface exhibited a much more uniform potential distribution across grains and grain boundaries, with the variation width reduced by more than 60% (Fig. 2d and e). Cross-sectional KPFM of complete devices also revealed that the DLP strategy produced a stronger and more uniform internal electric field, shown in Fig. 2f, which is favourable for efficient carrier separation and extraction. These results highlight that dual-ligand modulation not only improves surface uniformity but also preserves junction quality, thereby enhancing overall device performance.

To evaluate device-level performance, PSCs with a standard n–i–p structure (Fig. 3a) were fabricated. Devices treated with the DLP strategy consistently showed both better average and champion performance than the control devices, see Fig. 3b and c. The champion device performance was improved from a PCE of 24.8% with V_{oc} of 1181 mV and FF of 81.6% to a PCE of 25.9% with the V_{oc} of 1196 mV and FF of 83.7%. The measured external quantum efficiency (EQE) was used to show that the integrated short-circuit current density of the champion device can reach 25.57 mA/cm², see Fig. 3d. Perovskite devices with an area of 1 cm² and DLP treatment still delivered 25.1% efficiency (V_{oc} > 1.19 V, FF 81%), confirming the scalability of this dual-ligand strategy (Fig. 3e). Stability tests further highlighted the advantages of DLP passivation. Under continuous MPPT operation shown in Fig. 3f, DLP-treated devices retained 93% of their initial efficiency after 1000 hours, while single-ligand devices fell to 80% within 500 hours. Thermal stress at 85°C test showed a similar trend, with DLP devices maintaining over 80% efficiency after 300 hours, compared to rapid degradation in the control group shown in Fig. 3g. These results confirm the superior operational and thermal stability enabled by dual-ligand passivation.

5. Conclusions

In summary, we developed a dual-ligand passivation (DLP) strategy that effectively tunes the 2D quantum well distribution of the passivation layer, leading to enhanced interfacial passivation and improved durability. The DLP method promotes the exclusive formation of an n = 1 2D perovskite layer with a more uniform energy landscape, stronger defect passivation, and improved charge extraction. As a result, devices achieved a champion PCE of 25.9% (V_{oc} 1.196 V, FF 83.7%) and demonstrated scalability with 25.1% efficiency for 1-cm² cells. Operational stability was significantly improved, with DLP devices retaining 93% of their initial efficiency after 1000 hours of MPPT testing, alongside superior thermal robustness. These results highlight DLP as an effective means to overcome intrinsic drawbacks of 2D passivation and provide a promising pathway toward scalable and reliable perovskite solar cells. Moreover, the concept of dual-ligand modulation could be further extended to new ligand chemistries, diverse device architectures, and large-area module fabrication, thereby strengthening the prospects of perovskite solar technology for industrial deployment.

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Selected R&D Project

Machine learning driven insights for phase stable $FA_xCs_{1-x}Pb(I_yBr_{1-y})_3$ perovskites in tandem solar cells

Ran LUO, Dr Xiuxiu NIU, Dr Shunchang LIU, Xiao GUO, Asst Prof HOU Yi

1. Background

Organic-inorganic hybrid perovskites have attracted significant attention due to their tunable bandgap (1.4 - 2.3 eV) for different tandem solar cells and high power conversion efficiencies, with perovskite/Si tandem solar cells already reaching 33.9%, surpassing the Shockley-Queisser limit of single-junction devices [1, 2]. However, bandgap tuning typically relies on halide mixing, which often induces phase segregation and compromises stability, highlighting the urgent need to identify optimal compositions that simultaneously ensure efficiency and stability. Traditional composition optimisation, largely dependent on empirical trial-and-error, remains inefficient and environmentally unsustainable. Recently, machine learning (ML) has emerged as a promising tool for perovskite design, enabling accelerated and eco-friendly screening of candidate materials and significantly shortening the development cycle of functional materials [3]. Nevertheless, most existing models emphasise macroscopic property correlations while neglecting intrinsic physical insights [4]. Developing physics-informed machine learning frameworks that couple physical understanding with predictive capability holds great potential for guiding the rational design of stable, high-performance perovskite compositions.

2. Scope of project & objectives

In this work, we aim at employing the neural network (NN) potential technique [5] to address the functional relationship between atomic structures and system energy. We trained a perovskite NN potential to enable global screening of the commonly used organic-inorganic hybrid halide perovskite system, $FA_xCs_{1-x}Pb(I_yBr_{1-y})_3$, where $0 \leq x \leq 1$ and $0 \leq y \leq 1$. Utilising the NN-predicted structures, we examined phase segregation through the calculated phase segregation energy. Subsequently, we performed accurate band gap calculations to identify compositions suitable for various tandem solar cell applications. Through this process, we successfully predicted two optimal candidates for perovskite/Si and perovskite/perovskite tandem solar cells. The enhanced PV performance of these candidates, compared to traditional compositions, was corroborated by corresponding experimental validations.

3. Significance & impact of project

We have established a first-principles based perovskite structures database, which could be used for the benchmarking of future machine learning work in the community. Further, high accuracy neural network potential has been established for large-scale perovskite materials simulation. Based on the ML framework, the ability to realise high-throughput computational sampling of perovskite materials aligns directly with Singapore's green energy transition goals, which holds significant promise as a future method for the advanced design of tandem solar cells.

4. Methodology & Results

To address the prohibitive computational cost of first-principles global screening, we established a neural network (NN) potential for hybrid perovskites [5]. The targeted system involves seven elements (H, C, N, Cs, Pb, I, Br). A large structural database containing 602351 configurations was constructed through density functional theory (DFT)-based global optimisation, including cubic and tetragonal perovskites with different tilt degrees, 2D perovskites, and non-perovskite structures to ensure comprehensive potential energy surface (PES) sampling. Different lattice constants, atomic positions, and compositions were considered. From this database, 20500 structures were randomly chosen as the training dataset.

A very deep NN (configuration: 545/510-80-50-50-1) was constructed with customised feature engineering. Power type symmetry functions (PTSDs) were employed for their superior recognition of atomic features compared with conventional atom-centered symmetry functions. To further improve feature representation, PTSDs were tailored to the distinct local chemical environments in perovskites: the A-site cuboctahedral cage and the PbX_6 octahedron, resulting in two series of 545 and 510 symmetry functions, respectively.

The trained NN potential reached top accuracy, yielding errors of 1.91 meV/atom for energy and 0.064 eV/Å for forces, clearly outperforming models with routine feature engineering. Validation on independent datasets maintained low RMS errors (4.33 meV/atom for energy and 0.055 eV/Å for forces). These results validate the efficacy of the proposed framework and provide a robust seven-element NN potential, offering a powerful tool for subsequent theoretical design and screening of perovskite absorbers.

We investigated the thermodynamics of phase segregation in hybrid perovskites using NN potential-driven global stochastic surface walking (SSW) optimisation for 153 compositions with an $A_{16}B_{16}X_{48}$ framework, systematically varying FA/Cs and I/Br ratios. The lowest-energy structures were selected from global optimisations. The NN potential enabled a dramatic acceleration: while DFT-based local optimisation required 9216 core hours, the NN completed the same task in 4.8 seconds, demonstrating its superiority for large, complex systems. Based on the optimised structures, we performed Gibbs free energy analysis to assess the segregation tendency, thereby constructing the phase diagram of hybrid perovskites.

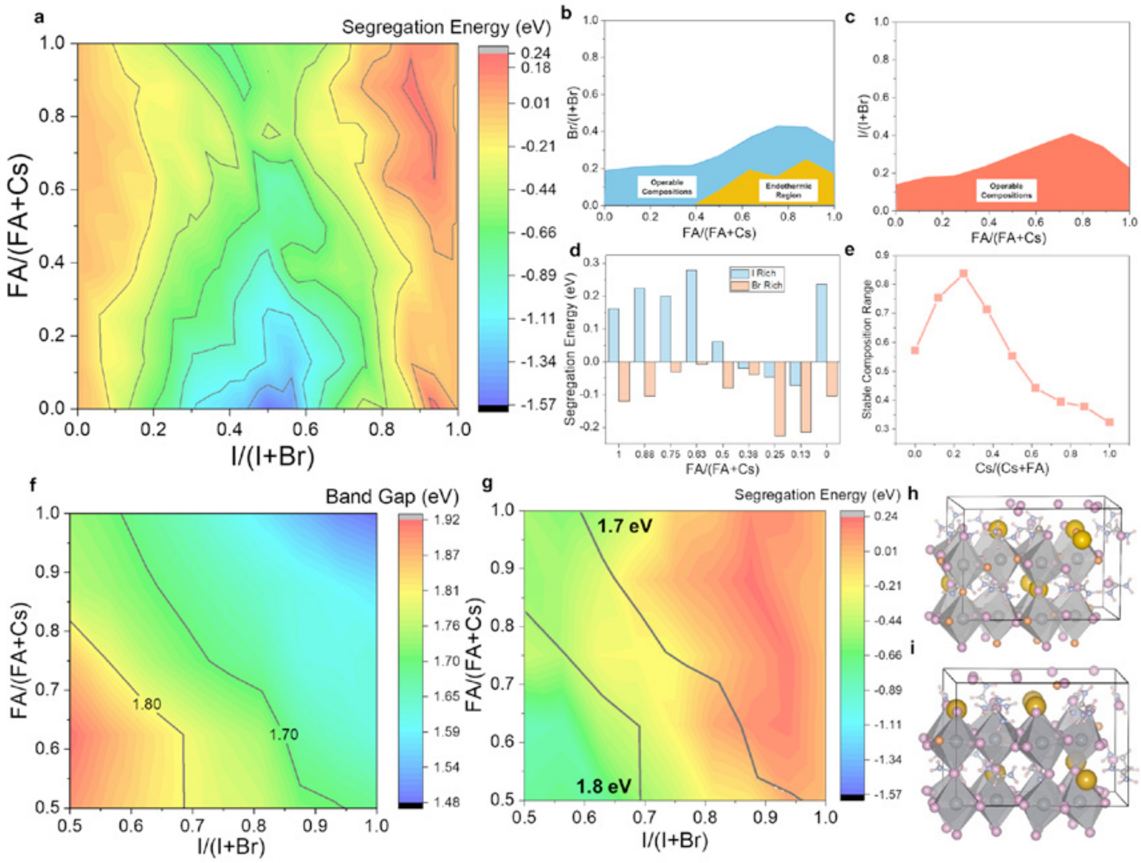

Fig. 1: (a) Neural network predicted halides perovskites ($FA_xCs_{1-x}Pb(I_yBr_{1-y})_3$) phase diagram with phase segregation Gibbs free energy as targeting property. (b) Operable and endothermic compositions range and for I-rich perovskites. (c) Operable composition range for Br-rich perovskites. (d) Peak values of segregation Gibbs free energies for I-rich and Br-rich perovskites with different A sites compositions. (e) The proportion of stable compositions versus addition amount of Cs. (f) Calculated band gap diagram. (g) Perovskites with 1.7 eV and 1.8 eV band gaps in the predicted phase diagram. (h) Predicted optimal 1.8 eV perovskites. (i) Predicted optimal 1.7 eV perovskites

The phase diagram reveals regions where segregation reactions are endothermic (red), indicating stability of the mixed state, and regions where reactions are exothermic (yellow–blue), indicating segregation preference. A clear trend emerges: as I/Br approaches unity, segregation tendency strengthens (Fig. 1a). The largest stable (red) region corresponds to I-rich, FA-rich compositions, consistent with experimental observations. Thus, our results both validate prior trial-and-error findings and provide, for the first time, a global view of phase segregation thermodynamics. Importantly, we define “operable compositions” as those with slightly exothermic Gibbs free energy (> -0.4 eV), where segregation may be kinetically suppressed. These regions were mapped for both I-rich and Br-rich phases (Fig. 1b and 1c). While both exhibit comparable operable domains, exothermic segregation is exclusive to I-rich perovskites; Br-rich phases universally display negative Gibbs free energies. Nevertheless, I-rich phases show higher peak segregation energies, indicating intrinsically greater stability (Fig. 1d).

For the A site, Cs plays a crucial role: below 40% concentration, Cs addition mitigates segregation, expanding the tolerance of perovskites to Br incorporation, with the strongest effect near 20% Cs. However, exceeding 40% Cs reduces segregation energy, likely due to tolerance factor reduction (Fig. 1e).

Band gap calculations further guided composition screening in the ranges 0.5 ≤ FA/(FA+Cs) ≤ 1 and 0.5 ≤ I/(I+Br) ≤ 1 (Fig. 1f). Band gaps increase from I-rich to Br-rich and from FA-rich to Cs-rich compositions. Candidate 1.7-eV and 1.8-eV perovskites were identified, corresponding to Si/perovskite and perovskite/perovskite tandems, respectively (Fig. 1g). While 1.7-eV candidates exist over a broader composition range, 1.8-eV candidates require higher Br content and thus fall in exothermic regions. Integrating the phase and band gap diagrams, we determined $FA_{0.63}Cs_{0.37}Pb(I_{0.88}Br_{0.12})_3$ as the optimal 1.7-eV perovskite, located in a stable (red) region (Fig. 1h), while $FA_{0.63}Cs_{0.37}Pb(I_{0.69}Br_{0.31})_3$ is the optimal 1.8-eV perovskite but lies in a yellow region, implying thermodynamic instability (Fig. 1i). Therefore, Si/perovskite tandems using 1.7-eV absorbers are more promising, whereas achieving stable 1.8-eV perovskites for all-perovskite tandems will require novel A/X site combinations.

We investigated the kinetics of phase segregation in hybrid perovskites using NN potential based simulations. For the predicted 1.8-eV candidate, segregation proceeds via a stepwise mechanism with a high activation barrier of 5.53 eV, ensuring improved stability compared with a reference 1.8-eV perovskite (4.96 eV).

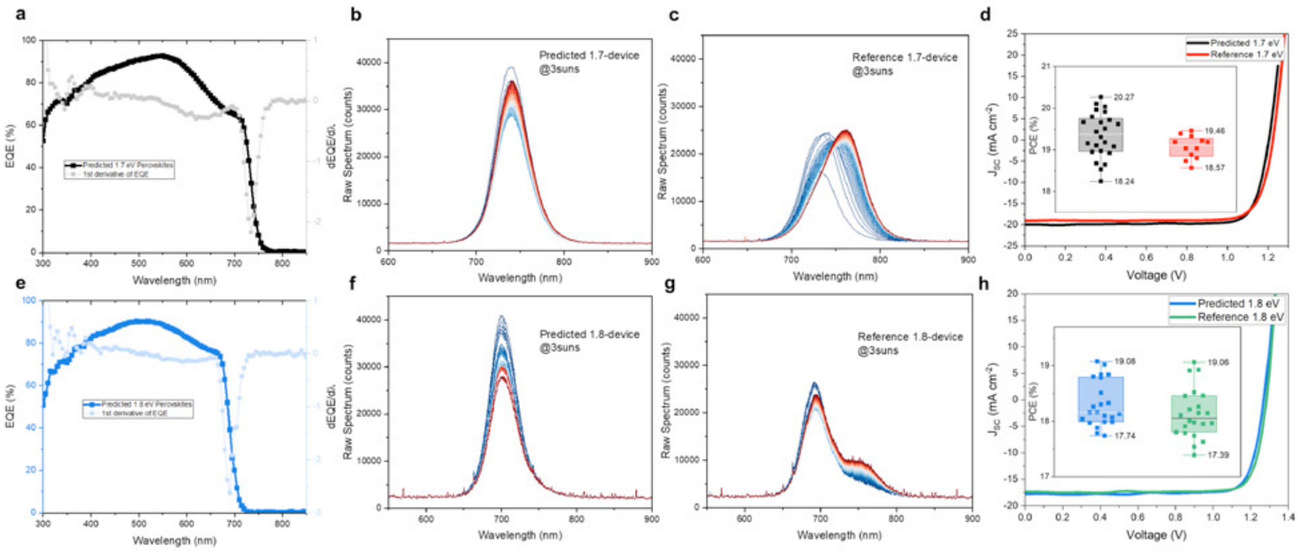

Fig. 2: (a) EQE spectra and PV band gap of predicted 1.7-eV perovskites. (b, c) Photoluminescence spectra evolution of predicted and reference 1.7-eV perovskites under 3 times 1-sun AM 1.5G intensity for 17 min. (d) I-V performance of predicted 1.7-eV perovskites and reference. Inset is their PCE distribution. (e) EQE spectra and PV band gap of predicted 1.8-eV perovskites. (f, g) Photoluminescence spectra evolution for predicted and reference 1.8-eV perovskites, respectively. (h) I-V performance of predicted 1.8-eV perovskites and reference. Inset is their PCE distribution

Mechanistic analysis reveals that Cs suppresses lattice tilting during segregation, thereby increasing the activation barrier, while reduced Br content leads to a simpler single-atom transfer pathway with lower barriers. Thus, Cs incorporation serves as an efficient kinetic suppression strategy, whereas Br concentration critically dictates segregation mechanisms.

We have experimentally verified our theoretical predictions by fabricating perovskite solar cells with the predicted $(FA_{0.63}Cs_{0.37}Pb(I_{0.69}Br_{0.31})_3$, $FA_{0.63}Cs_{0.37}Pb(I_{0.88}Br_{0.12})_3)$ and reference compositions. The measured band gaps (1.80 and 1.69 eV) closely matched calculations (Fig. 2a and 2e), confirming the reliability of our NN potential. Photoluminescence evolution under 3-suns illumination showed that predicted compositions maintained stable peaks (Fig. 2b and 2f), while references exhibited significant red shifts, indicating stronger segregation (Fig. 2c and 2g). Stability tests further validated the superior robustness of the predicted compositions. Finally, the I-V tests also indicated that our predicted compositions did not compromise the PV performance compared with reference compositions (Fig. 2d and 2h).

5. Conclusions

In conclusion, our goal is to use machine learning-based theoretical calculations to provide practical guidance and uncover new insights for the preparation or even manufacturing of realistic perovskite solar cells. By mapping out the global phase diagram of hybrid perovskites, we have successfully identified the optimal compositions with different band gaps that can inhibit the phase segregation process, thereby enhancing the stability of perovskite solar cells. Specifically, for perovskites with 1.8 eV band gaps, which are prone to phase segregation, we recommend adding an appropriate amount of Cs and adjusting the I and Br concentrations to raise the barriers to segregation and achieve kinetic control of phase segregation. This study showcases the power of machine learning-driven approaches in maximising the benefits of compositional engineering by efficiently pinpointing the best compositions. Thus, the integration of machine learning-guided computational design with precise experimental validation is poised to become the standard methodology for developing high-performance perovskite solar cells in the future.

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Selected R&D Project

Oxygen-dependent sputtered NiO_x for high-performance perovskite solar cells and mini-modules

Ling Kai LEE, Dr Nengxu LI, Xi WANG, Haoming LIANG, Jinxi CHEN, Dr Renjun GUO, Zijing DONG, Zhuojie SHI, Dr Tao WANG, Dr Donny LAI, Dr Shunchang LIU, Dr Zhengrong JIA, Yuduan WANG, Xiao GUO, Dr Jia LI, Qilin ZHOU, Prof Armin ABERLE, Asst Prof HOU Yi

1. Background

Perovskite solar cells (PSCs) have shown remarkable progress over the past 10 years, achieving power conversion efficiencies (PCEs) exceeding 27.3% at laboratory scale (typically 0.1 cm^2)[1]. Inverted PSCs are particularly attractive due to their fabrication simplicity, superior operational stability, and compatibility with large-scale production. For commercialisation, the adoption of industrially compatible deposition methods is essential. Sputtering, a well-established technique in the thin-film industry, offers excellent uniformity and scalability [2]. Nickel oxide (NiO_x) is a promising hole transport layer (HTL) that can be deposited via sputtering at low cost. However, its chemical reactivity with perovskite layers, particularly redox reactions, has been a bottleneck for device stability [3].

2. Scope of project & objectives

This project aims to investigate the oxygen-dependent interfacial reactions between the perovskite absorber and the sputtered NiO_x HTL. By systematically controlling the oxygen doping ratio during the sputtering process, we seek to optimise the electrical and optical properties of the NiO_x film while mitigating interfacial degradation. The ultimate objective is to demonstrate efficient, stable, and scalable PSCs using an industrially compatible deposition route.

3. Significance & impact of project

The findings of this study highlight the scalability and stability of efficient PSCs using an industrial sputtering process. We demonstrate that high-efficiency devices can be fabricated over large areas, achieving PCEs of 24.0% (1 cm^2) and 21.1% (20 cm^2 aperture area). These results show that sputtered NiO_x HTLs can effectively bridge the gap between lab-scale prototypes and commercial-scale modules, reducing performance losses at scale and supporting lower-cost solar energy production.

4. Methodology & Results

NiO_x films were deposited by pulsed DC sputtering under varying argon-to-oxygen gas flow ratios, resulting in two conditions: O_2-moderate and O_2-rich. XPS analysis revealed higher Ni^{3+} content in O_2-rich films (Ni^{3+}/Ni^{2+} ratio of 1.70) compared to O_2-moderate films (1.51) (Fig. 1a-b). After FAI deposition (Fig. 1c-d), the Ni^{3+}/Ni^{2+} ratio decreased more significantly in O_2-rich samples, indicating stronger interfacial reactivity with perovskites. Ni^{3+} species in O_2-rich NiO_x exhibited greater reactivity with organic cations in the perovskite layer. To probe this, the N 1s core-level spectra of FAI were deconvoluted into FA^+ cations and deprotonated FA (Fig. 1e-f). The relative content of deprotonated bridge the gap between lab-scale prototypes and commercial-scale modules, reducing performance losses at scale and supporting lower-cost solar energy production. FA is higher in the O_2-rich sample, confirming more severe deprotonation of organic cations. In addition, a pronounced decrease in the iodide signal of FAI was observed on O_2-rich NiO_x (Fig. 1g-h), indicating oxidation of iodide by Ni^{3+} sites to form gaseous iodine. Both organic cation deprotonation and iodide oxidation are detrimental to device efficiency and long-term stability, as they generate trap states at the HTL/perovskite interface and accelerate irreversible ion migration [4].

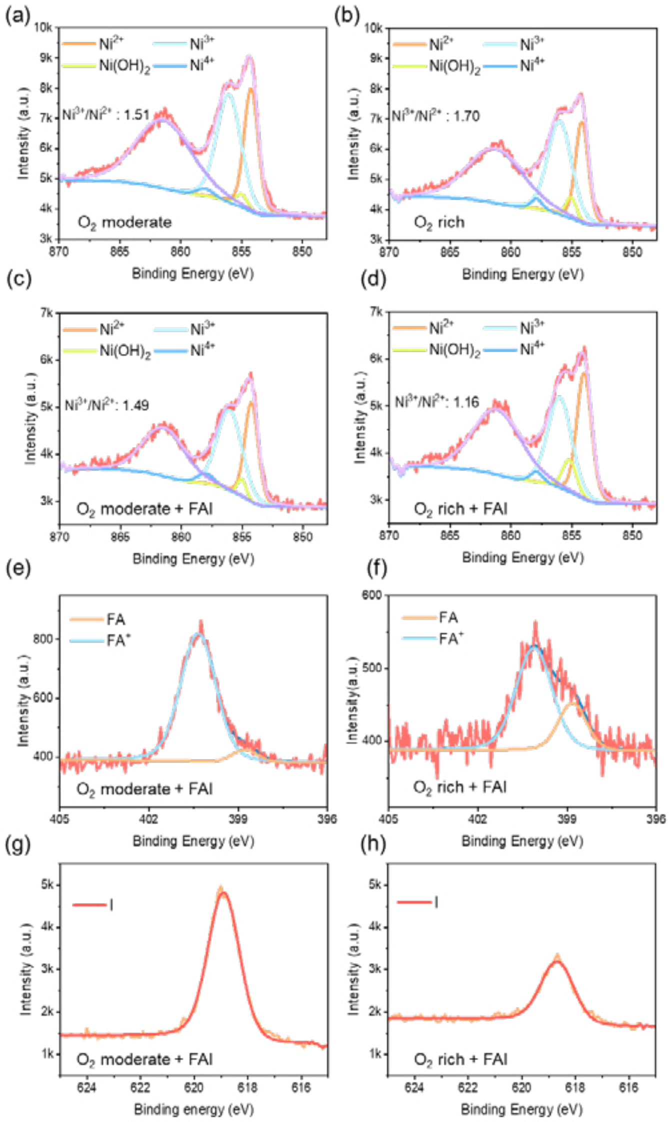

Fig. 1: Ni 2p 3/2 core level spectra for as-deposited a) O_2-moderate and b) O_2-rich NiO_x films. Ni 2p 3/2 core level spectra for c) O_2-moderate and d) O_2-rich NiO_x films after FAI treatment. N 1s core level spectra for e) O_2-moderate and f) O_2-rich NiO_x films after FAI treatment. I 3d 5/2 core level spectra for f) O_2-moderate and h) O_2-rich NiO_x films after FAI treatment

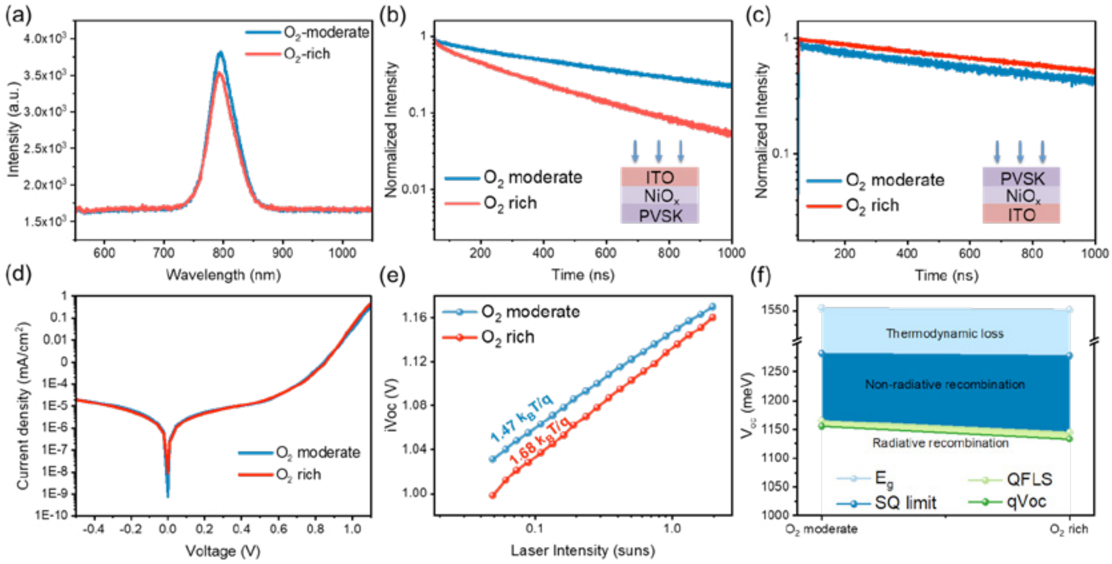

Fig. 2: a) Steady-state PL spectra of perovskites which were deposited onto the O_2-moderate and the O_2-rich based NiO_x films, respectively. TRPL measurements with the incident laser beam directed from the b) ITO side and c) perovskite side. d) The dark current of PSCs with O_2-moderate and O_2-rich based NiO_x films, respectively. e) iV_{oc} of PSCs with O_2-moderate and O_2-rich based NiO_x films, respectively. f) V_{oc} loss analysis of the PSCs with O_2-moderate and O_2-rich based NiO_x films, respectively

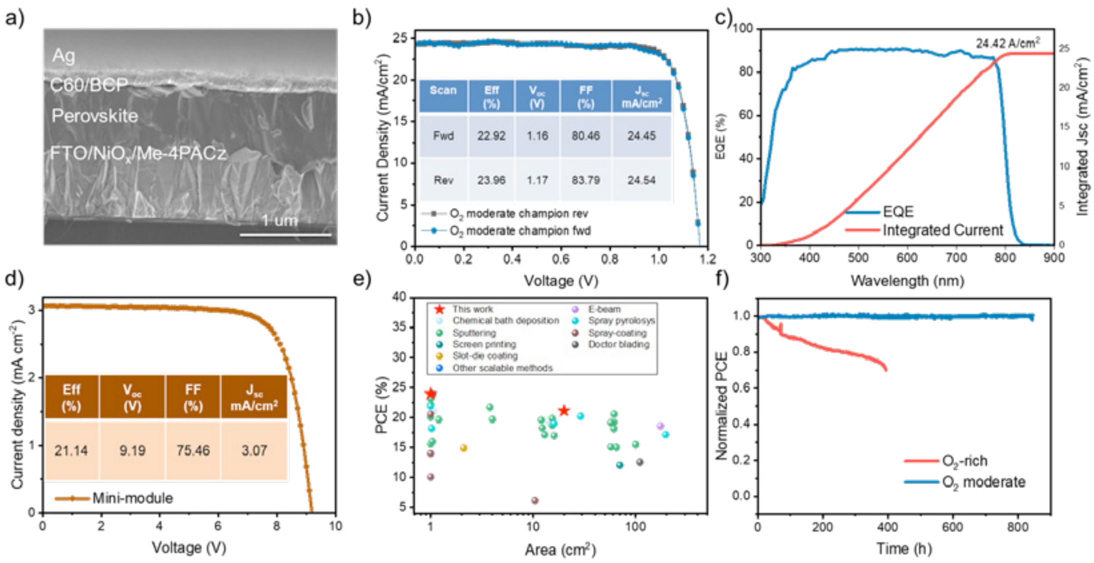

Fig. 3: a) Cross-sectional SEM image of PSC. b) J-V curves (including reverse scan and forward scan) of champion PSC (1.0 cm² aperture area) based on O_2-moderate sputtered NiO_x. c) EQE spectrum and integrated J_{sc} of champion PSC based on O_2-moderate sputtered NiO_x. d) J-V curves of champion mini-module (20 cm² aperture area) based on O_2-moderate sputtered NiO_x. e) Efficiencies of PSCs where the NiO_x films were fabricated through scalable technologies (sputtering, E-beam evaporation, atomic layer deposition, spray coating, blade coating, etc.) f) PCE evolution of O_2-moderate and O_2-rich based PSCs when devices were aged under continuous 1-sun illumination and MPP tracking

Photoluminescence and TRPL studies showed that O_2-rich NiO_x induced stronger nonradiative recombination at the perovskite/HTL interface. Steady-state PL spectra (Fig. 2a) and TRPL decay curves (Fig. 2b-c) confirmed faster recombination in O_2-rich samples, corroborated by higher dark currents (Fig. 2d). When excitation was from the ITO side, O_2-rich devices exhibited significantly faster recombination, whereas excitation from the perovskite side gave similar decays, confirming that recombination originates at the perovskite/NiO_x interface due to Ni^{3+} reactivity. iV_{oc} analysis (Fig. 2e) further supported this, with O_2-rich devices showing a higher ideality factor. PLQY combined with QFLS analysis (Fig. 2f) quantified the V_{oc} loss mechanisms in PSCs. Compared to O_2-rich devices, O_2-moderate devices showed lower nonradiative recombination losses, with qV_{oc} reaching over 90% of the Shockley-Queisser limit.

To evaluate the impact on device performance, we fabricated solar cells with the structure FTO/NiO_x/Me-4PACz/Perovskite/C60/BCP/Ag. The cross-sectional SEM of the device structure is shown in Fig. 3a. Champion devices achieved 24.0% efficiency (1.0 cm², (Fig. 3b), with EQE confirming the current density (Fig. 3c). Scaling to 20-cm² mini-modules yielded 21.1% efficiency (Fig. 3d), among the highest reported for sputtered NiO_x HTLs. Comparison with other scalable deposition techniques (Fig. 3e) highlights the competitiveness of sputtering. Stability tests showed that O_2-moderate devices have negligible efficiency drop after 845 h under MPP tracking, whereas O_2-rich devices degraded faster (Fig. 3f).

These results demonstrate that careful control of oxygen doping during sputtering is critical for optimising the interfacial chemistry of NiO_x, enabling scalable, efficient, and stable perovskite solar cells.

5. Conclusions

Sputtered NiO_x is an industrially compatible deposition technology that enables scalable, uniform film growth for large-area perovskite solar cells. This work demonstrates that oxygen doping strongly influences the interfacial chemistry and optoelectronic properties of NiO_x, where optimised conditions minimise nonradiative recombination while ensuring efficient charge extraction. As a result, we achieved record efficiencies of 24.0% (1.0 cm^2) and 21.1% (20 cm^2 mini-module), together with excellent operational stability of over 845 h under illumination and MPP tracking. These results underscore the potential of sputtered NiO_x for commercialisation of high-performance perovskite photovoltaics, especially in large-area modules and tandem devices.

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This article is an extract of a more comprehensive work published in 2025 in ACS Materials Letters: "Oxygen-Dependent Sputtered NiO_x for High Performance Perovskite Solar Cells and Minimodules", by Ling Kai Lee, Nengxu Li et alia. Reproduced with permission from the publisher American Chemical Society

Selected R&D Project

Optical losses in silicon heterojunction solar cells: analysis of record-efficiency devices and practical limits based on ray-tracing simulations

Erik M. SPAANS, Dr Selvaraj VENKATARAJ, Dr Krishna SINGH, Ashwath RAVICHANDRAN, Maria L. MANALO, Rosalie GUERRA, Prof Armin G. ABERLE, Dr Nitin NAMPALLI

1. Background

The power conversion efficiency (PCE) of record silicon heterojunction (SHJ) solar cells for both front-and-back-contacted (FBC) and interdigitated back-contacted (IBC) architectures has improved significantly in recent years. This is largely due to considerable improvements in short-circuit current density (J_{sc}) (see Fig. 1) driven by recent industrial innovations resulting in highly transparent layers and novel metallisation. Concurrently with these developments, the manufacturing capacity for SHJ solar cells has also increased significantly since 2019, and the SHJ solar cell market share is expected to reach 19% over the next ten years within a TW_p-scale global production capacity [1]. This rapid ramp-up in SHJ cell capacity has generated an increasing need in the PV industry to better understand (1) the drivers of the J_{sc} loss in industrial SHJ solar cells, (2) the most effective methods to further improve the J_{sc} of these cells, and (3) the practical upper limit of J_{sc} achievable in industrial FBC-SHJ and IBC-SHJ cells. Here, we tackle these questions with the help of ray-tracing-based optical modelling.

2. Scope of project & objectives

In this work, we present the first detailed side-by-side comparison of J_{sc} losses in recent record solar cells enabled by a carefully calibrated and thoroughly validated optical ray-tracing model and derive a practical J_{sc} limit for modern FBC-SHJ and IBC-SHJ solar cells for different silicon wafer thicknesses. By modelling recent SHJ record PCE cells based on published data, we obtain spectrally resolved J_{sc} losses as well as estimates of the complex refractive indices for all functional layers used in record SHJ solar cells as of 2024 from Hanergy, Maxwell, SunDrive, LONGi, Panasonic and Kaneka [2–6]. We derive important insights from this analysis to (1) clarify the optical requirements needed to achieve record-high J_{sc} in SHJ solar cells and (2) to identify the most effective pathways to improve the J_{sc} of industrial SHJ cells.

3. Significance & impact of project

With the recent increase in high-PCE SHJ solar cells and a worldwide surge in their manufacturing capacity, it is imperative to understand the developments needed to achieve high device J_{sc} and the potential opportunities that lie ahead. By elucidating the J_{sc} loss distributions of recent record SHJ solar cells, potential improvements are evaluated to quantify practical J_{sc} limits for both FBC-SHJ and IBC-SHJ. The insights derived in this work provide a useful technology roadmap for the continued enhancement of the optical performance of SHJ solar cells.

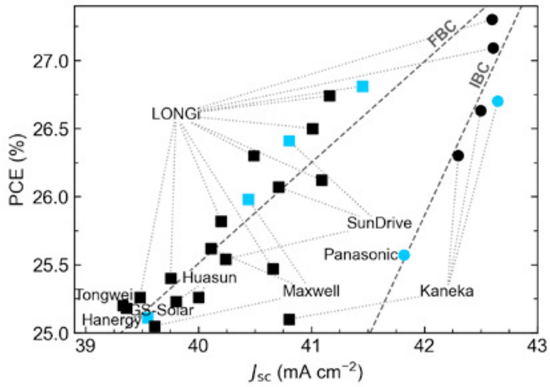

Fig. 1: Certified PCE of commercial FBC (squares) and IBC (circles) SHJ solar cells vs J_{sc}. The highlighted points are analysed in this work.

4. Methodology & Results

The first step in our investigation is the creation and validation of an optical model for SHJ solar cells, with optical structures shown in Fig. 2A and 2B. To this end, we calibrate an optical ray-tracing model with GenPro4 [7] to an in-house FBC-SHJ solar cell. Furthermore, we use a comprehensive dataset obtained from single-layer measurements, measurements on stacked layers, solar cell precursors and measurements on fully-finished FBC solar cells. This includes the following:

(1) Wavelength-dependent complex refractive indices (*n* and *k*) of all the thin films were determined by simultaneous fitting of spectroscopic ellipsometry (SE) and reflectance/transmittance (RT) measurements on planar substrates.

(2) RT measurements were performed on four different types of test structures: (a) on a bare textured wafer, (b) after single-layer depositions of all the layers present in the final solar cell stack [a-Si:H(i), a-Si:H(n), a-Si:H(p) and ITO], (c) on multi-layer stacks [a-Si:H(i)/a-Si:H(n), a-Si:H(i)/a-Si:H(p) and solar cell precursor], (d) after metallisation.

(3) Finished FBC solar cells were subjected to current-voltage (I-V) measurements as well as spot-EQE and R measurements.

Furthermore, we consider additional important aspects of the device and setup, including wafer texturing, the collection efficiency of the front a-Si:H(i) and the optics of the measurement setup. By cross-validating the datasets, an accurate model for FBC-SHJ solar cells was derived, as shown in Fig. 2C.

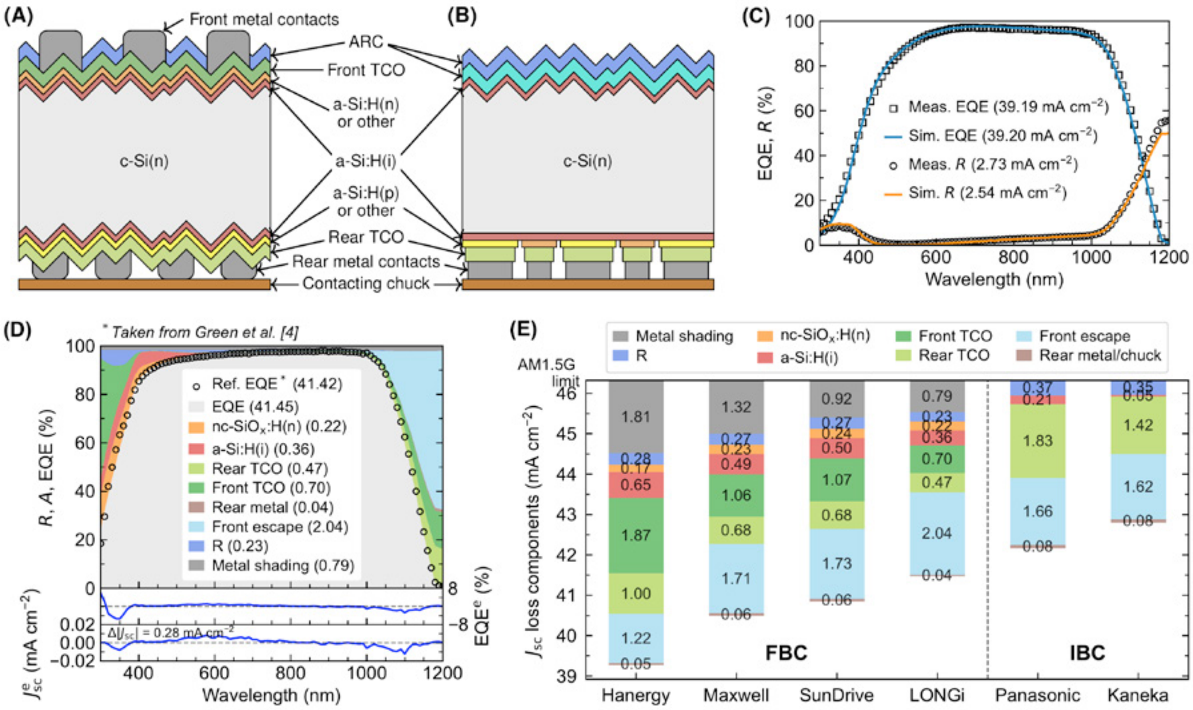

Fig. 2: Optical structure for (A) FBC-SHJ and (B) IBC-SHJ solar cells used in this work. (C) Simulated and measured spot-EQE and spot-R of our reference in-house FBC-SHJ solar cell. (D) Simulated spectral optical losses of the world-record FBC-SHJ by LONGi (PCE 26.81%), along with the certified EQE data, as modelled in this work. (E) Detailed breakdown and cumulative J_{sc} losses of all the record-efficiency FBC-SHJ and IBC-SHJ solar cells modelled in this work

To develop specific models for each reported record-SHJ cell from the literature, we incorporate into the in-house model all published information from the various record devices regarding the device structure, layer thicknesses and metallisation fractions, and model the refractive indices of the layers with dispersion laws. The parameters of the oscillator models were varied until a best-fit match was obtained to the reported EQE. Using this approach, customised models for all record SHJ cells targeted for comparison in this work could be successfully created. These are presented in Table 1, along with their certified and simulated J_{sc}.

Table 1: Summary of the FBC-SHJ and IBC-SHJ solar cells modelled in this work

Type	Name	PCE (%)	J_{sc} (mA cm^{-2})	
			Certified	Simulated
FBC	Hanergy [2]	25.11	39.29	39.28
	Maxwell [3]	25.98	40.44	40.47
	SunDrive [3]	26.41	40.80	40.83
	LONGi [4]	26.81	41.42	41.45
IBC	Panasonic [5]	25.57	41.16	42.17
	Kaneka [6]	26.7	42.77	42.80

A decomposition of the spectral losses of one of these devices (as determined in this work) is shown in Fig. 2D, along with the spectral errors in EQE and J_{sc} (per 10 nm) in the bottom subplots. Finally, a summary of all the integrated J_{sc} losses is presented in Fig. 2E. Despite the differences in the device structures and materials used across the six high-efficiency devices analysed in this work, a very low mismatch is obtained for all FBC-SHJ and IBC-SHJ devices, confirming the robustness of our modelling approach. The main innovations of the record devices can be summarised as follows:

(1) Hanergy (PCE 25.11%): Use of nc-SiO_x:H(n) as front charge transport layer.
(2) Maxwell (PCE 25.98%): Use of a novel TCO and a-Si:H(i) to increase transparency. Shading fraction is also reduced.
(3) SunDrive (PCE 26.41%): With an estimated shading fraction of 2%, the shading losses are further reduced with a Cu plating process.
(4) LONGi (PCE 26.81%): Further increase in optical transparency in a-Si:H(i) and a novel TCO. A rear low-refractive-index material also enhances the NIR response and a shading fraction of 1.7% is possible with a laser-transfer printing process.
(5) Panasonic (PCE 25.57%): Very transparent front passivation layer.
(6) Kaneka (PCE 26.7%): Further transparency enhancement of the front passivation layer and rear TCO.

A cross-comparison of the J_{sc} losses and gains from recent record PCE SHJ solar cells presented in this work allows us to gain important quantitative insights into the key advances needed to further improve the efficiencies of industrial SHJ solar cells. In addition, based on the layer transparency improvements derived in this work for the different record devices in the literature, we estimate practical limits for the J_{sc} of FBC and IBC configurations for varying wafer thicknesses, starting from the highest modelled record in each case.

For the record FBC-SHJ solar cell, the main J_{sc} losses are: (1) front escape, (2) TCOs, (3) metal shading, (4) front passivation layer, (5) reflection and (6) front charge transport layer. Loss (1) is not directly controllable, as it is a consequence of the low absorption coefficient of Si in the NIR and the level of FCA in the TCOs. For loss (3), we assume a shading fraction of 1.5%, which we deem possible given continuous improvements in metallisation techniques. For losses (2), (4) and (6), more transparent materials could be developed, but the transparency limit is not clear. Therefore, we assume the same layers as the ones fitted from the record FBC-SHJ cell. The reflectance loss (5) is already very low with the used double-layer ARC (DLARC), so no major improvements are expected by using other materials or adding more ARC layers. We only perform a thickness optimisation based on the existing materials in the record device, fixing the minimum TCO thickness to 50 nm to ensure that a sufficiently low sheet resistance can still be achieved. For IBC-SHJ solar cells, the main J_{sc} losses are: (1) front escape, (2) rear TCO, (3) reflection and (4) front passivation layer. Once again, loss (1) is not controllable. For the rear TCO loss (2), we use the same TCO as modelled for the record FBC-SHJ, which is considerably more transparent. For the reflection loss (3), we again do minor optimisations for the thicknesses of the DLARC. Further, we assume a fully transparent front passivation layer to eliminate loss (4) and use a similar rear structure as the FBC-SHJ practical limit.

We predict the ray-tracing-based practical J_{sc} limits of FBC-SHJ solar cells to be between 40.49 and 42.00 mA cm^{-2} within a 50 to 200 µm wafer thickness range, and between 42.09 and 43.57 mA cm^{-2} for IBC-SHJ solar cells in the same thickness range. These limits, along with the loss distributions, are shown in Fig. 3.

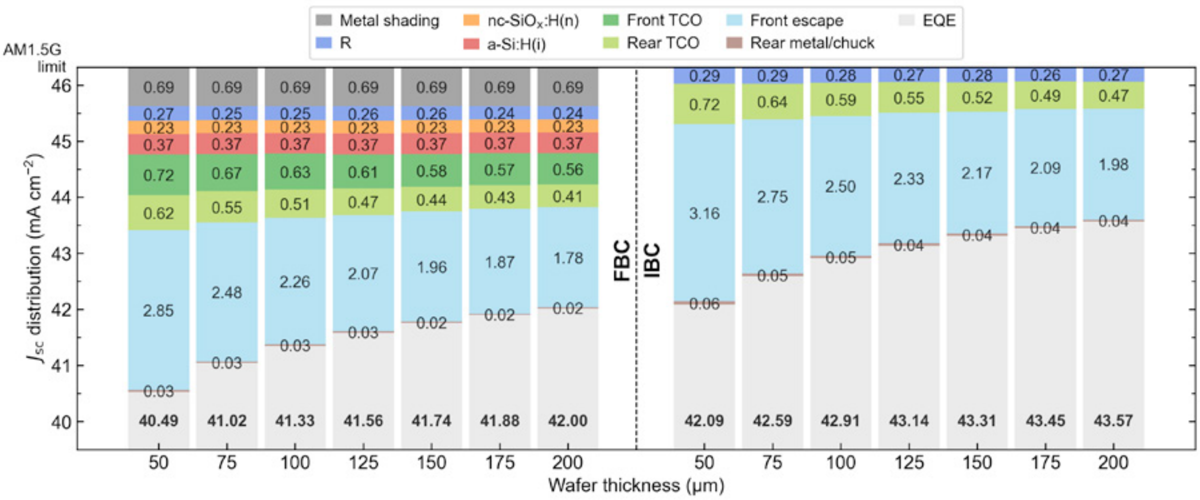

Fig. 3: Ray-optics-based practical J_{sc} limits and loss distributions as a function of the silicon wafer thickness for (left) FBC-SHJ and (right) IBC-SHJ solar cells

5. Conclusions

Having carefully calibrated a ray-tracing optical model of SHJ solar cells, we have identified the main drivers of J_{sc} loss in industrial SHJ solar cells with FBC and IBC architectures. The comprehensive optical analysis and accurate modelling of six recent record SHJ devices (FBC and IBC) reported in the literature provide unique insights into the optical losses of these high-efficiency devices. By assuming reasonable incremental improvements from the current SHJ record cells, we derive, to our knowledge for the first time, practical limits for such devices for both contact architectures, across a wide range of silicon wafer thicknesses. The new practical J_{sc} limit values derived in this work and possible improvement pathways could prove useful for achieving new record PCE SHJ solar cells.

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This article is an extract of a more comprehensive work published in EES Solar in 2025: E.M. Spaans et al., "Optical losses in silicon heterojunction solar cells: analysis of record-efficiency devices and practical limits based on ray-tracing simulations," EES Sol., vol. 1, no. 2, pp. 157–171, 2025. Reproduced with permission from the Royal Society of Chemistry

Selected R&D Project

Reliability of floating photovoltaics (FPV): evaluating the effects of hydrodynamic mechanical loads on photovoltaic modules

Dr Min Hsian SAW, Si Liang HENG, Dr Shin Woei LEOW, Aziz NAIRI, Dr Mauro PRAVETTONI

1. Background

Floating photovoltaics (FPV) have emerged as a promising solution to renewable energy generation in land-scarce regions. By utilising water surfaces (both on reservoirs and offshore), FPV systems alleviate competition for land use and can even be deployed in utility scales. However, the unique environmental conditions faced by FPV–especially wave-induced mechanical stresses–pose significant challenges to the long-term reliability of photovoltaic (PV) modules.

The performance and durability of PV modules in FPV applications are threatened by previously unaddressed mechanical stressors such as torsion, vibration, and wave-in-deck impacts, which are not captured in existing qualification standards for PV modules, such as IEC 61215, do not encompass these FPV-specific stresses. This project experimentally evaluates the impact of such hydrodynamic mechanical loads on commercial PV modules and proposes advanced stress tests for more robust type approval protocols.

2. Scope of project & objectives

This study aims to:

- Identify and classify the distinct mechanical stress environments encountered by FPV systems.
- Experimentally assess the impact of torsion, vibration, and wave-in-deck impact loads on the reliability and performance of commercial PV modules.
- Propose new mechanical stress testing protocols to supplement current international PV standards for FPV applications.

3. Significance & impact of project

This research provides essential guidance to the PV industry and standards organisations by highlighting previously overlooked risks in FPV deployments. Incorporating advanced stress tests into qualification procedures will:

- Enhance module reliability, reducing failure rates and maintenance costs in FPV installations.
- Contribute to international standards development, paving the way for safe and durable deployment of FPV systems globally.
- Support the Singapore Green Plan 2030 by improving the viability and safety of FPV as a key renewable energy option.

4. Methodology & Results

Experimental Design:

Mechanical stress tests were conducted at SERIS accredited laboratory using commercial mono-Si PERC modules from several Tier-1 manufacturers (glass-backsheet and glass-glass configurations). Modules were subjected to:

- Torsion test: Simulated torsional wave-induced loads using modified dynamic mechanical load test (DMLT) apparatus, with loads of 400–600 Pa and mounting variations to reflect real FPV scenarios.
- Vibration test: Applied sinusoidal vibration at 3 Hz for 8 hours, following IEC 60068-2-6, to emulate wave-induced oscillations.
- Impact test: Used a pneumatic piston and sandbag drop method to reproduce wave-in-deck impact loads. Impact forces up to 46 kPa (piston) and 5kg sandbag dropped from 2.2 m were applied.

Evaluation:

Module performance was assessed pre- and post-stress using I-V measurements and electroluminescence (EL) imaging to detect microcracks and power degradation (see Fig. 1)

Key Results:

- **Torsion**: Caused the greatest performance loss, with power degradation up to 3.1% and as high as 24% depending on the mounting configuration and loading. It also caused the highest number of cracks (see Fig. 2) appearing along a diagonal axis in the modules.
- **Vibration**: Induced minimal power loss (about 1%) and did not create visible microcracks (see Fig. 2); more severe/ combined testing may be required to reveal latent risks.
- **Impact** (Piston/Sandbag): Glass-backsheet modules showed limited power loss and microcracks (see Fig. 2) after repeated impacts (up to 1.3% after 50 drops), while glass-glass modules-maintained performance but exhibited frame bending under extreme loading.

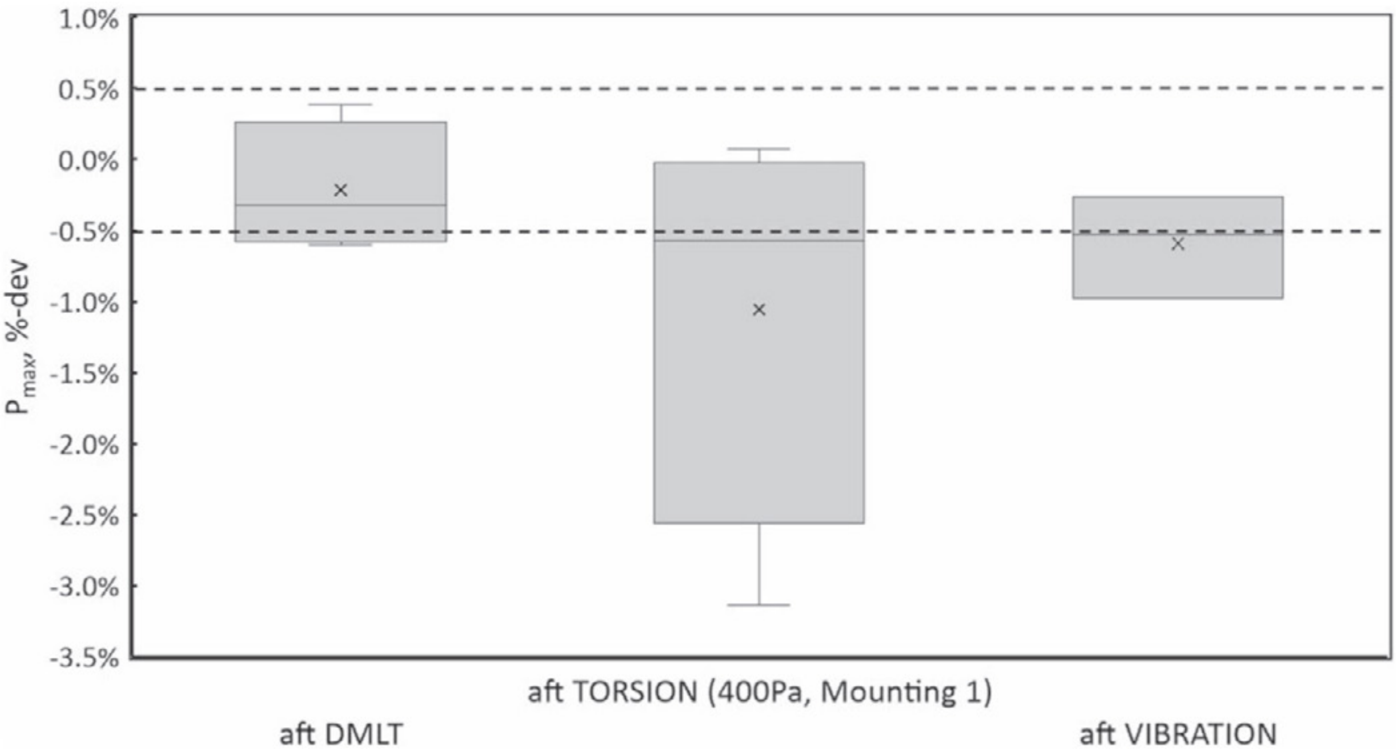

Fig. 1: Distribution of maximum power degradation (Pmax) after torsion, vibration, and DMLT

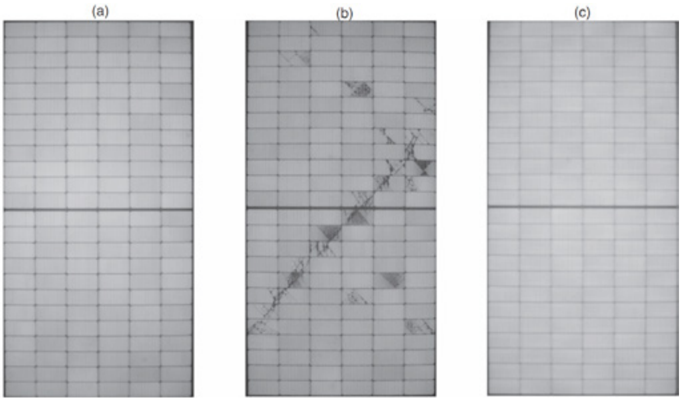

Fig. 2: Electroluminescence images of modules post (a) DMLT, (b) torsion and (c) vibration tests

5. Conclusions

This work demonstrates that current international standards for PV module qualification do not adequately address key mechanical stresses specific to FPV environments. Torsional loads in particular pose a significant risk to module reliability. We propose the adoption of advanced stress tests–including torsion, vibration, and impact–into type approval protocols for FPV. Further research will focus on combined environmental stressors, larger sample sizes, and field validation (e.g., in water tanks).

Such measures will help ensure the safe and reliable expansion of FPV, supporting Singapore's sustainability goals and global clean energy targets.

This article is an extract of a more comprehensive work published in Japanese Journal of Applied Physics in 2025, : Min Hsian Saw et al., "Reliability of floating photovoltaics (FPV): evaluating the effects of hydrodynamic mechanical loads on photovoltaic modules," Jpn. J. Appl. Phys. 64, 04SP50 (2025). DOI 10.35848/1347-4065/adc585.

Selected R&D Project

BIM for BIPV simulation and cost model development

Dr Tianyi CHEN, Suwen XIONG, Dr Carlos CLEMENT, Dr Thomas REINDL

1. Background

When considered during the early building design stages, BIPV can be integrated seamlessly with the building envelope, delivering superior technical and economic outcomes. Otherwise, it already becomes a retrofit which then is complex and costly.

Today, this early integration rarely happens. Fragmented workflows force architects, engineers, and BIPV consultants to work across multiple platforms, slowing iterations and creating data gaps [1]. Without a building information modelling (BIM) based approach that includes BIPV objects, energy simulations, and cost models, stakeholders lack the tools to evaluate the feasibility at the conceptual stage. Closing this gap is critical to mainstream BIPV adoption.

2. Scope & objectives

This project focuses on developing integrated workflows that bring BIPV technology into existing BIM environments. The objective is to enable technical simulations and economic cost modelling directly within the BIM tools architects and engineers already use. At the core of this effort is an open-source digital PV component library, providing standardised, verified data for industry-wide adoption. These workflows allow stakeholders to evaluate energy performance and financial viability during early design stages, transforming BIPV planning from fragmented, sequential steps into a unified, concurrent process.

The impact is substantial. Technical and economic optimisation at the conceptual stage reduces time and resources needed for feasibility assessments and eliminates the traditional back-and-forth between siloed teams. This streamlined approach accelerates project timelines and supports Singapore's Green Plan 2030 [2] by making BIPV integration practical and scalable.

3. Methodology & Results

The methodology centres on developing a comprehensive digital component library integrated with algorithmic tools embedded directly into Autodesk Revit's BIM environment. The digitalisation process transforms manufacturer datasheets into parametric BIM components containing complete geometric and non-geometric information (Fig. 1). Each component incorporates electrical parameters including power output, voltage characteristics, and temperature coefficients; mechanical specifications such as weight, wind load resistance, and impact ratings; dimensional data for precise spatial planning; and economic factors including module costs, installation requirements, and maintenance projections [3].

The algorithm development focused on creating bidirectional data flow between simulation engines and the BIM model. Solar radiation analysis tools calculate surface-specific irradiance values based on building geometry and orientation, while the embedded economic model processes these technical outputs alongside cost parameters to generate financial metrics. The system performs calculations of levelised cost of electricity (LCOE), net present value (NPV), return on investment (ROI), and payback periods, automatically updating as design parameters change.

The dashboard interface (see Fig. 2) represents a crucial innovation in stakeholder communication. Rather than presenting separate technical reports and financial analyses, the integrated visualisation platform displays all relevant metrics simultaneously. The interface accommodates different user perspectives, allowing engineers to examine technical performance while financial stakeholders assess economic viability using the same underlying data model. This unified presentation facilitates consensus-building during design meetings, as changes to panel selection, configuration, or financial assumptions immediately update all related metrics.

Initial implementation demonstrates substantial workflow improvements. Design iterations that previously required weeks of coordination between separate teams now occur within single working sessions. The open-source component library and BIM-BIPV platform, ensures that all stakeholders work with verified performance data, eliminating discrepancies arising from different data sources or calculation methods.

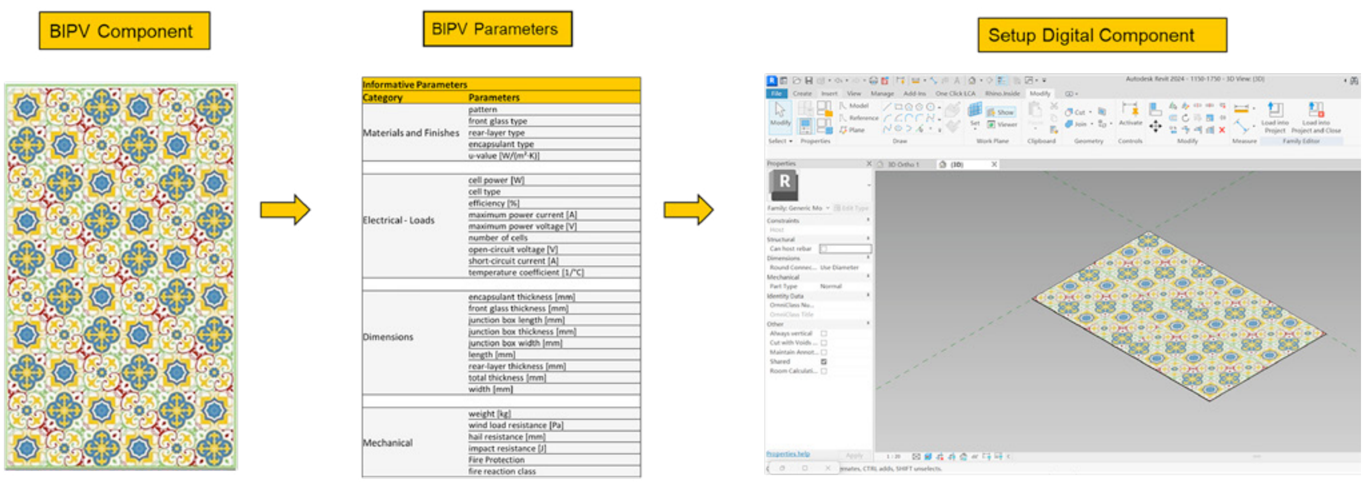

Fig. 1: SERIS-made Peranakan BIPV panel digitalised as a parametric component in Revit, showcasing the comprehensive parameter space which includes electrical, mechanical, and economic specifications.

4. Conclusions

The successful integration of BIPV simulation and economic modelling within a unified BIM platform represents a significant advancement in sustainable building design methodology. The developed system transforms fragmented workflows into streamlined processes, enabling rapid design optimisation during the crucial early planning stages. The open-source digital component library provides the industry with standardised, verified product data that ensures consistency across projects and stakeholders. Future development will focus on expanding the component library to include emerging BIPV technologies and establishing partnerships with industry players for pilot implementation. This platform positions Singapore as accelerate or for BIPV adoption by removing technical and procedural barriers that have historically limited implementation for specialised niche projects.

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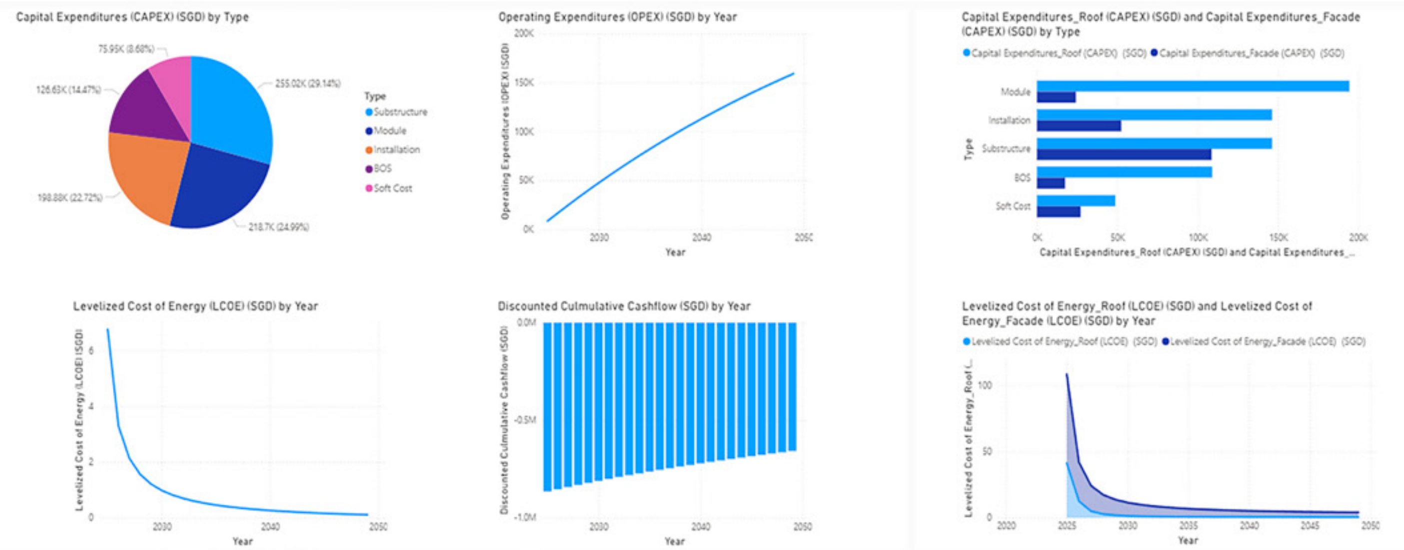


Fig. 2: Interactive dashboard interface showing integrated technical and economic performance metrics, enabling stakeholders to visualise the complete impact of design decisions in real-time

Performance evaluation of day-ahead solar irradiance forecasts from numerical weather prediction models in Singapore

Dr Gokhan Mert YAGLI

1. Background

At higher penetration levels, the integration of solar energy into electric power grids requires accurate forecasting of solar irradiance to manage variability and ensure grid stability. Day-ahead forecasts are particularly critical for energy market operations, effective energy trading, optimisation of dispatch schedules for conventional power plants, and reserve management.

Numerical Weather Prediction (NWP) models serve as the primary tool for generating these day-ahead forecasts by simulating atmospheric dynamics to predict global horizontal irradiance (GHI). Their performance, however, can vary significantly in tropical environments like Singapore, where rapid cloud formation and high humidity pose challenges. This can lead to significant errors in predicting localised meteorological events, especially the formation and movement of clouds, which are the primary determinants of GHI variability. The tropical maritime climate of Singapore introduces unique and substantial challenges for these models as well. Therefore, with Singapore aiming for at least 2 GWp of solar capacity by 2030, a comprehensive performance evaluation of various state-of-the-art NWP models is crucial to benchmark their accuracy, understand their inherent limitations in this region, and identify the most reliable forecasting sources.

2. Scope of project & objectives

This project assesses the performance of day-ahead GHI forecasts from multiple global NWP models, focusing on Singapore's tropical climate. The analysis uses hourly resolution data over a one-year period (August 1, 2024, to July 31, 2025). Forecasts from the closest grid point to Singapore (1.37°N, 103.80°E) are compared against measurements from the SERIS 25-ground irradiance sensor network, aggregated to island-wide averages. The primary objectives are:

a. Evaluate the accuracy of GHI forecasts from selected NWP models.
b. Quantify the forecast accuracy of each model using standard error metrics and identify the best-performing model or ensemble for the Singapore region.
c. Identify strengths and limitations of NWP models for tropical day-ahead solar forecasting applications.
d. Analyse the general performance characteristics of the models to establish a benchmark for future forecasting improvements.

3. Significance & impact of project

Accurate day-ahead GHI forecasts are vital for optimising solar energy systems in Singapore, where high solar variability – exacerbated by sudden thunderstorms and heavy rains in the tropical climate – can lead to rapid fluctuations in solar power output, posing significant challenges for solar forecasting accuracy and overall grid reliability. The key benefits of this project include:

a. Enhanced grid reliability: Better forecasts enable proactive management of energy supply and demand, reducing reliance on reserves, particularly during extreme weather events such as intense rainfall that can cause abrupt drops in solar generation.
b. Cost savings: Improved predictions minimise curtailment and balancing costs for utilities and solar operators, while facilitating efficient day-ahead electricity market clearing in Singapore by supporting accurate bidding, scheduling, and market outcomes.
c. Model selection guidance: Identifying top-performing models supports the development and improvement of solar forecasting systems tailored to tropical conditions.
d. Support for policy and planning: Insights contribute to Singapore's solar roadmap, aiding the transition to higher renewable shares.

4. Methodology & Results

This study evaluates five global NWP models: the European Centre for Medium-Range Weather Forecasts (ECMWF), the Australian Community Climate and Earth-System Simulator (ACCESS), the Global Forecast System (GFS), the Icosahedral Nonhydrostatic Model (ICON), and the Global Environmental Multiscale Model (GEM). Additionally, a blended (BLEND) model was developed by calculating an equal-weight average of the forecasts from all models available at a given timestamp. This ensemble approach mitigates model selection risk and addresses potential issues arising from missing forecast data.

For the analysis, hourly next-day (d+1) forecasts were retrieved from each model's most recent operational run at 4:00 PM Singapore Time on day d. This retrieval time was selected to align with the scheduling of the next-day electricity market dispatch. For each model, the forecast from the grid point closest to 1.37°N, 103.80°E was selected. Ground truth data were obtained from the SERIS network, which consists of 25 high-quality irradiance sensors distributed across the island. The readings were quality-controlled, spatially averaged to create an island-wide representative value, and aggregated into hourly GHI values.

Table 1: Performance metrics for raw and post-processed day-ahead hourly GHI forecasts from individual NWP models and the BLEND ensemble. Forecasts are validated against the island-wide average from the SERIS 25-sensor network.

Station	nMBE [%]	nMAE [%]	nRMSE [%]
		Raw	
ECMWF	8.29	11.88	17.86
ACCESS	10.91	16.95	23.65
GEM	**4.44**	12.60	18.16
GFS	10.56	18.70	25.75
ICON	8.28	12.03	17.39
BLEND	8.49	**11.59**	**17.19**
		Post-processed	
ECMWF	1.35	10.29	14.97
ACCESS	**-0.03**	12.70	18.30
GEM	-1.38	11.13	16.40
GFS	-3.54	13.53	19.43
ICON	0.11	10.28	14.61
BLEND	1.54	**9.91**	**14.31**

Operational solar forecasting with NWP models is subject to two primary challenges. First, the process is susceptible to disruptions, including missing model outputs, data extraction errors, computational delays, network failures, and inconsistencies from model updates. A forecasting system must therefore be robust to ensure operational continuity. Second, the performance of any single NWP model can vary significantly with day-to-day conditions and specific weather patterns, making the identification of a consistently "best" model impractical.

To address these challenges, we implemented an ensemble strategy by computing the BLEND forecast, which is an equal-weight average of all available NWP models at the time of forecast issuance. This approach ensures robustness, as a forecast can be generated as long as at least one model is available, thus preventing system failure due to missing data. Furthermore, it mitigates model selection risk by leveraging the collective output rather than relying on a single, potentially underperforming model. This strategy is founded on the principle of ensemble forecasting, where combining predictions from multiple sources has been shown to potentially improve overall reliability and accuracy compared to the individual components.
Systematic biases in NWP models often arise from factors such as the imperfect parameterisation of cloud processes, insufficient spatial resolution to resolve small-scale atmospheric features, errors in initial conditions or data assimilation, and inaccuracies in representing aerosol-radiation interactions.

To mitigate these inherent biases, a statistical post-processing model was developed. The dataset, comprising paired NWP forecasts and sensor observations, was partitioned into training and testing subsets. For the training phase, 50% of the data was used to identify and quantify the systematic relationships between the model forecasts and the observations. The correction coefficients derived from this training were then applied to the remaining 50% of the NWP forecasts to adjust for the identified biases. A comparison of the raw and post-processed forecast results is presented in Table 1.

The validation was performed for daytime hours, defined by a solar zenith angle of less than 85°. Forecast performance was assessed using three error metrics, expressed as percentages: the normalised mean bias error (nMBE), normalised mean absolute error (nMAE), and normalised root mean square error (nRMSE). Each metric was normalised by the maximum hourly GHI value observed across the sensor network during the validation period.

The validation results, summarised in Table 1, reveal considerable performance variability among the raw day-ahead GHI forecasts. Over the six-month evaluation period, all models exhibited a positive bias (nMBE from 4.44% to 10.91%), a systematic overestimation likely attributable to the underestimation of cloud cover or aerosol effects in the tropical environment. In terms of overall accuracy, ICON and ECMWF demonstrated the best performance among the individual models (nMAE ≈ 12%; nRMSE ≈ 17%), while GFS was the weakest performer.

The BLEND ensemble consistently surpassed every individual raw model, achieving an nMAE of 11.59% and nRMSE of 17.19%. This improvement is due to the averaging of diverse model physics and parameterisations, which smooths errors and reduces uncertainty.

Statistical post-processing yielded marked improvements across all forecasts. This bias correction was highly effective, reducing the nMBE to near-zero for all models and lowering nMAE and nRMSE by an average of 10-30%. The post-processed BLEND model produced the most accurate forecast overall, with an nMAE of 9.91% and an nRMSE of 14.31%. These results underscore the efficacy of using a simple, unweighted ensemble combined with statistical post-processing to mitigate model-specific errors and enhance forecast reliability.

Figure 1 illustrates an example of island-wide GHI forecasts after post-processing from ECMWF, ICON, and BLEND compared to measured values over a sample period from March 1 to 8, 2025.

5. Conclusions

This project established a comprehensive benchmark for day-ahead solar forecasting performance using global NWP models in Singapore. The evaluation identified ECMWF and ICON as the strongest individual models but demonstrated conclusively that a simple ensemble blend consistently yields superior accuracy. The forecast errors highlight the necessity of statistical post-processing to mitigate systematic biases and improve overall forecast skill.

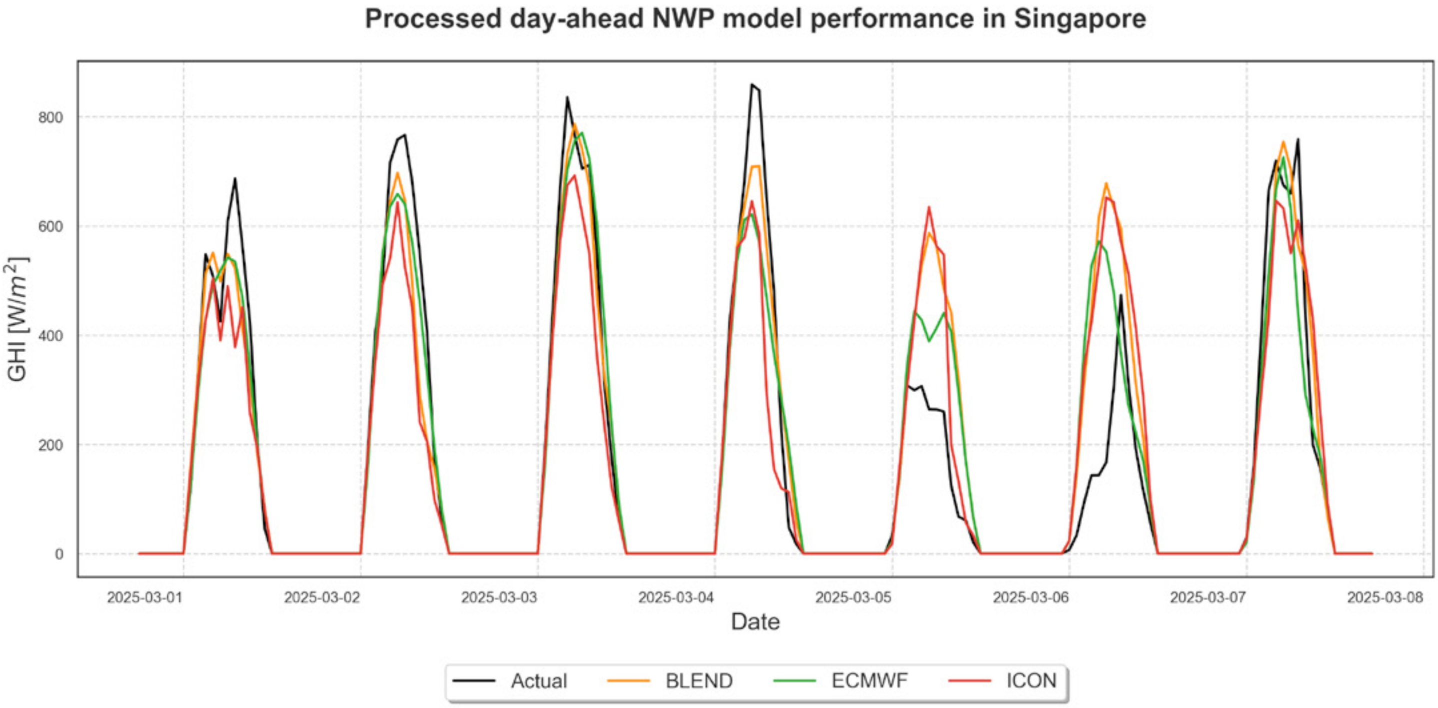


Fig. 1: Comparison of post-processed, day-ahead forecasts from the BLEND, ECMWF, and ICON numerical weather prediction models

The findings provide a baseline for grid operators and energy market participants. Furthermore, this work lays the foundation for future research into advanced forecasting systems tailored to Singapore's unique climate. Ultimately, improving forecast accuracy is essential for supporting the nation's transition towards a more sustainable energy future.

Selected R&D Project

Global floating PV potential in inland reservoirs: a comparison of different technologies

Dr Oktoviano GANDHI, Dr Huixuan SUN, Dr Carlos RODRÍGUEZ

1. Background

The transition to 100% renewable energy is crucial for addressing climate change and energy security. Solar energy has become one of the most affordable sources of electricity worldwide, surpassing wind in global installed capacity in 2021. However, PV systems require large areas, posing challenges in land-scarce countries such as Japan and the Netherlands. Floating PV (FPV), which utilises water bodies for installation, addresses this challenge while offering additional benefits, such as reduced module temperatures, faster deployment and improved water security (through the reduction of evaporation losses).

Despite the growing interest in FPV, previous studies have focused on fixed-tilt angles and not considered emerging technologies such as trackers and bifacial panels, which could significantly enhance energy generation. This study aims to fill this gap by analysing FPV configurations–including tracking and bifacial panels–across 249,717 inland reservoirs, covering 2.2 million km², and assessing their potential to meet global electricity and water needs.

2. Scope of project & objectives

The project evaluates the global potential of inland FPV and examines the energy yield performance of different system configurations, comparing bifacial vs. monofacial panels, different tilt angles and tracking methods. Subsequently, the global FPV potential in fulfilling countries' electricity consumption and water consumption are assessed, distinguishing reservoirs that might experience ice formation.

3. Significance & impact of project

Using the results of this project, FPV project developers can determine the most optimal system configuration based on energy generation potential and site-specific factors, such as wind speed, water depth and anchoring costs. Meanwhile, the regulators can use the country-specific results on FPV electricity generation and water saving potential to incorporate FPV into their energy transition strategies.

4. Methodology & Results

A database of 249,717 reservoirs worldwide — both natural and artificial, with a total area of 2,220,623 km^2 — has been compiled in SERIS' geographic information system (GIS) platform. 57 databases for water bodies and dams on regional or global scales were evaluated based on availability of geo-referenced information, water body geometries, and key attributes, such as surface area. At the end, three databases with the most complete information, are selected. When combining the multiple reservoirs from the three databases into our GIS platform, we conducted further detailed screening to avoid duplicates of the same reservoirs, which resulted in 1.77% of the number of reservoirs identified as duplicates. The reservoirs in the platform are overlayed with 1) weather information, such as global horizontal irradiance (GHI), ambient temperature, and relative humidity (RH), from NASA's Clouds and the Earth's Radiant Energy System (CERES), as well as 2) Köppen-Geiger climate classification.

The global FPV capacity potential is calculated assuming 10% of the reservoir area would be covered by FPV. This 10% value is not a recommendation on FPV system design, but rather a conservative estimate of the global FPV potential. As FPV systems with trackers start to be implemented (25 tracking FPV systems, totalling 28.1 MWp, have been installed by the end of 2024) with at least 9 active FPV tracker suppliers globally, this project analyses the energy generation potential for both fixed-tilt and tracking FPV systems. The considered FPV configurations are illustrated in Fig. 1. Finally, the global FPV potential in fulfilling countries' electricity consumption and water consumption are assessed, distinguishing reservoirs that might experience ice formation.

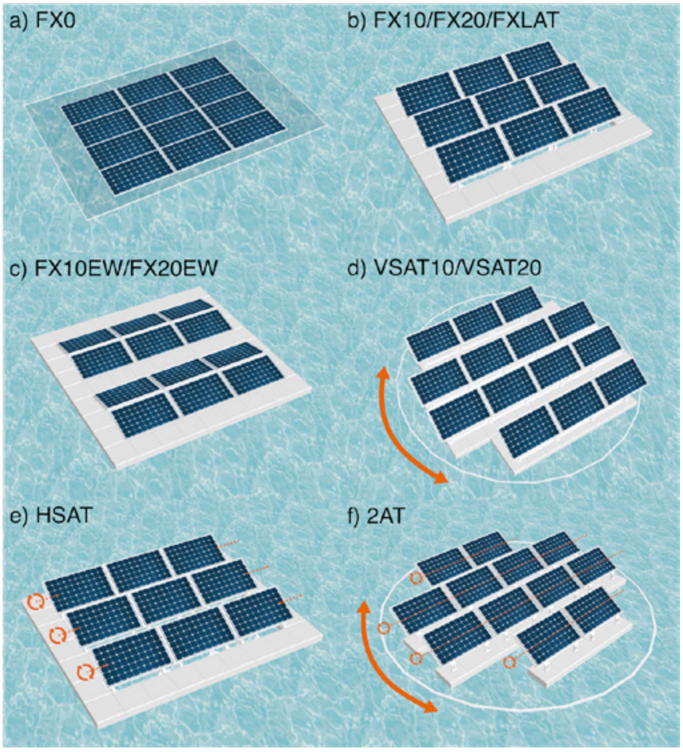


Fig. 1: The different FPV configurations considered. This figure is only for illustrative purposes and does not portray actual float design or panel arrangement from commercial systems.

Fixed-tilt systems like FX10 and FX20 (fixed 10° and 20° tilt facing the equator) are the most common, while FX10EW and FX20EW configurations (fixed 10°and 20° tilt with East-West orientation) are commercially available from companies such as Scotra and Zimmermann. FX0 (horizontal) systems are provided by Ocean Sun, and FXLAT (tilt angle equal to latitude) is typically applied in land-based PV (LBPV) systems but is less common for FPV due to mechanical constraints at high latitudes. Tracking systems such as vertical single-axis (VSAT) tracking have been used since the early years of FPV. Newer systems like horizontal single-axis tracking (HSAT, tilt angle can change from −60° to 60° facing East–West direction) and dual-axis tracking (2AT, combination of VSAT and HSAT) offer increased energy generation potential, although they pose challenges to system stability and design complexity.

Assuming a power density of 1 MWp/ha (100 Wp/m²), the global FPV potential exceeds 22 TW_p, over 2,300 times the total FPV capacity installed by 2024 (9.31 GW_p) and almost 10 times the combined capacity of terrestrial PV systems (LBPV + water-based PV). The estimated annual energy production, based on monofacial panels and 10% coverage (using the FX10 configuration), is shown by the circle colour. FX10 systems could generate over 28 PWh annually, enough to meet the energy needs of many countries, despite being smaller than global LBPV potential.

Figure 2 compares the energy production of various FPV configurations, showing that performance varies with latitude. Key takeaways from the evaluation include:

1. East-West configurations (FX10EW, FX20EW) produce less energy than FX10 at all latitudes. FX20EW performs the worst for most locations, only outperforming FX10EW at latitudes above 70°.
2. FX10 systems outperform FX20 configurations at latitudes around 10°, but due to their steeper tilt, FX20 systems generate more energy at higher latitudes.
3. Tracking systems (VSAT, HSAT, 2AT) consistently outperform fixed-tilt systems. Vertical single-axis tracking (VSAT10) yields more than FXLAT at latitudes between −40° and 40°. HSAT and 2AT configurations perform best overall, especially at higher latitudes.
4. FXLAT configurations yield similarly to FX10 and FX20 within ±30° latitude but significantly more at latitudes beyond this range, with up to 52.9% higher yield compared to FX10.

When comparing bifacial with monofacial panels, the following observations are noted:

- Bifacial gains increase with latitude for configurations like FXLAT, HSAT, and 2AT, peaking at 34% for FXLAT at 83.5° latitude.
- For latitudes below 60°, bifacial gains are generally below 2.5% for FX10 and FX20.
- HSAT outperforms VSAT20 in bifacial gain, making it more favourable for bifacial panels.

The lower bifacial gains in this study may be due to conservative albedo assumptions, but other benefits, such as lower degradation rates, make bifacial panels advantageous for FPV systems. In addition to energy generation, FPV systems can reduce water evaporation. Small-scale studies show reductions ranging from 17% to 90%, with some experimental findings suggesting up to 95%. The countries that have high energy production potential also showing high water savings. In fact, several countries (e.g., Canada, Mongolia, Uganda) could fulfill all their water needs through FPV's evaporation reduction.

5. Conclusions

FPV has the potential to meet global electricity demand, with up to 22TW_p available by covering just 10% of inland reservoirs, in addition to 5% of global water demand through water evaporation reduction. Analysis of the performance of FPV systems with various tilt angles and tracking approaches (VSAT, HSAT, 2AT) shows that trackers can boost energy yield by up to 163% for 2AT systems at latitudes beyond 80°. Bifacial gains increase with tilt angles, ranging from 3% to 7.5% globally for HSAT and 2AT systems. As PV deployment grows, it is crucial to assess real-world FPV installations to optimise design, installation and maintenance, and address environmental impacts. Clear regulatory frameworks for FPV installations, operations and compensation are also necessary. FPV should be seen not as a competitor to land-based PV, but as a complementary solution to accelerate global electricity decarbonisation in areas where traditional PV is impractical or uneconomical.

This article is an extract of a more comprehensive work first published in PV-Tech (subscription required to read premium content) in 2025: Rodríguez C., Gandhi, O., and Sun, H., "Global floating PV potential in inland reservoirs: a comparison of different technologies". Reproduced with permission from the publisher PV-Tech.

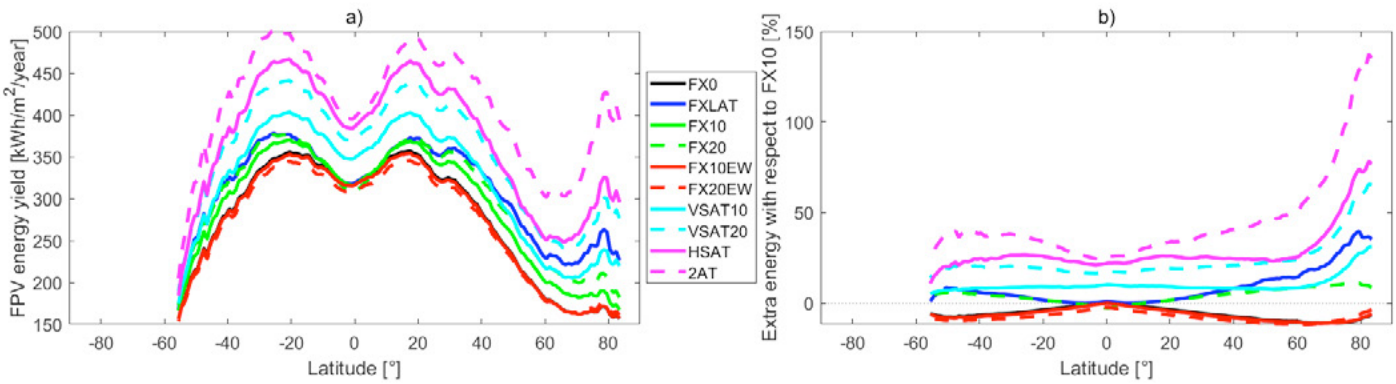


Fig. 2. (a) Average FPV energy yield based on their latitude by considering all inland reservoirs worldwide, and (b) the energy gain/loss of different configurations relative to FX10 system. Only monofacial solar panels are considered.

Selected R&D Project

Economic analysis for agrivoltaics farms in Singapore

LIU Tianyuan, Dr Serena LIN Fen, Dr Thomas REINDL

1. Background

Agrivoltaics is the practice of integrating agriculture for crop growing and photovoltaics (PV) for solar energy production on the same area, allowing them to coexist and benefit each other while increasing the land-use efficiency. This is extremely relevant in Singapore, as it could improve food security without demanding more of the scarce land resources. In addition to the dual use of land, agrivoltaics also makes decentralised small farms more viable by utilising the low cost and sustainable solar energy. However, farm owners and investors may hesitate to adopt agrivoltaics due to concerns about the overall economics and impact on crop yield. Thus, it is of great importance to develop viable setups and to demonstrate the profitability of agrivoltaics.

2. Scope of project & objectives

The objectives of this study are to investigate the economics of various types of agrivoltaics systems in Singapore, and to select viable designs based on the findings by developing a financial calculator for the concurrent analysis of operational cost (OpEx) and gross profit of agrivoltaics versus conventional agriculture.

3. Significance & impact of project

The findings provide valuable insights on the economic impact of adopting agrivoltaics and options for viable designs, offering quantitative information for decision-making. This would not only encourage farm owners and investors to adopt agrivoltaics with confidence but also promote sustainable local food supply.

4. Methodology & Results

The parameters and assumptions for the calculation are derived from simulation results and field measurements from SERIS' Yuhua Agritech Solar (YAS) testbeds, as well as information provided by our collaborators.

For example, the crop yield, the expenses on water, electricity, other consumables and manpower were surveyed from farms employing various farming systems, ranging from 1,000 m^2 to 20,000 m^2, as well as from SERIS testbeds.

Solar irradiation is estimated based on Singapore's historical data. It is used to estimate PV generation and photosynthetically active radiation (PAR) received by the crops, ensuring that crops could receive sufficient sunlight for growth while maximising PV generation. In the past 2 years, SERIS has conducted both simulations and field experiments to investigate the impact of different rooftop PV configurations on crop growth, including layouts, orientations, and sun-tracking features. It was observed that with appropriate greenhouse and PV designs, the rooftop PV coverage could be up to 50% without affecting the growth of common leafy green vegetables. For example, a 4.5-meter-high roof with 50% PV coverage by checkered pattern has an effective transmittance of 63%, which translates to 656 mol/m^2 of PAR received by the crops - sufficient for common leafy green vegetables. Thus, the maximum PV coverage allowed in the calculator is 50% of the land area.

By default, it is assumed that PV systems are installed via 'solar leasing' model with power purchase agreement (PPA), which does not incur additional capital expenses (CapEx) for farm owners. The farm owners enjoy cheaper electricity without owning the PV system, while the leasing company installs, owns and maintains the system. This is more realistic and relevant for existing farms in Singapore as there is no upfront cost required.

With input of the type of growing system, land area and PV coverage, the calculator accounts for the following components for growing common leafy green vegetables:

- Expenses on land, water, electricity, consumables and manpower
- PAR received by crops
- PV generation
- Crop yield
- Gross revenue from crop sales

Types of agricultural and agrivoltaics systems evaluated are shown in Table 1.

As a result, the OpEx and gross revenue can be calculated accordingly, followed by the gross profit. Results (scenarios I to VIII) based on a 1,000 m^2 farm with 4.5-meter-high roof and 50% PV coverage by checkered pattern, growing common leafy green vegetables, are shown in Fig. 1.

Table 1: Types of growing systems evaluated

1	Conventional soil based	
2	Conventional soil based + PV	Partial PV coverage
3	Vertical hydroponic towers	
4	Vertical hydroponic towers + PV	Partial PV coverage
5	Horizontal hydroponics	
6	Horizontal hydroponics + PV	Partial PV coverage
7	1.5-layer horizontal hydroponics + PV + LED	Partial PV coverage; 50% of PAR requirements of bottom layer supplied by LED, fully powered by PV
8	1.25-layer horizontal hydroponics + PV + LED	Partial PV coverage; 100% of PAR requirements of bottom layer supplier by LED, fully powered by PV
9	2-layer horizontal hydroponics + PV + LED	Partial PV coverage; bottom levels with 100% of PAR requirements from LED
10	1-layer indoor horizontal hydroponics + LED	100% of PAR requirements from LED
11	1-layer indoor horizontal hydroponics + LED + PV	Full PV coverage; 100% of PAR requirements from LED
12	2-layer indoor horizontal hydroponics + LED + PV	Full PV coverage; 100% of PAR requirements from LED

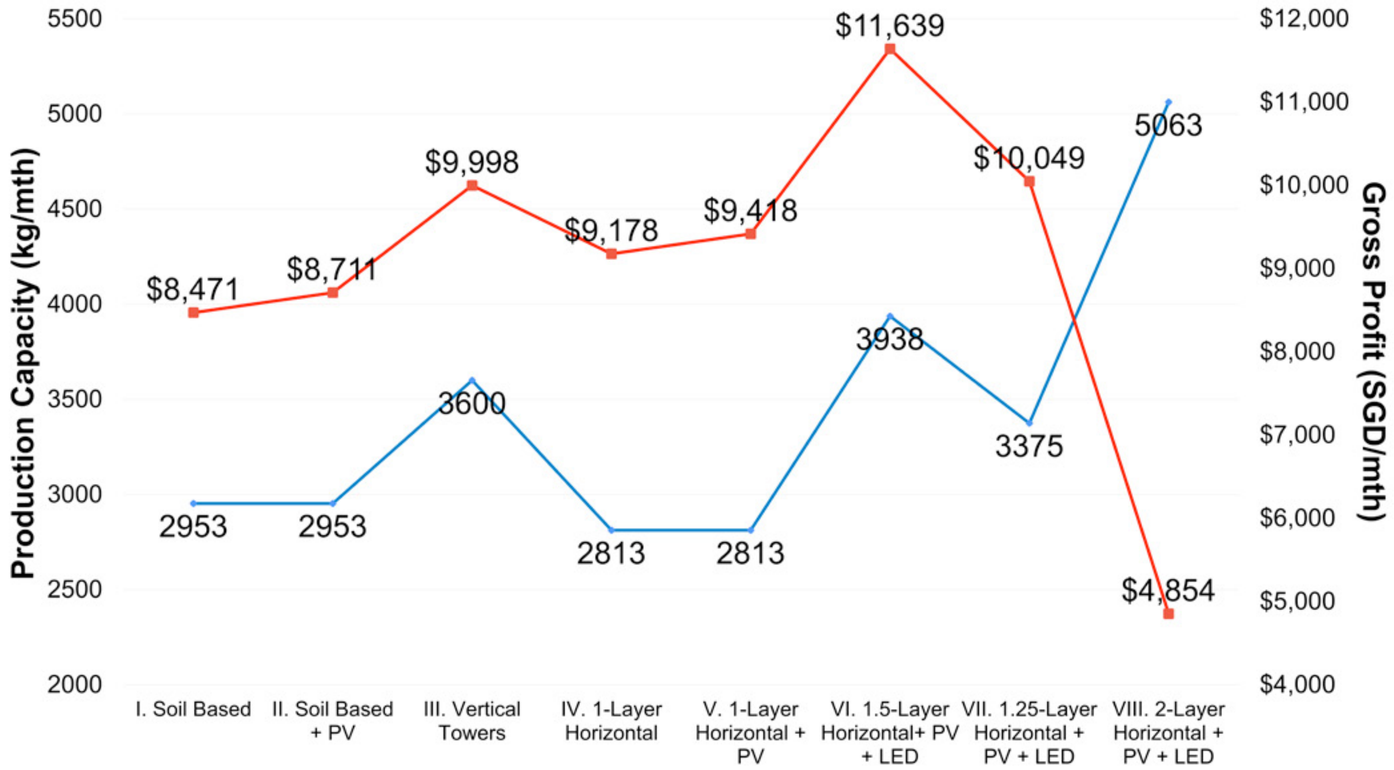


Fig. 1: Production capacity and gross profit of different types of agrivoltaic systems (blue - primary y-axis: production capacity, red - secondary y-axis: gross profit)

As compared to traditional soil-based farming in scenario I, hydroponics with both vertical (scenario III) and horizontal (scenario IV) configurations could generate additional profits. Hydroponics systems offer better water conservation and eliminate soil-borne pests and diseases, reducing the need for water, pesticides, and herbicides. Additionally, vertical configurations have higher plant density by more efficiently utilising vertical space, yielding higher production capacity. When strategically integrated with PV (agrivoltaics) in scenarios II and V, cheaper electricity generated from PV systems would lower OpEx without incurring additional CapEx (compared to scenarios I and IV), while the PV cover could improve climate resilience of the farm and thus resulting in more consistent crop yield.

When there is surplus electricity from PV generation, planting area could be expanded accordingly by adding a bottom layer. With 50% PV coverage, for example, the surplus could meet 50% of the PAR requirements of additional 50% planting area or fully meet the PAR requirements of additional 25% planting area using supplementary LEDs. In scenario VI, (1.5-Layer Horizontal + PV + LED), the additional 0.5 bottom layer relies on both sunlight and supplementary LED for PAR, with 50% of PAR coming from sunlight and the other 50% from LEDs, which are fully powered by the own PV generation. The use of additional electricity for LED slightly increases the OpEx per unit yield, but the gross profit significantly improves due to the increased crop yield. As for scenario VII (1.25-Layer Horizontal + PV + LED), PV generation is only sufficient for an additional 0.25 bottom layer that fully depends on LED for PAR. Thus, the planting area and crop yield are reduced compared to scenario V, and the total profit has dropped as a result. Although growing capacity is not the highest, this configuration offers better climate resilience as it is less dependent on sunlight for PAR. It could still be attractive when better climate resilience is required, or when sunlight could not reach the bottom layer of certain types of growing systems. When more planting area is added as a bottom layer, the surplus electricity from the PV system is not sufficient anymore to cover the consumption. More additional electricity must be drawn from the grid, which significantly increases the OpEx and the design is no longer financially viable although crops yield increases, as shown in scenario VIII. Investors need to either select crops with higher values/lower PAR requirement or adopt systems with higher energy-efficiency.

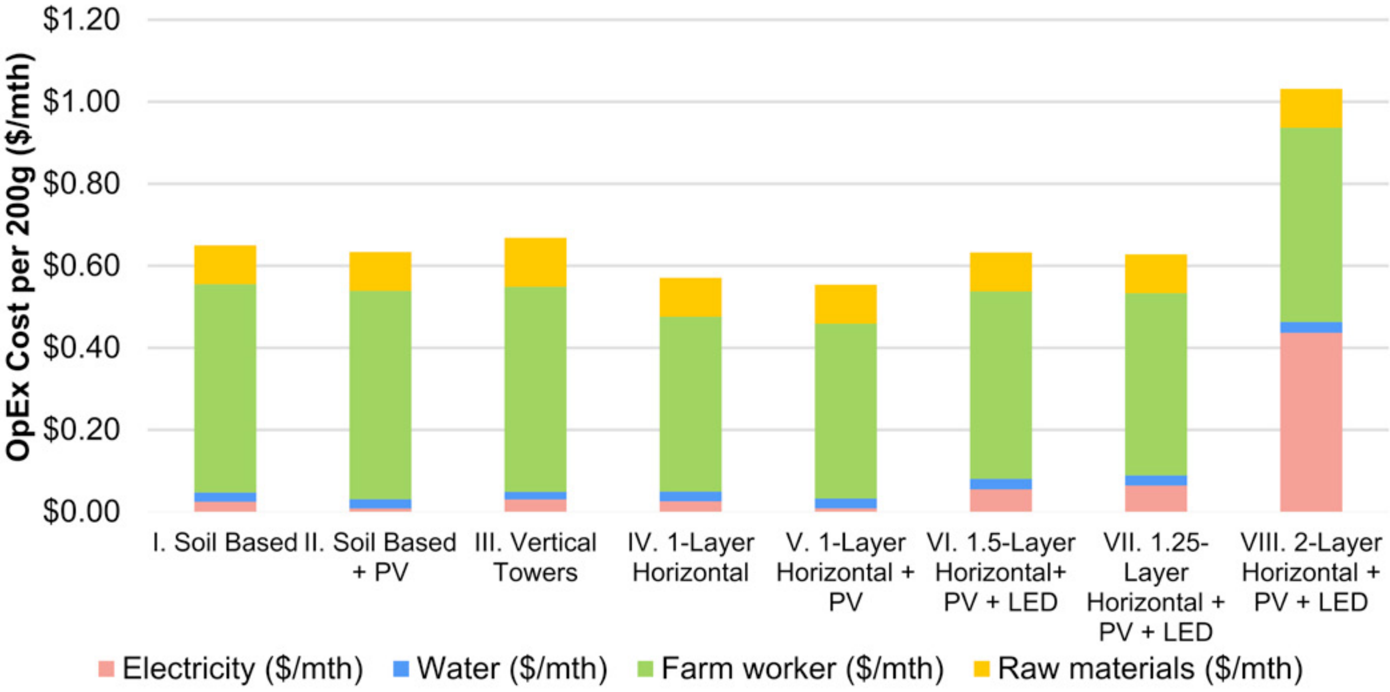


Fig. 2: Break-down of OpEx cost of crops (per 200g)

As shown in Fig. 2, OpEx for Singapore farms is significantly impacted by manpower cost for all scenarios where LEDs are fully powered by the own PV generation or minimal electricity is drawn from the grid. Otherwise, electricity cost becomes the dominant factor, followed by manpower cost, indicating that deploying PV on farms (agrivoltaics) is beneficial for most scenarios in terms of cost reduction.

Additionally, when considering the trade-off between PV generation and the PAR requirements of the crops, it can be concluded that priority should be given to crop growth and PAR needs, especially for high-value crops. This is because crop sale generates higher value than savings from cheaper electricity (or revenue from the sale of electricity for farmer-owned PV systems); sacrificing crop yield for higher PV generation may only be feasible when the crop value is low or the electricity price is high.

Although only eight representative scenarios are discussed for an overview of the economics of integrating agriculture with PV systems, further optimisations could be conducted for different objectives and constraints by adjusting the PV coverage and planting area. In addition, if farm owners or investors could provide more information on their farms, such as crop sale price and utility consumptions, the parameters could be updated and become more representative of their farms.

5. Conclusions

By integrating energy, resource, and production models, this financial analysis showcases the profitability of agrivoltaics in Singapore based on gross profit, supporting informed decision-making for sustainable and climate-resilient farming transitions. Future work will include more crop types, capital cost estimation and return-on-investment (ROI) analysis for more flexible and comprehensive modelling.

SERIS FACILITIES AND LABORATORIES

PEROVSKITE SOLAR CELL LABORATORY

This 190-m^2 class-100,000 cleanroom laboratory is dedicated to the fabrication and characterisation of perovskite solar cells, including advanced device integration such as perovskite mini-modules and perovskite-based tandem solar cells and mini-modules.

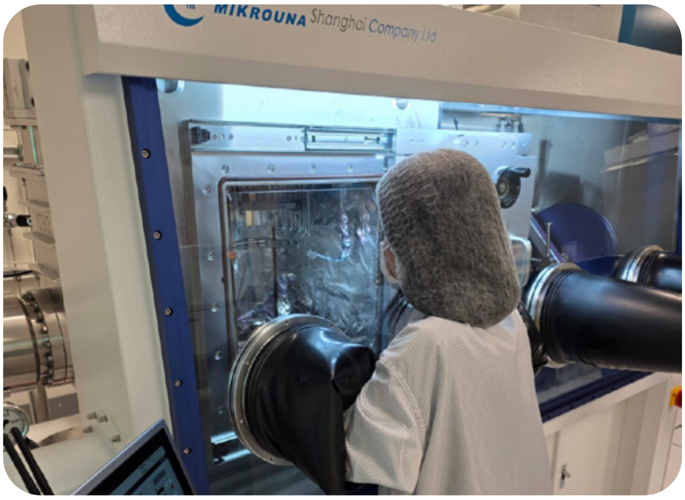
Several compartmental gloveboxes in the Perovskite Laboratory dedicated to various processes such as synthesis, deposition, metallisation and characterisation of perovskite materials and solar cells

Glovebox Workstations (Mikrouna & Inert)

The multi-compartment glovebox systems with controlled N_2 environment (less than 1 ppm O_2 and moisture) house coating equipment such as spin coaters for the deposition of thin films via solution processing under inert atmospheric conditions. In addition, the Mikrouna system is integrated with an air-conditioning unit for better climate control, which is critical for temperature sensitive processes. There are several auxiliary compartments, each dedicated to specific processes such as sample preparation, characterisation of samples and encapsulation of devices.

Glovebox-integrated Thermal Evaporator System (ReBorn)

This thermal evaporation system is used for the deposition of metals and inorganic and organic functional thin films, e.g. Ag, LiF and C60, onto various substrates (glass sheets, silicon wafers) of a wide range of sizes up to 166 mm x 166 mm. The desired film can be as thin as 15 nm with a non-uniformity of only ±5%. A very low base pressure is required in the vacuum chamber, which is achieved with a high-performance pump system that reaches < 5×10^{-5} Pa. The tool has the capability to provide either substrate heating (up to 300°C) or cooling (5-30°C) for film quality optimisation. The vacuum chamber is integrated into a glovebox, allowing the process (sample preparation and loading/unloading) to be done in an inert N_2 environment (less than 1 ppm of O_2 and moisture).



Glovebox-integrated thermal evaporator for thin film deposition of metals and inorganic and organic functional layers

Other equipment for processing and device integration:

- Slot die coater (WAD)
- I-V measurement and solar simulator (Enlitech)
- Connected twin-chambered perovskite evaporator (Technol)
- Thermal evaporation system (Angstrom / ReBorn)
- Glovebox-integrated Atomic Layer Deposition System (Kemicro)
- Low-damage low-temperature sputtering system
- Photoluminescence quantum yield tool (QYB / Enlitech)
- X-ray diffraction bench-top unit (Malvern P.)
- Semi-automated wafer bonding system (EVG)
- Chamber furnace (Protherm)
- UVO cleaner (Jelight)
- Fume hoods (Fisher Scientific)
- Humidity chamber for sample testing (Memmert)
- Inert encapsulation system

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INDUSTRIAL THIN-FILM LABORATORY

The Industrial Thin-Film Laboratory (ITFL) provides world-class facilities for the development of high-efficiency (> 30%) perovskite-silicon tandem solar cells. Equipped with a state-of-the-art cluster tool integrated with a glovebox system, the laboratory enables advanced thin-film deposition, large-area device integration (up to M6 wafer size, 166 mm x 166 mm), and innovative process development, paving the way for next-generation high-efficiency perovskite-silicon tandem solar cell technologies.

The cluster tool system (right) is integrated with a glovebox (left), allowing silicon wafers (up to M6 size) to be vacuum coated with various thin films and then be transferred under inert conditions to the glovebox for additional thin-film depositions. The glovebox provides spin coating and slot-die coating of thin films and annealing of the full-size wafer samples, enabling the fabrication of high-quality perovskite-silicon tandem solar cells.

Thin-Film Cluster tool

The multi-chamber cluster tool from Infovion, Korea, consists of 5 chambers equipped with thermal evaporation sources dedicated to specific processes. These include metal halide deposition for forming perovskite absorbers, deposition of hole and electron transport layers, plasma treatment and substrate surface cleaning, and a sputter chamber with an RF power source for transparent conductive oxide (TCO) deposition. This setup allows various layer stacks to be deposited without breaking the vacuum and/or exposing the samples to the atmosphere. The thermal evaporators are engineered to deposit laterally uniform perovskite and other functional layers onto full-size wafers (up to M6 size), providing a scalable pathway towards the commercialisation of perovskite-silicon tandem solar cells. The cluster tool is connected with a N_2-controlled 2-section glovebox system, enabling seamless material transfer and thin-film depositions in an inert atmosphere.

Glovebox system

The glovebox system comprises two independent compartments dedicated to:

1. Dry-chemical preparation, including solid precursors, additives, and material synthesis
2. Solution processing encompassing ink preparation and wet-chemical deposition techniques (spin coating, slot-die coating)

The slot-die coating unit in the glovebox enables uniform film depositions onto full-size wafer substrates (up to M6) - an essential process for high-quality solution-processed perovskite layers for solar cell applications.

Other processing tools:

- Slot-die coater (FOM)
- Fume hoods (Thermo Scientific, Waldner, Esco)
- Oven (Thermo Scientific)
- Hot plate (Polos, Wenesco)
- Spin coater (Polos, Lebo Science)

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SILICON SOLAR CELL LABORATORY

This laboratory is located on levels 1 and 2 of the E3A building on the main NUS campus. Equipped with Industrial-scale tools capable of processing more than 100 wafers per hour, it enables industry-relevant R&D on solar cells using monocrystalline silicon wafers.

Silicon Cleanroom Lab 1A:

Lab 1A is dedicated to wet-chemical processing of silicon wafers. It is equipped with highly versatile R&D equipment for developing advanced processes aimed at high-efficiency Si solar cells as well as Si bottom cells for application in perovskite-silicon tandem cells. The lab also houses industrial-scale high-throughput wet-chemical process tools, enabling rapid technology transfer to industry.

Manual Batch Wet-Benches (MediaMac, Singapore)

These batch wet-chemistry tools, custom-built by MediaMac, are designed for flexibility and precision in silicon solar cell process development. They feature versatile process baths for developing various wet-chemical processes (cleaning, texturing, etching) related to silicon solar cell processing. The tools can process up to 50 silicon wafers per batch, with wafer sizes up to M10 and half-cut G12, enabling seamless scalability from lab to industry.

Automated Batch Wet-Chemistry (BatchTex, RENA Technologies, Germany)

The BatchTex tool from RENA Technologies is a high-throughput (> 250 wafers/hr), automated wet-chemical processing system for etching, alkaline texturing and cleaning of silicon wafers (up to M10 size and half-cut G12). It features multiple process baths with automated bleed and feed function, ensuring stable chemical concentrations and exceptional process consistency via real-time sensors. The tool also has state-of-the-art O_3-based wet-chemical baths. It enables advanced wafer cleaning, producing tailored surface morphologies and the formation of thin oxide films. The integrated robotic arms ensure fast, safe and uniform wafer processing, delivering reliable performance and industry-ready results.

Inline Wet-Chemistry (InPilot, RENA Technologies, Germany)

The InPilot tool from RENA Technologies is an inline wet-chemistry processing system designed for single-side etching of silicon wafers (up to M10 size and half-cut G12). This is a semi-automated single-lane machine for inline wet-chemical etching. It comprises an HF bath, an alkaline bath, and an acidic bath for single-sided wafer etching, with a water rinse section to ensure process purity and consistency. Both the HF and alkaline baths can be heated separately, allowing precise control over etching conditions and surface quality.

Silicon Cleanroom Lab 1B:

Lab 1B houses several chemical vapour deposition (CVD) tools capable of depositing a wide range of thin-film materials, with thicknesses ranging from a few atoms thick to several hundred nanometres.

Inline dynamic PECVD tool (MAiA 2.1, Meyer Burger, Germany)

The MAiA 2.1 from Meyer Burger is an R&D inline plasma-enhanced CVD (PECVD) machine designed for quasi-continuous, high-throughput operation – achieving processing speeds of over 1000 wafers per hour for selected processes. The thin-film deposition process uses a 'remote' plasma energised by 2.54-GHz microwaves, which minimises plasma-induced wafer damage compared to the conventional parallel-plate designs. The loading module is equipped with an infrared lamp array for rapid substrate heating to the desired process temperature (350-550ºC). The machine is capable of depositing silicon nitride (SiN_x), silicon oxide (SiO_x) and aluminium oxide (Al_2O_3) thin films onto large silicon wafers (M2 to G12).

Spatial ALD tool (Manual ALD Lab tool, SoLayTec, Netherlands)

This manual ALD Lab tool from SoLayTec is a pioneering R&D system for the deposition of Al_2O_3, intrinsic ZnO, Al-doped ZnO and SnO thin films using the spatial atomic layer deposition (sALD) technology, where precursors are separated in space rather than in time. This versatile tool is able to deposit thin films onto a wide range of substrate types and sizes (up to G12 size wafers or 21 cm x 21 cm glass panes). Al_2O_3 films play an important role in advancing various silicon solar cell technologies, while ZnO and SnO-based films enable the development of transparent conductive oxides or transparent metal oxides for high-efficiency large-area perovskite-silicon tandem solar cells.

Versatile Tube furnace (TS81254, Tempress Systems, Netherlands)

The TS81254 from Tempress Systems is a 4-stack high-throughput R&D tube furnace with several capabilities:

- Low-pressure chemical vapour deposition (LPCVD) of doped & intrinsic poly-Si films for passivated-contact solar cell applications (double-sided deposition)
- Deposition of doped & intrinsic silicon nitride films
- Oxidation process for advanced surface passivation applications

PECVD tool for ultra-fast deposition of doped silicon and metal oxide films (CAiA Lab, Meyer Burger, Germany)

The CAiA Lab tool is a unique prototype PECVD machine for the ultra-fast deposition of intrinsic and doped silicon thin films and associated stacks, as well as doped transparent metal oxide films. It was jointly developed by SERIS and Meyer Burger. The tool has two process chambers to prevent cross-contamination. It enables the single-sided deposition of thin high-quality interfacial oxide layers and low-absorbing and dense doped-layer stacks on large silicon wafers (M2 to half-cut G12). The tool is used for cutting-edge R&D on single-junction silicon solar cells as well as tandem devices incorporating a silicon bottom cell.

PECVD tool for the deposition of intrinsic and doped (boron, phosphorus) amorphous silicon layers (Octopus II, INDEOTEC SA, Switzerland)

The Octopus II is a state-of-the-art PECVD tool for the deposition of intrinsic and doped (boron, phosphorus) a-Si layers for applications in heterojunction silicon solar cells. The machine is capable of processing up to G12-size silicon wafers and is designed in a cluster form to provide the process flexibility needed by the R&D activities. The tool is also able to deposit various nanocrystalline layers like nc-Si, nc-SiO_x and nc-SiC.

Silicon Cleanroom Lab 2A:

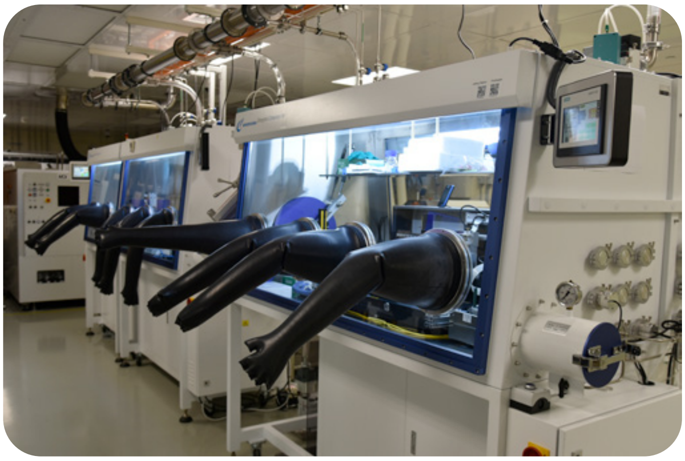
Lab 2A houses tools for precision and advanced processing of high-efficiency solar cells. It features a versatile laser tool and an inkjet printing tool, enabling the creation of sophisticated cell features with high accuracy and flexibility.

Versatile Laser System (ILS LT 124, Innolas Solutions, Germany)

The ILS LT is an R&D laser processing workstation for high-precision applications in PV. The machine features three laser sources to provide excellent flexibility: a 2-W UV continuous source, a 20-W green ns source, and a 30-W fs source that can be tuned to operate at either UV, green or IR wavelengths. This configuration enables several process applications for high-efficiency solar cells, including contact opening, selective mask processing or edge/junction isolation, wafer drilling, wafer cutting, silicon shadow mask fabrication and laser marking for substrate ID tracking purposes. The tool has automated handling for substrates up to M6 size, and is also capable of processing larger wafers (up to G12 size) using manual handling.

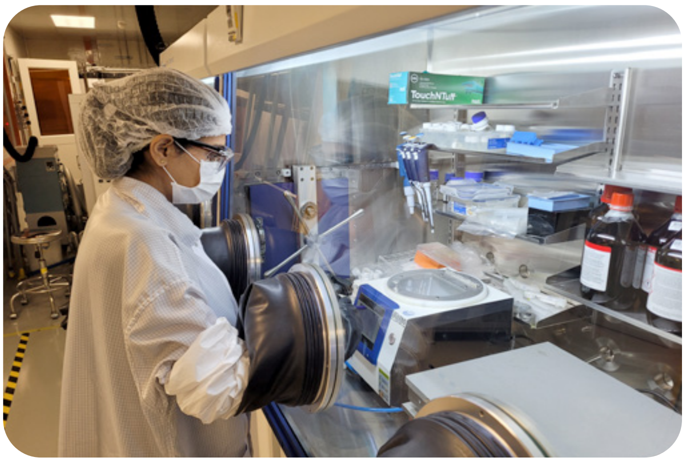
Pilot-scale Inkjet Printer (IP410, Meyer Burger, Netherlands)
The IP410 is a versatile pilot-scale inkjet printer designed for solar cell masking and patterning applications. It supports a wide range of functional inks, including hotmelt inks, UV curable inks, solvent-based metal inks, and chemical precursor inks (e.g. for perovskite cells). Multiple printing modules are available to quickly switch between different ink types while preventing cross contamination. An ink evaluation module with disposable cartridges allows the testing of small volumes of experimental inks. Printing patterns are digitally defined and thus can be quickly updated, which makes the machine ideal for process development and rapid prototyping. It is fully automated and includes cassette loading and unloading of wafers up to M6 size. Manual handling of larger wafers (up to G12) is also possible.

Lab 2A Glovebox Setup (Mikrouna, China)
A 3-section glovebox setup provides the controlled, moisture-free environment required for the processing of moisture-sensitive materials. This setup accommodates an inkjet printer, a spin coater, a hotplate and a chemical storage area. The integrated design ensures seamless contamination-free transfer of the samples throughout the system.



Pilot-Scale Inkjet Printer (PiXDRO, SUSS MicroTec, Netherlands) in a glovebox
The PiXDRO inkjet printer in the glovebox setup is a pilot-line tool capable of handling substrates up to G12 size, making it ideal for the precise deposition of moisture-sensitive films such as perovskite and charge transport layers for industrial-size perovskite-silicon tandem solar cells. Supporting a wide range of functional inks, the PiXDRO printer enables rapid switching between ink types with minimal risk of cross-contamination, offering excellent flexibility for advanced process development.

Spin Coater (LEBO Science, China) in a glovebox
This spin coater, paired with a hotplate, is housed in a separate section of the glovebox setup. This configuration ensures uniform deposition and curing of perovskite and other functional layers, enabling precise and high-quality layer formation for advanced solar cell development.



Solar Cell Metallisation Lab 2B:

Lab 2B facilitates metallisation and contact formation for various types of solar cells. Equipped with several advanced metallisation tools, it caters to both high- and low-temperature processes, enabling precise and efficient fabrication of high-performance solar cells.

R&D screen printer (ASYS, Germany)

This versatile R&D screen printer from ASYS is capable of screen printing metal contacts onto a wide range of substrate sizes, ranging from small (5 cm x 5 cm) to very large (21 cm x 21 cm, G12). The printer is also capable of stencil printing for added flexibility. It is equipped with a patented vision alignment lens capability, i.e. a smart assistance system, which uses a free-moving camera and thus provides a lot of flexibility for aligning the substrates. This enables a repeatability of ± 10 μm by utilising a high-precision measuring system and an automatic screen adjustment system.

Fast firing furnace (SinTerra, BTU, USA)

The SinTerra is an automated fast firing furnace from BTU/AMTECH Systems. It is equipped with automated cassette loading & unloading and has 6 zones with infrared lamps for heating silicon wafers (up to M6 size) to temperatures in the 300-1000°C range. Ramp-up and ramp-down rates can be precisely controlled in order to tailor the firing profiles.

Thermal Evaporator (SCT, System Control Technologies, USA)

The SCT thermal evaporator is a lab-scale tool for evaporating thin films of metals (Al, Ag, etc) and other materials onto various substrates (wafers, glass panes, etc) of sizes up to G12. The deposition chamber uses a cryogenic pump to achieve a very low base pressure (< 10^{-6} Torr), ensuring high-purity films. The evaporator features dual resistively heated sources and a rotating substrate holder to ensure uniform depositions across large-area substrates.

Inline multi-chamber sputter machines #1 and #2 (SV-540 & Line-540, FHR Anlagenbau, Germany)

This physical vapour deposition (PVD) sputtering platform is designed to handle silicon wafers and glass panes. Substrates of sizes up to 30 cm x 40 cm or up to six M6-size or four half-cut G12 wafers can be processed per run.

The SV-540 tool has dedicated processing chambers for the sputtering of metallic, dielectric and TCO/TMO layers. They are equipped with planar magnetron sources for DC and RF sputtering of metals, oxides and oxynitrides in the reactive mode, and with a cylindrical dual-magnetron source and planar sources for pulsed DC ("DC+") sputtering of dielectrics and TCOs/TMOs, with substrate heating up to 400ºC. It is also possible to deposit graded layers, or multi-layer stacks of up to 6 different materials, without breaking the vacuum conditions. Materials that can be sputtered include indium tin oxide, aluminium-doped zinc oxide, Ag, Al, Ti, In, ZnO and thin oxide and oxynitride films tuned to specific requirements.

The Line540 tool has 3 planar magnetron sources, whereby 2 are connected to a DC power supply for DC sputtering of metal layers, while the third is connected to an RF power supply for the deposition of metal oxide films such as NiO_x, $Mg:NiO_x$, iZnO and $MgZnO_4$. The substrates can be heated up to 200ºC in this tool.

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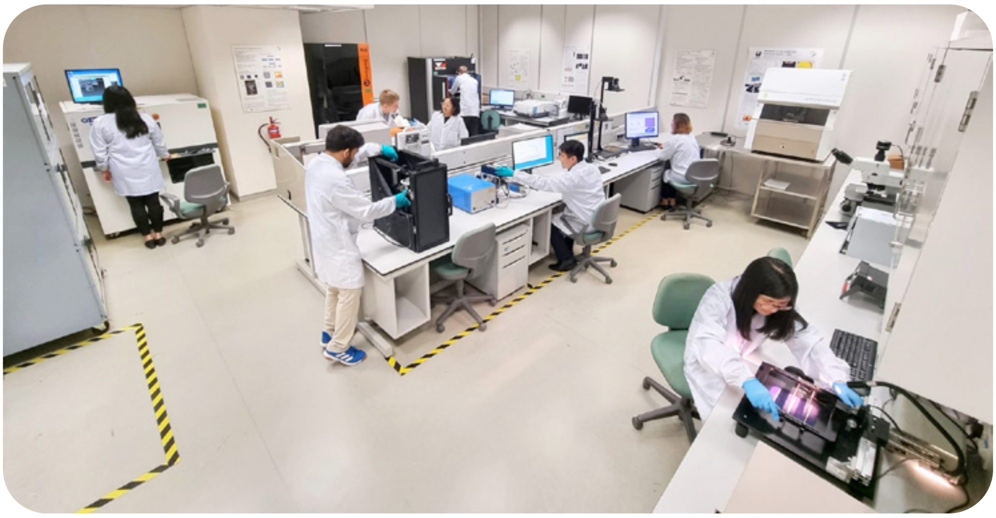
PHOTOVOLTAIC DEVICES CHARACTERISATION LABORATORIES

The PV Devices Characterisation Laboratories at SERIS are equipped with a comprehensive suite of measurement tools designed to examine both material and device properties. The characterisation of optical & passivation layers, bulk materials, and solar cell metallisation enhances the understanding of their impact on solar cell efficiency. This complements device-level measurements of perovskite-based and silicon-based solar cells, tandem cells, and single-cell mini-modules. By combining meticulous characterisation with specialised simulation techniques, advanced solar cell analysis can quantify performance-limiting factors and predict potential efficiency improvements.

Materials Characterisation Laboratory

This laboratory houses both general-purpose materials characterisation tools, such as 3D optical microscopy, FTIR and Raman spectroscopy, as well as silicon-based materials characterisation techniques, including a luminescence imaging tool, an effective minority carrier lifetime tester, and a TLM resistance measurement tool. It also contains a small-beam spectral response measurement system to study the optoelectronic properties of solar cells.



Materials Characterisation Laboratory

Small-beam spectral response measurement system (IVT Solar, PVE-300)

External quantum efficiency (EQE) and total reflectance (R) measurements enable detailed current loss analysis and the identification of areas for improvement related to diffusion lengths and light management. The PVE-300 provides quick and localised measurements of both EQE and R over a wavelength range of 300-1700 nm for various types of solar cells.

Luminescence imaging (BT Imaging, LIS-R2)

Photoluminescence (PL) and electroluminescence (EL) tools are considered the "X-ray scanners" of the silicon PV community, capable of quickly producing luminescence images for routine inspections or detailed two-dimensional data sets used for sophisticated computational analysis.

Solar cell metal line and contact resistance measurement (IVT)

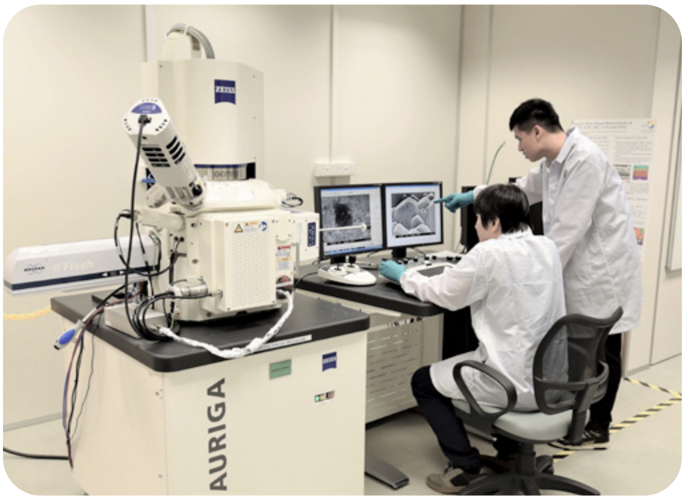
The transmission line method (TLM) enables metal-semiconductor contact resistance measurements down to 1 mΩ-cm^2. Different probe heads are available for a wide range of metallisation finger pitches, suitable for measuring both screen-printed solar cells as well as test structures with evaporated metal contacts. Busbar-to-busbar resistance and line resistance measurements are complementary techniques used to determine the metal grid resistance.

Electron Microscope Laboratory

The centrepiece equipment of this laboratory is the FE-SEM (field-emission scanning electron microscope), an electron microscope used to obtain high-magnification images of sub-micron structures of electrically conductive samples. Our SEM has additional accessory ports for elemental composition studies using an EDX (energy-dispersive X-ray) detector, crystallographic grain studies using an EBSD (electron back-scatter diffraction) detector, and electrical semiconductor properties using an EBIC (electron-beam induced current) setup. The lab also houses optical characterisation tools, such as a UV-VIS-NIR spectrophotometer which provides a direct method of measuring the total transmittance and reflectance of a sample. Additionally, the lab contains a spectroscopic ellipsometer, an advanced method for determining the optical properties (thickness, refractive index and extinction coefficient) of thin-film samples.

Scanning Electron Microscope (SEM) (Carl Zeiss, Auriga)

This field-emission SEM can achieve a resolution of 1 nm at low acceleration voltages of 1 kV. It is ideal for imaging sub-micron morphologies, cell surface textures, and micro- and nano-patterned structures. The SEM is equipped with the following additional features: electron backscatter diffraction (EBSD) (Bruker, e-Flash), electron-beam induced current (EBIC) (Kammrath & Weiss), and energy-dispersive X-ray (Oxford Instruments, Aztec X-MaxN).



Scanning electron microscope

UV-VIS-NIR spectrophotometer (Agilent, CARY-7000)

The UV-VIS-NIR optical spectrophotometer enables the determination of the specular and diffuse reflectance and transmittance of materials/devices in the 190-2500 nm wavelength range. These measurements are routinely used to assess cell front texture quality, antireflection layer properties, and transparency of TCOs. The CARY-7000 is also equipped with a sophisticated universal measurement accessory, which is useful for determining the angular distribution in reflectance and transmittance in solar module components or cell front texture.

Spectroscopic ellipsometer (SEMILAB, SE-2000)

Ellipsometry measures the change in polarisation of light reflected by a sample surface. By comparing the measurements with an optical model, this technique enables the determination of the complex refractive index (n, k) and thickness of thin optical coatings. The non-destructive technique is coupled with a X-Y mapping stage to perform automated mapping of large-area samples.

Solar Cell Measurement Laboratory

This laboratory focuses on measuring solar cell efficiencies, one of the most important parameters of solar cell devices. The lab is divided into two sections. The dark room houses a xenon lamp-based steady-state solar simulator, a large-area spectral response measurement tool, and an area measurement tool. These are used for high-precision I-V and spectral responsivity measurements to determine the efficiency of solar cells provided by SERIS researchers or external customers. The other section of the lab contains LED-based I-V testers, where SERIS researchers can quickly perform their daily I-V measurements on perovskite, silicon or tandem solar cells, and a light soaking system for long-term cell degradation studies.

High-precision solar simulator for I-V measurements (OAI, TriSOL)

This xenon lamp-based solar simulator meets the specifications of the AAA solar simulator class, with a spectrum that achieves better than 12.5% spectral match to the Sun's AM1.5G spectrum. It provides laterally uniform illumination intensity across an area of 300 mm × 300 mm, making it well suited to I-V measurements of solar cells.

LED solar simulators for solar cell I-V measurements (WAVELABS, SINUS-220)

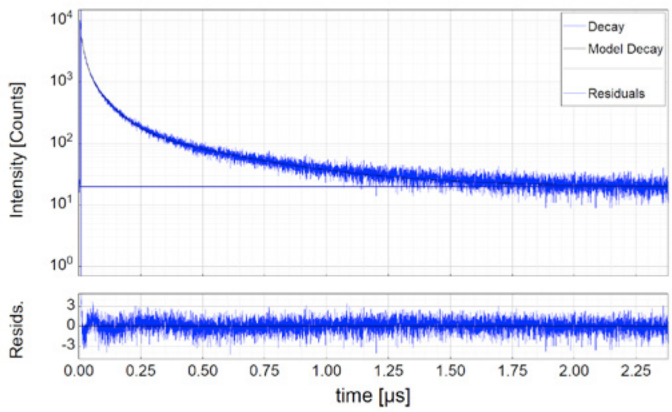
Two Class-AAA solar simulators featuring state-of-the-art LED array technology provide spectrum tunability across the 300 - 1100 nm wavelength range. These solar simulators are capable of measuring solar cells with metallisation grid patterns ranging from traditional H-patterns to newer busbarless designs.

Advanced Characterisation Laboratory

This laboratory houses cutting-edge commercial characterisation tools as well as tools currently being developed by SERIS. It contains a time-resolved photoluminescence tool, which is used to measure the luminescence spectrum of perovskite materials and their effective carrier lifetime, ranging from picoseconds to microseconds. The lab also has a LED-based modulated PL setup and a high-resolution spectral response system, modified in-house to study the optoelectronic properties of perovskite samples.

Time-resolved fluorescence spectrometer (PicoQuant, FT300)

Time-resolved fluorescence spectroscopy is a technique used to study various transient events in fluorescent and semiconductor samples, such as charge carrier transfer and recombination, down to sub-nanosecond time resolution. This capability makes it ideal for studying carrier lifetimes in direct-bandgap semiconductors like InGaP, GaAs, InGaN, and perovskites. The setup currently employs two pulsed lasers providing optical excitation at 520 and 760 nm.



Time-resolved photoluminescence (PL) of a perovskite film showing the PL decay, and fitted model decay. The residual trace (bottom panel) indicates good agreement between the fitted and measured data.

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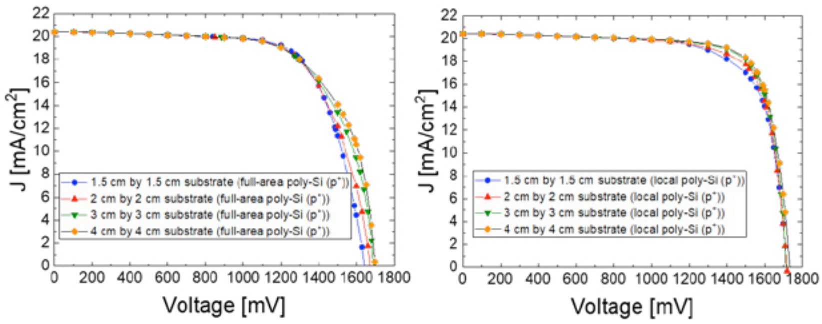
PV DEVICES MODELLING AND SIMULATION

SERIS is operating a simulation infrastructure which can assist in solar cell optimisation. Both commercial and SERIS-developed simulation tools are available and can be executed on a powerful computer cluster. We have in-depth knowledge simulating standard passivated-contact (TOPCon) silicon solar cells as well as perovskite solar cells and perovskite-silicon tandem cells. Through metrology modelling combined with machine learning (simulation using measurement data, i.e. intensity dependent photoluminescence imaging), it is possible to extract hidden device parameters (like bulk/edge/interface/metal recombination rates) from contactless PL imaging measurements. We offer a detailed loss analysis for solar cells and PV modules, and predict the annual energy yield of PV modules and systems in different locations and climate zones. Examples of our activities are:

• Device simulation	TOPCon & perovskite cells, perovskite-Si tandems
• Metrology simulation	I-V, EQE/IQE, carrier lifetime, EL/PL imaging
• Energy yield simulation	PV modules and systems
• Optical simulations	Transfer matrix, ray tracing, path tracing
• Loss analysis	Solar cells (silicon, perovskite), PV modules and systems



(Left) Simulated J-V curves of perovskite-TOPCon (biPoly™) tandem cells with full-area poly-Si (p$^+$) layers assuming different substrate sizes. (Right) Simulated J-V curves of perovskite-biPoly™ tandem cells with local poly-Si (p$^+$) layers assuming different substrate sizes. (Image source: Fig. 5 of publication "P. Wang et alia, Unlocking the full potential of monolithic perovskite/biPoly™ Si tandem devices through in-depth analysis and detailed engineering, Solar Energy Materials and Solar Cells, vol. 262, 2023, 112556, Elsevier")

SERIS has developed the following capabilities/facilities in the area of modelling/simulation.

Device simulation

The SERIS-developed Griddler software is used to model standard passivated-contact TOPCon silicon solar cells (e.g., monoPoly, biPoly, abcPoly) as well as perovskite-Si tandem cells. More details on Griddler can be found in the Services chapter of this Annual Report (see "Characterisation and Testing of PV Materials and Solar Cells"). Organic and perovskite solar cells as well as two-terminal perovskite-silicon and all-perovskite tandem cells are modelled and solved numerically with in-house developed codes and AI.

Metrology simulation

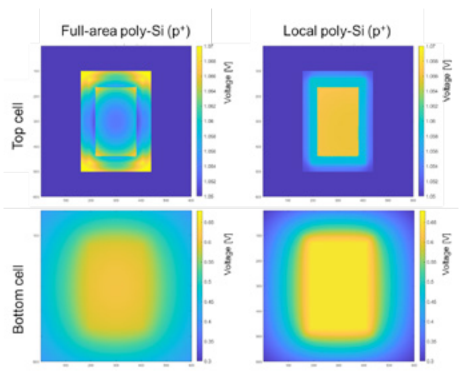
We have developed various programmes for reliable simulations of the PV device characterisation methods in use at SERIS. For example, we can simulate injection dependent carrier lifetime measurements, bias and injection dependent quantum efficiency (EQE/IQE) measurements, as well as injection and bias dependent luminescence images (EL and PL). This enables a self-consistent parameter extraction for PV devices using a raft of characterisation methods.

Energy yield simulation

Our solar cell models can be interlinked with analytical models or circuit models in order to simulate PV modules and PV systems. These calculations focus on predicting module or system characteristics like I-V, EQE and, most importantly, the annual energy yield, considering actual illumination conditions (including shading) and a given location or climatic zone (arid, tropical, high altitude or temperate environment).

Loss analysis

A quantification of the main power loss mechanisms in solar cells and PV modules can be provided in close collaboration with SERIS' PV Devices Characterisation Group. Furthermore, the efficiency potential of various solar cell technologies can be predicted. More details on these services can be found in the Services chapter of this Annual Report (see "Solar Cell Doctor: Detailed health check for silicon wafer solar cells").



The simulated diode voltage map of the top perovskite cell and the Si bottom cell for perovskite-biPoly™ tandem devices featuring full-area poly-Si (p$^+$) and local poly-Si (p$^+$) layers.
(Image source: Fig. 6 of publication "P. Wang et alia, Unlocking the full potential of monolithic perovskite/biPoly™ Si tandem devices through in-depth analysis and detailed engineering, Solar Energy Materials and Solar Cells, vol. 262, 2023, 112556, Elsevier")

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PV MODULE DEVELOPMENT LABORATORY

Located at CleanTech Park, this 300-m² laboratory houses a fully equipped PV module pilot line for industry-scale PV module R&D and related services.

Automatic solar cell stringer (left) and TLS solar cell cutter (right) in SERIS' PV Module Development Laboratory at CleanTech Park

Thermal Laser Separation (TLS) cell cutter (3DMicromac, microPRO TMS)

This advanced tool uses thermally induced mechanical stress to separate brittle semiconductor materials like silicon wafers. As opposed to conventional laser cutting, no bulging and no formation of particles occur, because the substrate is merely heated and not vaporised. The mechanical stability of TLS-processed solar cells is significantly greater than conventionally processed solar cells. The tool is used at SERIS for cutting full-size silicon solar cells in half, for example for making PV modules with shingled solar cells.

Automatic solar cell stringer (Teamtechnik, TT1800)

This machine is used for the automatic soldering of metal ribbons onto solar cells and interconnecting solar cells into strings. SERIS' customised TT1800 stringer is capable of interconnecting standard silicon solar cells with up to 6 busbars as well as interdigitated-back-contact solar cells. Both full-size cells and half-cut cells can be processed.

String repairing station (P.Energy, RP12M)

Soldering station used for making spot repairs to solar cell strings or manual ribbon soldering.

Semi-automatic PV module laminator (HengHui HB-C6D)

This single-chamber semi-automatic laminator has a large lamination area of up to 2600 x 1500 mm. Using a membrane vacuum system to apply pressure, the tool is rated to handle up to 20 mm thick glass-glass modules with an operating temperature of up to 180°C.

Semi-automatic PV module laminator (HengHui HB-C6D)

Electrohydraulic fragmentation system (ImpulsTec GmbH, EHF-HF-RS200-T1-F1-10)

This machine is used for the continuous processing of pre-crushed silicon solar modules into separate components for material recovery during recycling. In contrast to high-temperature separation processes such as furnaces which burn off the encapsulant, this plant operates by generating shockwaves through high-voltage arc discharges. The shockwaves travel through a working fluid to separate the constituent materials within a solar module stack based on their different acoustic properties. SERIS uses this tool to recover silicon cells, metal ribbons and even encapsulant materials for further recycling.

Electrohydraulic shockwave fragmentation system

Outdoor BIPV testbed

Located on the rooftop of CleanTech One, the outdoor BIPV testbed features a 5 m × 2 m vertical racking system oriented in the four principal directions. Equipped with a state-of-the-art weather and performance monitoring system, the testbed is designed for flexibility – supporting different BIPV module types and accommodating a variety of mounting and interconnection strategies.

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SERIS' ISO/IEC 17025 LABORATORY FOR PV MODULE TESTING

The PV Module Characterisation & Reliability (PVMC&R) Group at SERIS offers testing of PV modules to the PV industry. It also collaborates in research projects, offering high-accuracy characterisation and consultancy on PV module reliability. The Laboratory is accredited since 2012 to ISO/IEC 17025 for the electrical testing of PV modules. Over time, the Laboratory expanded its accreditation to reliability and safety tests, with special focus on the degradation modes that occur in the hot and humid tropical climate of South-East Asia. In 2021 the Laboratory further expanded its accreditation to potential induced degradation, and the classification of solar simulators. In 2024, the laboratory added the measurement of bifacial modules according to IEC TS 60904-1-2 Edition 1.0 to its scope to meet the increasing demand from industry for accurate measurements and characterisation of such modules. The Laboratory has established collaborations with local and international PV test centres and module manufacturers, being the reference centre for PV module characterisation and reliability for Singapore and the region.

Equipment available in the accredited Laboratory

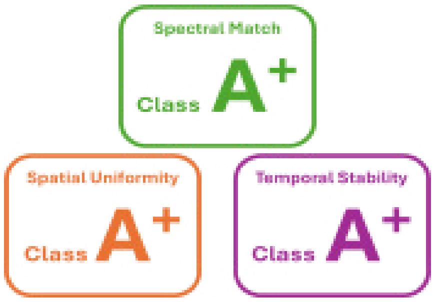
The Laboratory has high-level instrumentation that makes it one of the best-equipped test laboratories in the world for PV module testing, and the top module testing laboratory in South-East Asia.

Solar simulator classification

The "ABC" rating

Our laboratory offers on-site classification of solar simulators in the region, according to the newest edition of IEC 60904-9, including spectral match classification in the extended range from 300 to 1200 nm.

The classification of solar simulators is performed by assigning a rating that ranges from class CCC to class A+A+A+ for the following characteristics: spectral match (including AM1.5 Spectral Coverage and AM1.5 Spectral Deviation; SPC and SPD, respectively), spatial uniformity, and temporal stability.



Defining criteria to rate a Solar Simulator

PV module characterisation

Solar Simulators

Electrical characterisation of PV modules is performed in our laboratory on two of the best solar simulators in the market:

- a 10-ms pulse Pasan SunSim 3B by Meyer Burger;
- a 100-ms ModuleTest3 solar simulator by h.a.l.m. for slow-response high-capacity modules.

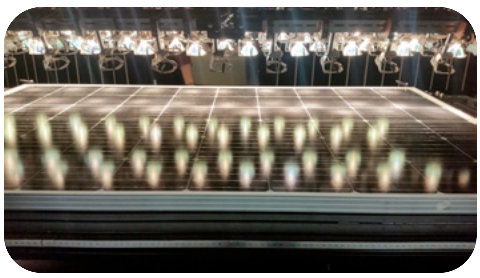
"Golden module" certificates can be produced by combining the results from both simulators, giving the world-class uncertainty of ± 1.4% for the module's measured maximum power.

"Golden module" testing at SERIS

Spectral responsivity and spectral mismatch correction for the highest accuracy

The laboratory is fully equipped to assess the optical characteristics of the module under test for both spectral responsivity measurements and spectral mismatch correction, providing best-in-class precision in the electrical measurements.

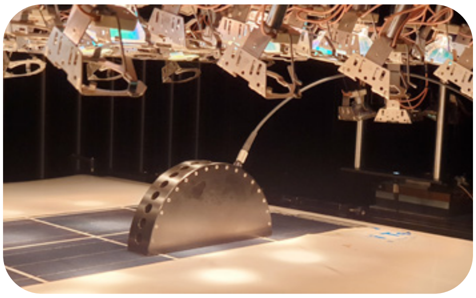
The spectral irradiance of the solar simulators is routinely monitored with fast-response spectrometers, capable to measure in the 200 - 1700 nm spectral range.



Spectral responsivity measurement system

Incident Angle Modifier (IAM)

The level of irradiance that a PV module receives varies with the Sun's position in the sky throughout the day and over the seasons. It is therefore important to analyse the impact of the angle of incidence on the output of PV modules and determine a correction factor, commonly referred to as the Incident Angle Modifier (IAM). Our Laboratory is equipped with a novel experimental setup to analyse the Incident Angle Modifier (IAM) at full-size commercial module level. The method has been included in the draft of an update to IEC 61853-2 which is expected to be adopted in early 2026.



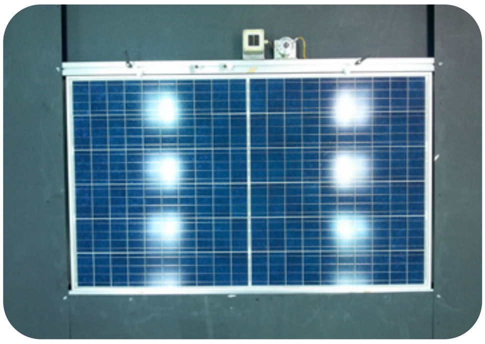
Measurement of the IAM of a commercial-size PV module

PV module reliability and durability testing

Light Induced Degradation, Hot-spot and Temperature Test

Module stabilisation against Light Induced Degradation (LID) can be done outdoors with natural light but also indoors in our continuous solar simulator for time efficiency. Additionally, our solar simulator allows us to perform hot-spot and module operating temperature tests in steady and controlled conditions.

These tests are important to assess the durability and long-term reliability of PV modules.



Module stabilisation

UV Exposure

The UV pre-conditioning test is an ageing test that aims at identifying any susceptibility to UV degradation.

The PV module is irradiated with UV light, accelerating the outdoor UV exposure by a factor of 5 to 10 (depending on the considered location). In a typical test flow, the tested module is then checked against damages (visual inspection, insulation, and electrical characterisation if required).

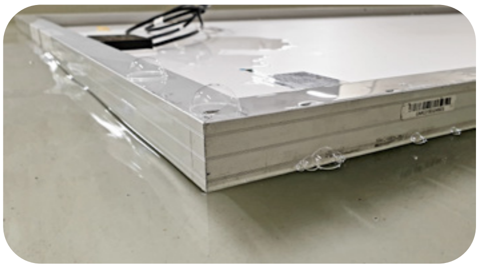
UV exposure test

Insulation Tests

A range of test is designed to assess the electrical insulation resistance of a PV module under various conditions (dry, wet, pulsed voltage or reverse current).

Examples:
"Insulation Test" (Dry)
Designed to assess module electrical insulation between active parts and accessible parts. A high voltage is applied to the module and the insulation resistance is measured.

"Wet Leakage Test"
The test is carried out in a similar way as for the insulation test, except that the module under test is immersed in a water solution of given resistivity. This is particularly relevant for PV modules in tropical or equatorial climates.



Wet leakage test

PV module reliability and durability testing

Mechanical stress tests

There are various tests to assess the mechanical stability and durability of PV modules:

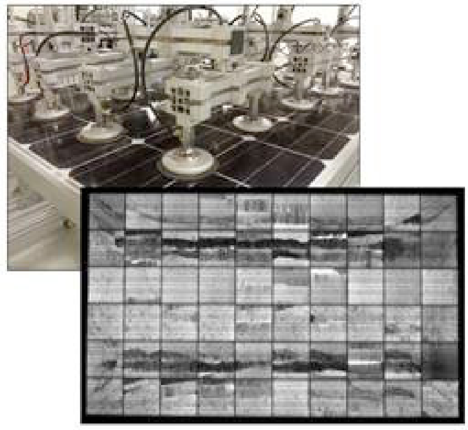
"Mechanical Load Test" (MLT) to simulate for extreme weather stress conditions (e.g., heavy winds, snow): a static load of up to 5400 Pa is applied for a certain duration.

"Dynamic Load Test" (DLT) uses lighter loads but is repeated 1000 times. This simulates vibrations from storms and repeated wind gusts.

"Hail test", for which a projectile (ice ball) is shot at the modules with speeds of up to 30 m/s.

"Junction Box and Connectors Test" is used to assess the strength and assembly quality of the modules.

"Module Breakage Test" aims to ensure safe operations when replacing a broken module. It entails a bag filled with steel balls to 'pendulum swing' onto a module from a known height.



Damages after dynamic MLT

Thermal reliability tests, PID and LeTID

Climate chambers are the "work horses' in reliability and durability testing of PV modules. Tests such as damp heat, thermal cycling, humidity-freeze, hot and cold conditioning with Potential Induce Degradation (PID) options require the use of such equipment to vary the temperature and humidity in a controlled way over a wide range of conditions. The Laboratory is also equipped to perform the pre-normative Light and Elevated Temperature Induced Degradation (LeTID) test, a degradation mechanism that may slowly deteriorate PV module performance in hot climates.

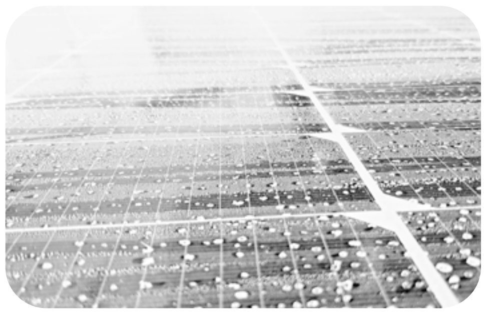
Given the PV industry trend to larger modules, the laboratory's climate chambers were upgraded in 2022 to larger volumes, now capable of testing modules up to 3 m long and 2 m wide. In 2024, a large salt mist chamber with full climate chamber capabilities was added.

Large-volume climate chamber for reliability testing

Extended reliability for tropical regions

The location in the tropics makes SERIS' testing laboratory an ideal place for conducting extended PV module stress tests relevant to South-East Asia. Specifically designed PV module tests include:

- Accelerated ageing tests with extended durations or toughened test conditions
- Comparative indoor and outdoor potential induced degradation (PID) testing
- Seven different salt mist corrosion tests
- Hot-spot identification due to soiling
- Acid rain impact to the modules
- Assessing degradation of the encapsulants
- Customised mechanical load testing for modules in floating PV applications



Salt mist test

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OUTDOOR PV MODULE AND SYSTEM TESTING FACILITIES IN DIFFERENT CLIMATES

As part of the “TruePower Alliance”, which was initiated and is driven by SERIS, the institute operates high-precision outdoor testing facilities for PV modules and systems in different climate zones. For energy yield assessments, and eventually investment decisions, knowledge of the actual generated *energy per year* rather than the rated *peak power* under standard test conditions (STC) in the laboratory is much more relevant. However, the actual energy output depends strongly on the geographic location of the PV system. Therefore, SERIS has implemented outdoor testing facilities on both module and system level in the three most important climate zones: temperate (Germany, China), tropical (Singapore) and desert (Australia). Some of the world’s leading PV manufacturers are collaborating with SERIS and are field-testing their modules within the TruePower Alliance.

SERIS applies its self-developed data acquisition system at the TruePower sites. To date, through many years of working with clients and carrying out R&D projects, SERIS has achieved outstanding data acquisition rates of more than 99% per year, proving the robustness and reliability of its equipment.

The various PV module and system data (available in time intervals as short as 1 minute) include:

- Module temperature
- DC characteristics: V_{oc}, V_{mpp}, I_{sc}, I_{mpp}, P_{mpp}, I-V curve
- AC characteristics: voltage, current, active and reactive power, etc.
- Cumulative energy yield (DC and AC side)

In addition, every site location has a state-of-the-art meteorological station, using the following equipment:

- Pyranometer (horizontal and in-plane)
- Silicon sensor (horizontal and in-plane)
- Pyrheliometer
- Spectro-radiometer
- UV radiometer
- Ambient temperature
- Other meteorological sensors (wind speed & direction, humidity, rainfall)

SERIS’ Outdoor Module and System Testing facility at Marina Barrage, Singapore (tropical)

SERIS’ Outdoor Module and System Testing facility in Alice Springs, Australia (desert)

SERIS’ Outdoor Module and System Testing facility in Xinyang, China (temperate)

SERIS’ Outdoor Module and System Testing facility in Bernburg, Germany (temperate)

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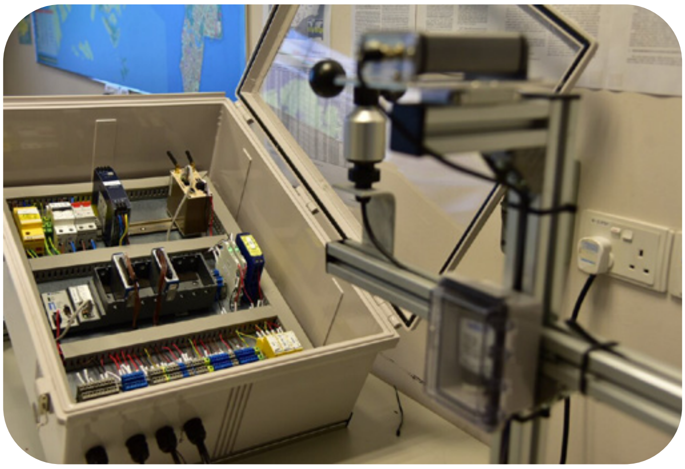
PV SYSTEM MONITORING LABORATORY

This laboratory showcases SERIS' real-time analytical monitoring capabilities of photovoltaic systems as well as meteorological parameters. Our proprietary award-winning monitoring system is based on rugged industrial-grade hardware from National Instruments and LabVIEW software for remote data logging and remote control of SERIS-monitored PV systems and meteorological stations. The monitoring system is highly versatile and can be customised to meet any specific project requirements. It has been deployed successfully in numerous PV projects across Asia-Pacific and Europe, and it also fulfils the stringent data requirements of EMA PSO, Singapore's power system operator, for PV systems larger than $1MW_{AC}$ in Singapore.

The PV System Monitoring Lab's video wall, displaying the live solar irradiance map of Singapore (also available at www.solar-repository.sg/solar-irradiance-map), real-time performance data of several rooftop PV systems, as well as real-time meteorological parameters from several remote stations deployed across Singapore

Features of SERIS' live monitoring systems include:

- Real-time ("live") data transmission for key PV system and meteorological parameters
- Submission of live power and irradiance data compliant with requirements from power system operators (PSO), e.g. Singapore's Energy Market Authority (EMA)
- 1-second resolution of various DC and AC parameters of PV systems, power quality parameters, and meteorological parameters, such as irradiances measured with different sensor devices and inclinations, module and ambient temperatures, relative humidity, wind speed, wind direction, air pressure, etc.
- ± 150 ms time synchronisation with cloud-based time servers
- Greater than 99% data acquisition availability
- Secure data communication via VPN over 4G/5G networks
- Live irradiance map for Singapore (spatially resolved). The map can be accessed online at the National Solar Repository (NSR) website, www.solar-repository.sg/solar-irradiance-map
- Solar irradiance forecasting algorithms with different forecast horizons (from 5 minutes to 24 hours ahead)
- Tailored alarm system according to customer needs (such as inverter trips, grid outages, system underperformance), including SMS and email services
- High-quality online or screen visualisation for various target groups: Operations managers, engineers, general public (for example through displays in corporate entrance areas). Daily summary reports of PV system status and performance data via email.



Demonstration setup of a remote meteorological station

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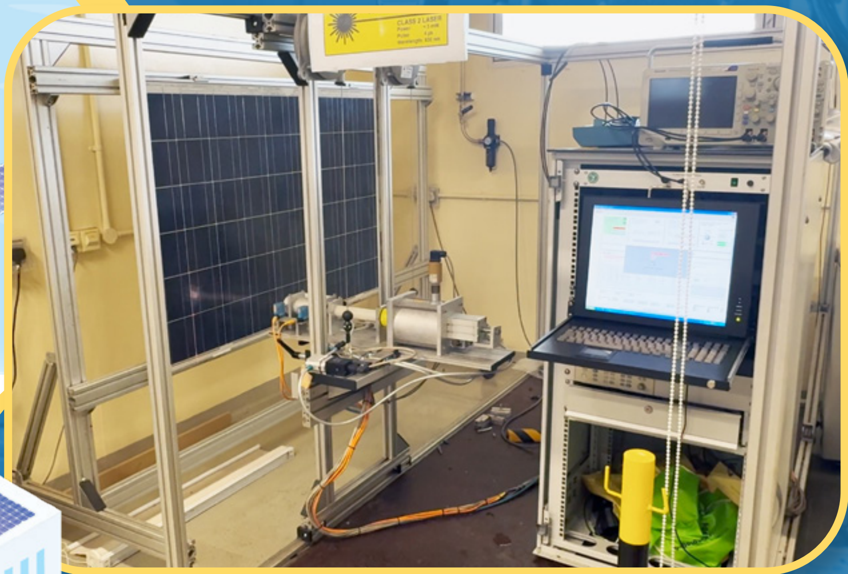
SERIS SERVICES



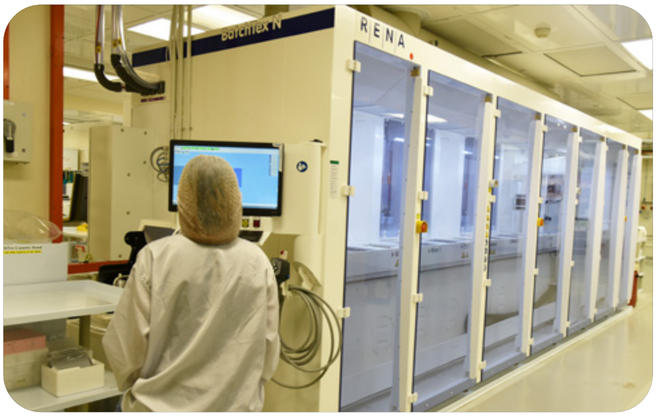
PROCESSING SERVICES FOR SILICON AND PEROVSKITE SOLAR CELLS

SERIS operates state-of-the-art industrial solar cell processing equipment from leading manufacturers for its internal R&D on silicon wafer solar cells and perovskite thin-film solar cells. To support the global PV research community, we offer a broad range of processing services in our Solar Cell Labs to external customers. Selected examples of processing services for research-type silicon and perovskite solar cells are listed below.

Processing of large-area silicon wafer solar cells and perovskite-silicon 2T tandem cells:

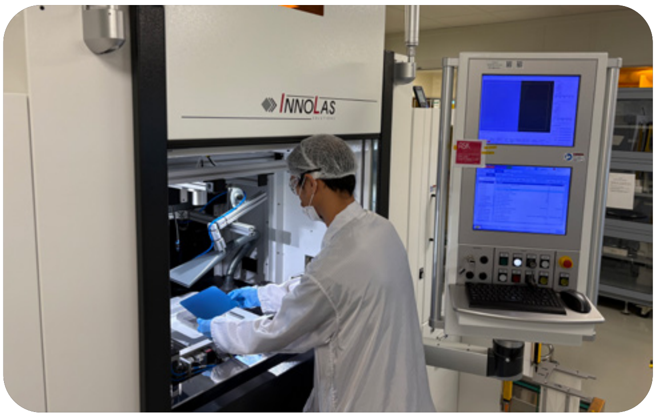
- M2 to G12 silicon wafer size (up to 210 mm x 210 mm)
- Batch-type wet-chemical processes for silicon wafers, including cleaning, etching and texturing (acid or alkaline)
- Inline wet-chemical processes (both acid and alkaline chemistries) for silicon wafers, including cleaning and etching
- PECVD of dielectric layers (SiN_x, AlO_x, SiO_x, SiO_xN_y etc)
- PECVD and LPCVD of intrinsic or doped (boron, phosphorus) a-Si layers for applications in polysilicon based passivated-contact solar cells
- PECVD of intrinsic or doped (boron, phosphorus) a-Si layers for applications in heterojunction silicon wafer solar cells
- ALD of Al_2O_3, SnO_2 and AZO layers
- PVD of various thin films (metals, TCOs, TMOs) by sputtering and thermal evaporation
- Thermal evaporation of metal contact layers and anti-reflection coating layers
- Sputtered and evaporated charge transport layers for perovskite solar cells
- Laser processing using ns pulses (green) and ps or fs pulses (UV, green, IR light)
- Inkjet printing of masking layers for patterning applications
- Screen printing of metal contacts (Ag, Al, Cu) and fast firing in a belt furnace

PECVD tool for deposition of intrinsic and doped amorphous silicon layers for heterojunction silicon wafer solar cells



Inline wet-chemical processes (both acid and alkaline chemistries) for silicon wafers, including cleaning and etching

PVD sputtering platform for depositing metal layers, transparent conductive oxides and multi-layer stacks on silicon wafer solar cells and perovskite thin-film solar cells



Laser processing of silicon wafer solar cells using ns pulses (green) and ps or fs pulses (UV, green, IR light)

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MAGNETRON SPUTTERING OF METAL AND TRANSPARENT CONDUCTIVE OXIDE (TCO) COATINGS FOR INDUSTRIAL PROTOTYPING

Magnetron sputtering is a vacuum-based physical vapour deposition (PVD) process that is widely used in the coating industry to deposit thin films onto various substrates (glass, foil, steel, etc), for a wide range of applications. SERIS is offering magnetron sputtering services for small numbers of samples to allow clients from industry and academia to explore the use of this versatile technology for their prototypes and products.

SERIS' PVD sputtering platform is designed for medium- to high-throughput applications such as solar cells, architectural glass, and flat-panel displays. The machine can handle any flat substrate with a size of up to 300 mm x 400 mm, with a maximum thickness of 5 mm. Typical substrates would be glass and silicon wafers. This state-of-the-art machine has dedicated vacuum chambers for the sputtering of metallic, dielectric and transparent conductive oxide (TCO) layers. The processing chambers are equipped with planar magnetron sources for DC sputtering of metals, oxides and oxynitrides in the reactive mode, and with a cylindrical dual-magnetron source and planar sources for pulsed DC (DC+) and RF sputtering of dielectrics and TCOs, with substrate heating up to 400°C. This allows to deposit thin layers of metals, TCOs and dielectrics onto various substrates. It is also possible to deposit graded layers with varying refractive index, or multi-layer stacks of up to six different materials, without breaking the vacuum conditions. As the platform is comparable with large-scale production machines, processes developed on this machine can easily be scaled up to industrial production lines. At SERIS we use this tool for depositing metal layers, TCOs and multi-layers for silicon and thin-film solar cells, as well as perovskite-Si tandem solar cells. The main features of our sputtering machine are listed in Table 1.

In addition to AZO and ITO, we are able to deposit a variety of other layers, including Ag, Al, Ti, In, ZnO, IZO, NiO_x, Mg:NiO_x and thin layers of metal, oxide and oxynitride tuned to customer requirements.

In-line multi-chamber magnetron sputtering machine at SERIS

Table 1: Process capabilities of the in-line sputtering machine at SERIS

Parameter	Details
Substrate	Glass, Si wafers and foils
Substrate size	Minimum 50 mm x 50 mm, maximum 300 mm x 400 mm
Substrate movement	Linear and oscillating
Substrate temperature	Up to 400°C
Power supply	DC , DC+ (0 - 10 kW) and RF (0 to 2 kW)
Sputter targets	Planar (Ti, Zn, Ag, Al, ITO) Dual cylinder (2 wt % Al-doped ZnO)
Gas supply	Ar, O_2, N_2, Ar+O_2 (98% + 2%)
Layers	Ag, Al, TiO_2, ZnO, AZO, ITO, IZO, NiO, Mg:NiO_x

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CHARACTERISATION AND TESTING OF PV MATERIALS AND SOLAR CELLS

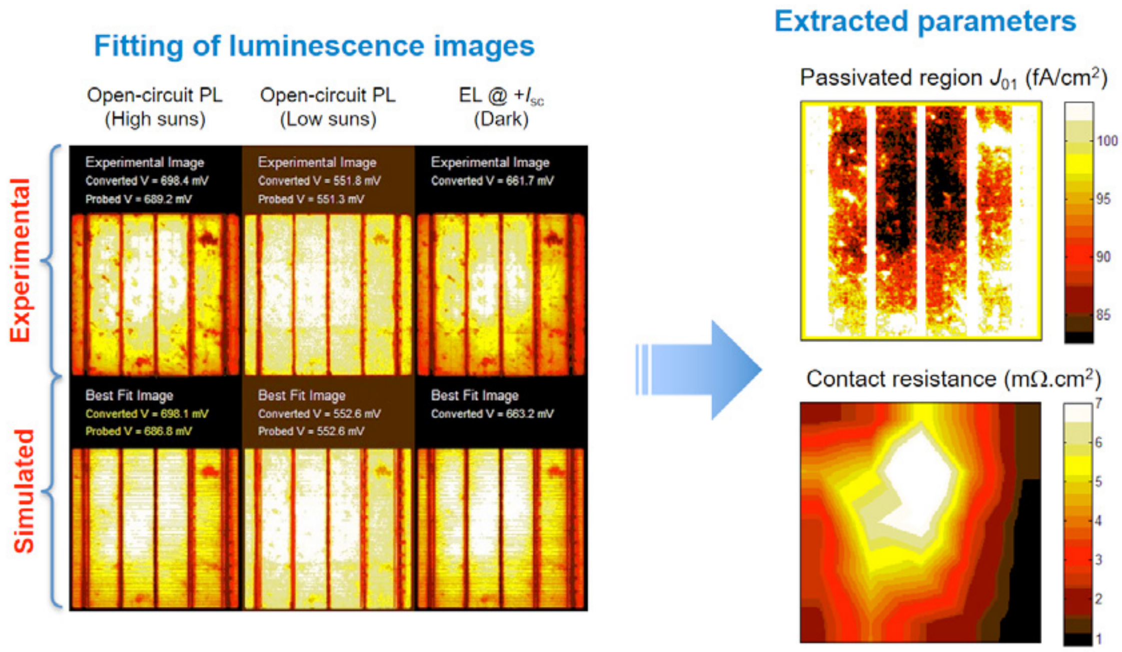
An efficient solar cell maximises the conversion of photons in the sun's spectrum into energetic charge carriers, and minimises undesirable recombination processes that reduce the cell's current and voltage output. SERIS is equipped with a comprehensive suite of tools that can deduce the optical properties (related to photon-to-charge carrier conversion) and electrical properties (related to charge carrier recombination) of solar cells and materials. Technology Computer-Aided Design (TCAD) process and device simulators, as well as large-area network model representations of the solar cells are used extensively to trace the origins of the measurement features to the layers and structures of the cell, analyse them, and predict the potential for efficiency improvements with respect to process or cell design changes.

Sample testing and analysis
(see also PHOTOVOLTAIC DEVICES CHARACTERISATION LABORATORIES)

- High-precision steady-state light I-V and spectral response measurements for solar cell devices
- Solar Cell Doctor: Detailed health check for solar cells
- Photoluminescence and electroluminescence imaging
- Determination of thickness and optical properties of thin films by spectroscopic ellipsometry
- Total and angular spectral transmittance and reflectance measurements by UV-VIS-NIR spectrophotometer.
- Steady-state and transient carrier lifetime characterisation by photoconductance and photoluminescence-based measurements
- Measurement of photoluminescence/fluorescence spectra and decay lifetime using time-resolved photoluminescence spectroscopy
- Absolute luminescence quantum yield measurement of thin-film stacks and devices
- Dopant profile determination by electrochemical capacitance-voltage (ECV) measurements
- Scanning electron microscopy, including cross-sectional elemental analysis by energy dispersive X-ray (EDX), and determination of crystalline grain orientation by electron back scatter diffraction (EBSD)
- Carrier concentration and carrier mobility determination of transparent conductive oxides, conductive films and semiconductor layers by the Hall effect
- Mapping of impurity zones and defects in silicon wafers

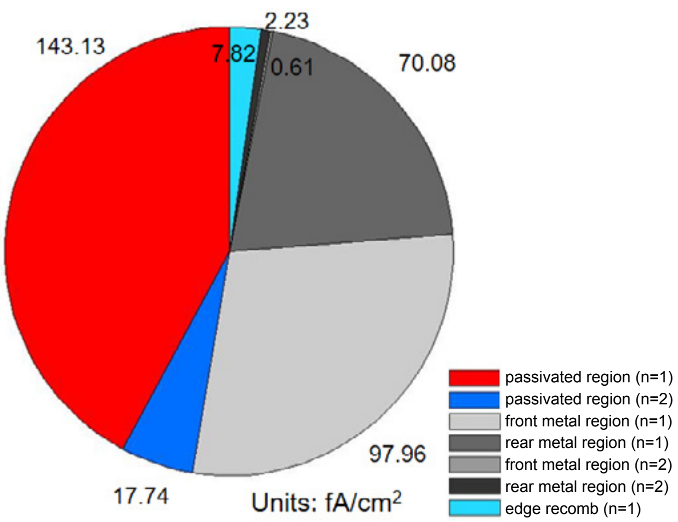
Solar Cell Doctor: Detailed health check for silicon solar cells

By combining solar cell characterisation methods with easy-to-make test structures and partially processed silicon solar cells from the production line, the *Solar Cell Doctor* loss analysis routine uses sophisticated computational methods to break down various cell loss mechanisms to generate process-related diagnostics. Exemplary analyses of several silicon solar cells are shown below. Fitting of specific luminescence images permits the extraction of the spatial distribution of the saturation current density J_{01} of the passivated cell region and the contact resistance. By creating an accurate representation of the solar cell under test, factors limiting the short-circuit current density, open-circuit voltage and fill factor are identified. Design and process changes can also be evaluated in terms of their influence on the cell efficiency.

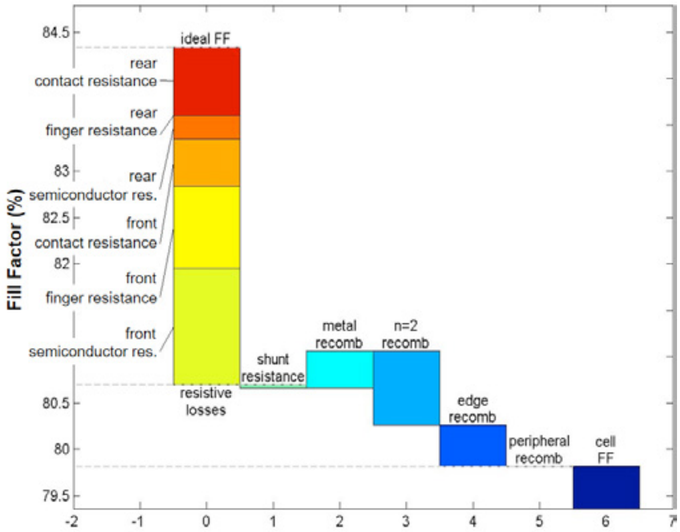


Fitting of Griddler simulated luminescence images to experimental data allows the extraction of device parameters in this p-type multicrystalline silicon solar cell. This includes the spatial distribution of the saturation current density J_{01} of the passivated region and the contact resistance.

Equivalent J_{01} at V_{oc}



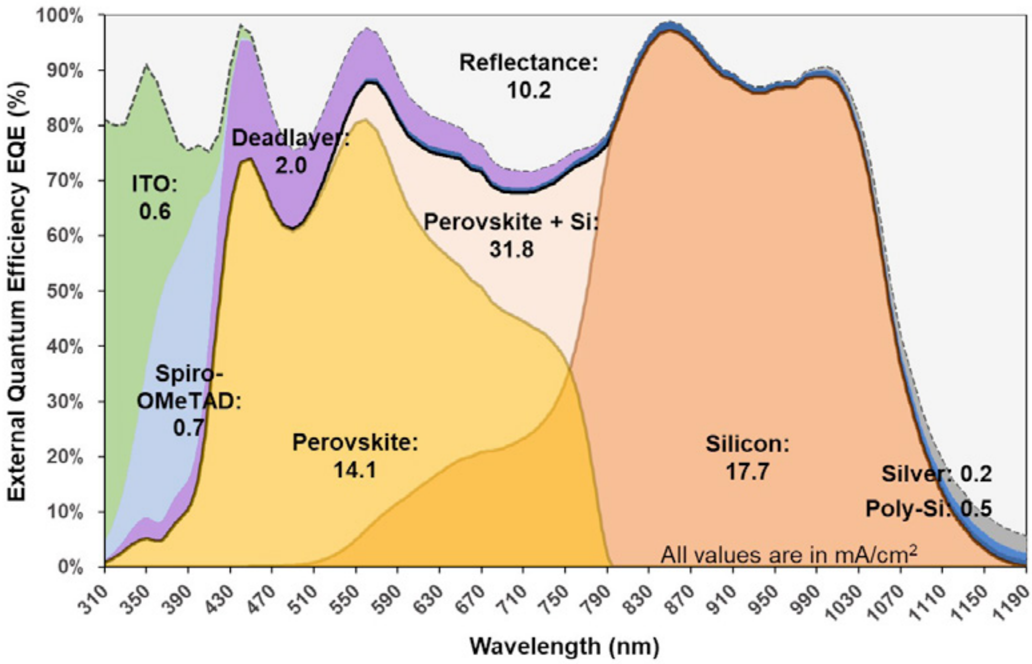
Fill Factor (FF) Drop Waterfall Diagram



The accurate representation of a silicon solar cell allows the precise quantification of the various recombination currents at open circuit that affect its voltage, as well as the myriad of factors which influence its fill factor.

Analysis of next-generation solar cells

Through in-depth advanced solar cell/material characterisation and device modelling, SERIS has developed powerful loss analysis techniques that can be applied to next-generation high-efficiency solar cells such as perovskite thin-film cells and perovskite-Si tandem solar cells. The influence of various layers in the solar cell stack on electrical current losses can be clearly delineated. Studies of the impact of bulk and interface recombination can also be performed for the quantification of related voltage losses. Such analysis provides crucial information for material screening, understanding and optimising device performance.



Delineation of the short-ciruit current density (J_{sc}) losses of a perovskite-silicon tandem solar cell by analysing spectral response, reflectance & ellipsometry measurements. Knowing the contributions of individual layers to the J_{sc} losses facilitates better solar cell design and optimisation.

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DEVELOPMENT OF PV MODULES

SERIS operates a PV Module Development Laboratory where PV modules ranging from small single-cell modules for testing purposes up to full-size 2.4 m × 1.2 m modules (full wafer or half-cut) can be fabricated. Services offered by the lab include:

- PV module fabrication
- Processing of individual module components into prototype modules for subsequent testing and qualification
- Detailed characterisation of PV module components (glass panes, encapsulants, ribbons, backsheets, etc.)
- Partial processing of PV modules for process or component verification
- Quality and yield analysis of PV module components
- Solar cell cutting using thermal laser separation (TLS)

Consultancy for Building Retrofits and BIPV Installations

- Solar potential analysis and yield estimation
- Selection of PV technologies and layout design for non-conventional installations
- BIPV module prototyping and qualification testing

Selected research activities currently conducted in the BIPV Group include:

- Development of PV modules and integrated products for various urban solar applications in Singapore (e.g. BIPV modules and bifacial PV noise barriers)
- Design of novel plug-and-play module concepts
- Design of aesthetic PV modules (Peranakan PV, pointillism PV, etc)
- Integration of BIPV into Building Information Modelling (BIM)
- Design of BIPV modules for Prefabricated Prefinished Volumetric Construction (PPVC)
- Recycling of PV modules

Cell-To-Module Loss/Gain Diagnosis

We offer a comprehensive cell-to-module (CTM) analysis for silicon wafer-based PV modules to minimise the CTM losses or maximise the CTM gain. We also provide guidance on the selection of module materials and the optimisation of the module fabrication processes, as well as extensive characterisation services to materials manufacturers to add value to their product development and product optimisation.

Selected elements of our PV module service:

1. Power loss analysis for active module area

Quantify the reflectance loss, parasitic absorptance loss and optical coupling gain of front encapsulation layers (glass, EVA, POE, etc).

2. Light harvesting analysis from inactive module area

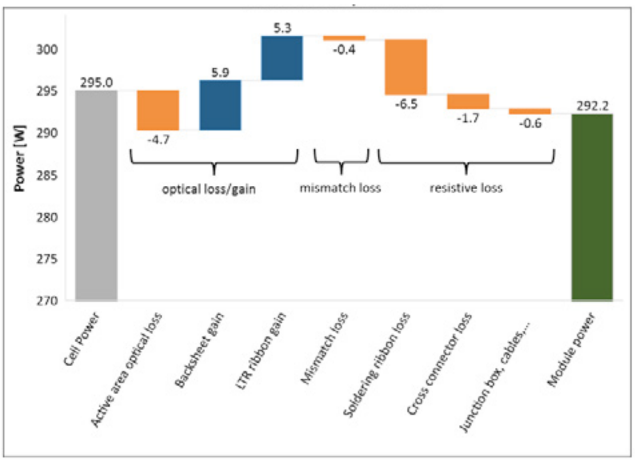
Quantify the light harvesting from inactive areas of a PV module (e.g. cell-gap area, ribbon) using EQE line scans.

3. Cell mismatch analysis

Quantify the loss occurring due to the differences in the maximum power point currents (I_{mp}) of the individual series-connected solar cells.

4. Resistive power loss analysis

Quantify the power loss in various components used to interconnect the solar cells, as well as leakage currents at various points in the module.



Cell-to-module (CTM) power loss analysis at SERIS

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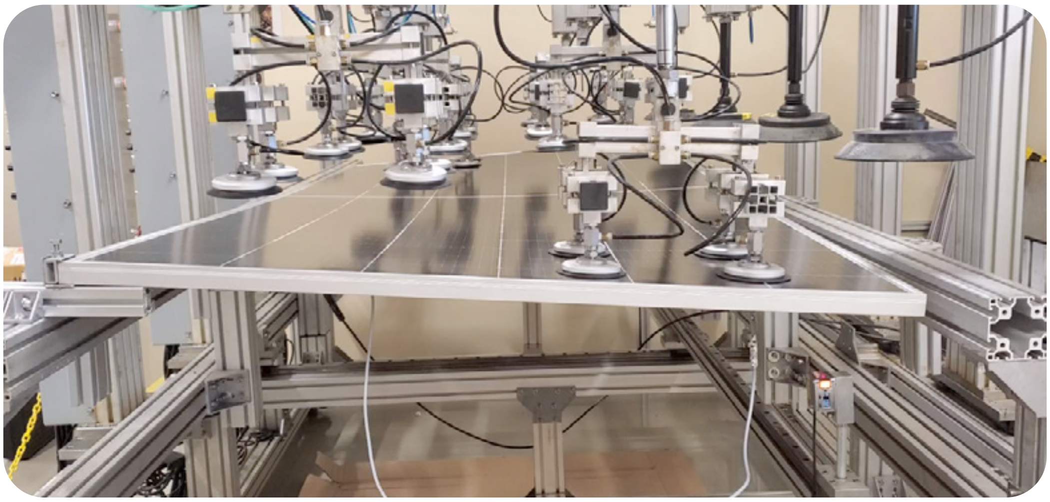
ADVANCED RELIABILITY TESTING OF PV MODULES

The fast pace of development of PV modules, with new materials as well as module & cell geometries launched every year, represents a challenge for PV module reliability. Additional challenges arise from the deployment of PV modules in novel environments (e.g. building integration, floating PV, agrivoltaics), which require additional reliability studies. To address emerging challenges observed in the field, we are actively developing and refining innovative testing methods for PV modules.

Floating PV module testing:

For the case of floating PV, SERIS has expanded its scope at the module level by introducing new stress methods that include vibrations, torsion tests, and Potential Induced Degradation (PID) testing in a salt mist environment.



Torsion test at SERIS for the pre-qualification of modules for floating PV applications (simulating different wave conditions)

Outdoor Potential Induced Degradation (PID) testing:

PID is one of the most damaging degradation processes of PV modules in field conditions, and its effects can be exacerbated, for example, in the maritime environments. Furthermore, in tropical Singapore the temperature of PV modules can exceed 60°C during daytime, whereby the annually averaged relative humidity is 81%. The combination of these climatic conditions makes the risk of PID particularly high in the tropics, and PV modules that are usually considered “PID-free” in temperate climates may exhibit PID here. SERIS has therefore set up an Outdoor Module PID Test Facility to monitor PV modules for PID in the tropics. In this set-up, a bias voltage corresponding to the module’s rated maximum system voltage is applied. The modules are also connected to load resistors to keep them near their maximum power point (MPP), to simulate the real-life operation. In addition, PV module temperature, ambient temperature, relative humidity, wind speed, irradiance and leakage current are being measured.

SERIS’ Outdoor Module PID Test Facility

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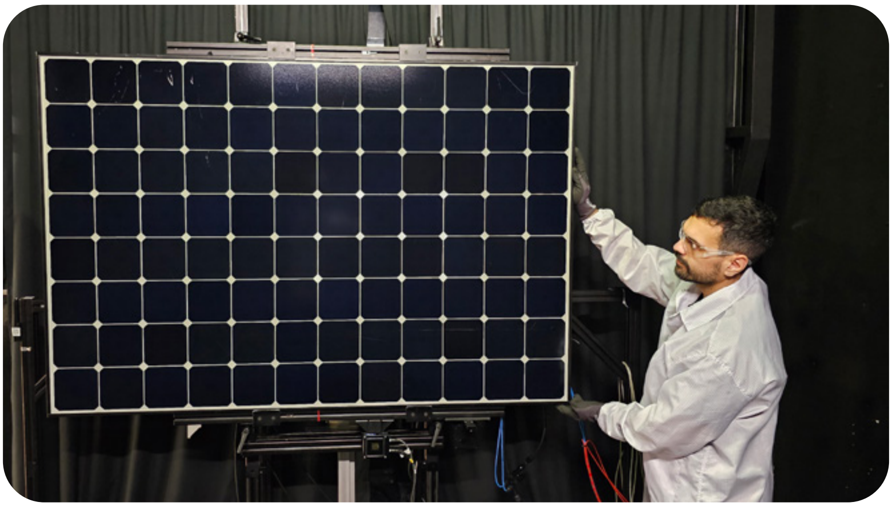
CHARACTERISATION OF PV MODULES

SERIS' ISO/IEC 17025 accredited PV Module Laboratory started its testing operations in 2010. Located in CleanTech Park, it has regularly embarked on equipment upgrades and system updates to remain relevant to the changing needs of research centres and the solar industry. In addition to the standard testing, research activities such as on Potential Induced Degradation (PID), measurement of the Incident Angle Modifier (IAM), and reliability of modules for floating PV applications enable the Laboratory to address specific concerns of the PV industry. The Laboratory has ISO 17025 accreditation from the Singapore Accreditation Council (SAC) for PV module qualification and safety. It is also accredited for the electrical characterisation of secondary reference standards ("Golden modules") according to IEC 60904-2, and for the classification of solar simulators according to Edition 3 of IEC 60904-9. The Laboratory offers, among others, the following tests to the industry and to research partners.

Golden modules (or "secondary reference standards"), temperature coefficients, and irradiance dependence.
Equipped with two Class A+A+A+ large-area pulsed solar simulators, the Laboratory can characterise all types of commercially available PV modules at Standard Test Conditions (STC), including bifacial and heterojunction modules. This is particularly important for PV module manufacturers who need a set of secondary reference standards (also referred to as "Golden modules") to calibrate their own solar simulators on their production lines. In 2024, the laboratory has expanded its scope to cover bi-facial modules, measured according to IEC TS 60904-1-2 Edition 1.0, to meet increasing demands from the industry for measurements and characterisation of such modules.

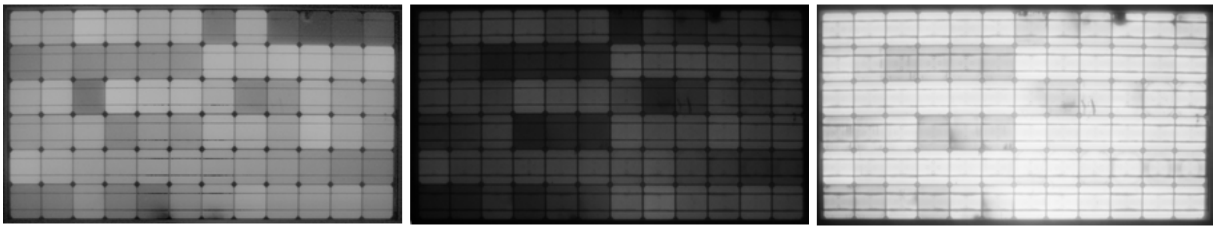


"Golden module" characterisation at SERIS

Electroluminescence (EL) and Photoluminescence (PL) of PV Modules
Reliability studies often require identifying the underlying causes of failures or performance degradation in photovoltaic (PV) modules. Electroluminescence (EL) is a well-established imaging technique used to detect issues such as microcracks, corrosion, or missing/delaminated contacts. Interestingly, EL works in a manner that is essentially the reverse of normal PV cell operation: while a PV cell typically generates current when it absorbs light (light absorption generates current), in EL, an external current is injected into the cell, causing it to emit infrared (IR) light (current generates light emission in the Infrared). Areas with defects or interruptions in current flow show reduced IR emission, making these problems easy to spot.

Alongside EL, SERIS also conducts photoluminescence (PL) analysis. In PL, IR emission is produced by photon absorption under open-circuit conditions, using powerful LEDs to uniformly illuminate the module. Low-emission areas in PL images usually point to intrinsic cell defects rather than issues with current flow.

By applying both EL and PL imaging to the same module, it becomes possible to gain a more comprehensive understanding of the module's quality and to better identify the root causes of power losses.



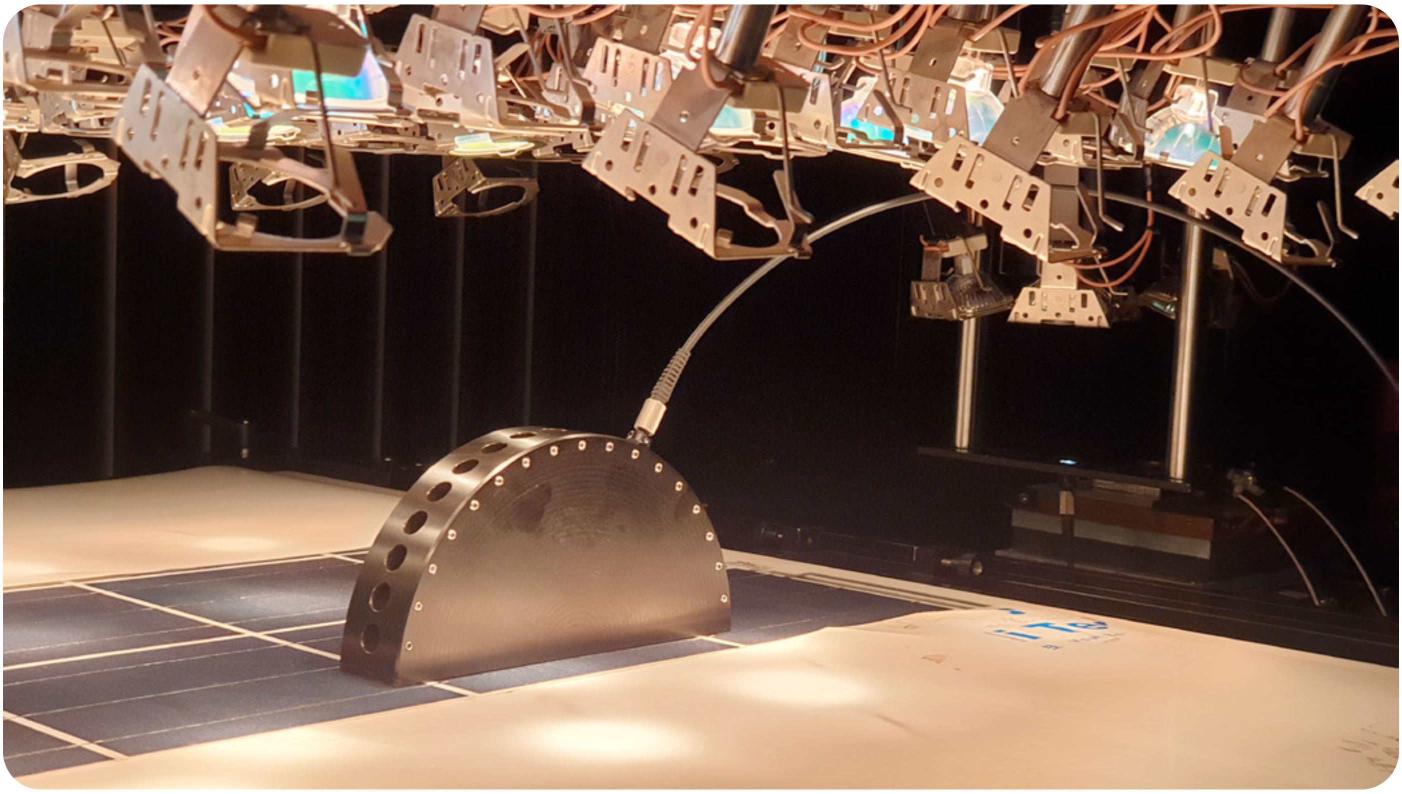
(a) (b) (c)

Comparison between PL and EL imaging of the same tested module: (a) PL; (b) EL at 10% I_{sc} current injection; (c) EL at 100% I_{sc} current injection

Incident Angle Modifier (IAM)

New PV module architectures, with increasing number of busbars, textured surfaces, smart-wire connections, IBC cells and shingling of cells, have raised the interest in the investigation of the angular responsivity of PV modules.

Our laboratory has developed an advanced experimental setup specifically designed to measure IAM in full-size commercial PV modules. This approach enables a detailed analysis of how various module architectures affect angular responsivity. Notably, our measurement method has been included in the draft revision of IEC 61853-2, which is anticipated to be officially adopted in early 2026.



Measurement equipment for IAM measurement at full-size commercial PV module level

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CLIMATE-SPECIFIC ASSESSMENT OF PV MODULE AND SYSTEM PERFORMANCE

Outdoor Module and System Testing Services

As part of the "TruePower Alliance", which was initiated and is driven by SERIS, the institute operates high-precision outdoor testing facilities for PV modules and systems in different climate zones. For energy yield assessments, and eventually investment decisions, knowledge of the actual generated *energy per year* rather than the rated *peak power* under standard test conditions (STC) in the laboratory is much more relevant. However, the actual energy output depends strongly on the geographic location of the system. Therefore, SERIS has implemented outdoor testing facilities on both module and system level in the three most important climate zones: temperate (Germany, China), tropical (Singapore) and desert (Australia). Some of the world's leading PV manufacturers are collaborating with SERIS and are field-testing their modules within the TruePower Alliance.

SERIS applies its self-developed data acquisition system at the TruePower sites. To date, through many years of working with clients and carrying out R&D projects, SERIS has achieved outstanding data acquisition rates of more than 99% per year, proving the robustness and reliability of its equipment.

Before being installed at any of SERIS' Outdoor Module and System Testing facilities, each PV module undergoes power measurement at STC in SERIS' certified PV Module Testing laboratory, pre-conditioning for 5 days (outdoor exposure) for silicon wafer-based technologies (or as per manufacturer's recommendation for the various thin-film technologies), followed by a second power measurement in the laboratory at STC. This procedure not only determines the initial degradation and/or stable power generation, but also leads to a reliable "actual" wattage of the module, which is then used as the "baseline" (rather than the "nominal" name plate value) for any energy yield data that relate to the installed PV capacity.

The various PV module and system data (which are available in time intervals as short as 1 minute) include:

- Module temperature
- DC characteristics: V_{oc}, V_{mpp}, I_{sc}, I_{mpp}, P_{mpp}, I-V Curve
- AC characteristics: voltage, current, active and reactive power, etc.
- Cumulative energy yield (DC and AC side)

In addition, every TruePower site has a state-of-the-art meteorological station, using the following equipment:

- Pyranometer (horizontal and in-plane)
- Silicon sensor (horizontal and in-plane)
- Pyrheliometer
- Spectro-radiometer
- UV radiometer
- Ambient temperature
- Other meteorological sensors (wind speed & direction, humidity, rainfall)

For the case of the Outdoor Module Testing (OMT) facility in Singapore, customers can also select to get access to additional benchmark comparisons of up to six different commercially available PV module technologies (several thin-film technologies and several types of silicon wafer based technologies).

SERIS' Outdoor Module and System Testing facility at Marina Barrage, Singapore (tropical)

SERIS' Outdoor Module and System Testing facility in Alice Springs, Australia (desert)

SERIS' Outdoor Module and System Testing facility in Xinyang, China (temperate)

SERIS' Outdoor Module and System Testing facility in Bernburg, Germany (temperate)

Contact person:
Dr LIN Fen (lin.fen@nus.edu.sg)

PV SYSTEM DESIGN AND EVALUATION

SERIS supports project owners and developers in designing photovoltaic (PV) systems that maximise energy performance while meeting the highest quality and reliability standards, particularly in tropical climates where environmental conditions can be challenging. Leveraging extensive local expertise, SERIS has successfully designed and commissioned PV systems in Singapore that demonstrate exceptional long-term performance—for instance, one of its flagship systems has maintained a performance ratio (PR) of 85–90% consistently since 2011. Our project services encompass the full project lifecycle, starting with conceptual design and energy yield analysis, through detailed engineering and system optimisation, and continuing with construction oversight, testing, and commissioning (T&C). Beyond initial deployment, SERIS provides ongoing support to ensure that PV systems operate as intended, meet predicted energy outputs, and maintain long-term reliability. By combining technical expertise, tropical climate insights, and proven methodologies, SERIS delivers PV systems that not only achieve high efficiency and reliability, but also provide confidence and measurable value to owners, developers, and investors alike.

Typical PV system services offered by SERIS:

Yield estimation	Yield assessment	Optimised system design for high performance
Initial estimation of annual energy yield and performance ratio (PR)*, based on the following criteria: • Location • Module technology • Inverter concept • Tilt angle • Azimuth	Yield assessment of annual energy output and PR*, based on the proposed system design (by client) and various data for the global horizontal irradiation from several sources (by SERIS). This includes shading analysis and quantification of PV system losses	All "Yield assessment" services, plus: • Optimisation of the proposed system design (mechanical, electrical up to medium voltages) for high system performance, based on existing PR as benchmarks
Third-party verification	**Project due diligence**	**Full project partnership**
All "Optimised system design for high performance" services, plus: • Suitability of the key plant components • Detailed review of system design (mechanical, electrical up to medium voltage) and cross-check against current best industry practices Optional: • Review against given guidelines (statement of compliance)	All "third-party verification" services, plus detailed review of: • Track record of suppliers and turn-key providers • Project structure and obligations of project parties • Technical warranties • Project management • Operations and maintenance concept • Project risks and mitigations • Financial modelling • Factory inspections	All "Project due diligence" services, plus: • Site visit prior to project closure • Construction monitoring • Testing & Commissioning (T&C) • Final acceptance • Operations and maintenance reviews • Analytical on-site monitoring with calibrated equipment Optional: • Sample testing of PV modules

The performance ratio, PR, is the ratio of actual AC energy yield of a PV system over the theoretically expected DC energy yield. The latter is based on in-plane irradiance measurements as well as the module's indoor power output measured under standard test conditions (STC).

Top row: SERIS engineers performing third-party verifications during a project.
Bottom row: Rooftop PV installations on a metal roof and installed over water tanks

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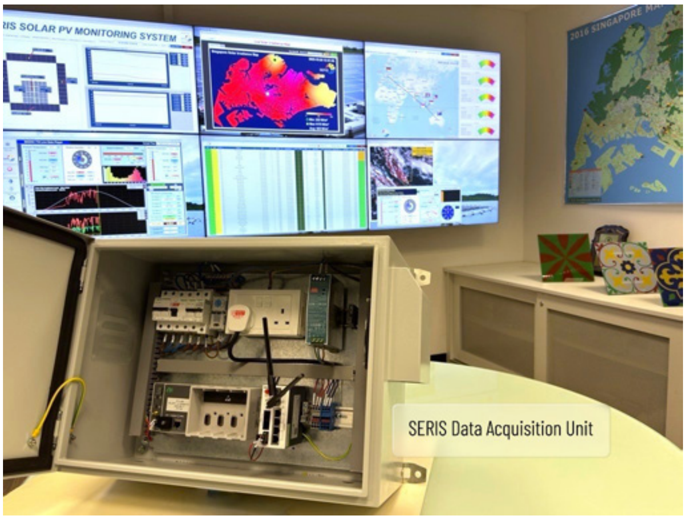
PV SYSTEM PERFORMANCE MONITORING

SERIS provides a cloud-based, real-time analytical monitoring platform for photovoltaic (PV) installations, ranging from small rooftop systems to large ground-mounted and floating PV plants in the multi-megawatt range. Designed for scalability and reliability, our platform supports multiple deployments worldwide and is currently operating across more than 150 systems in Singapore, Australia, Cambodia, Germany, India, Indonesia, Malaysia, the Philippines, and Vietnam.

Built on robust cloud infrastructure, the platform delivers advanced analytics that extend beyond standard monitoring. It continuously captures and analyses detailed performance matrices and error data, applying mathematical models and technical evaluation to identify faults, predict failures, and optimise system efficiency. This intelligent monitoring approach helps to minimise downtime, enhance energy yield, and ensure long-term reliability of assets.



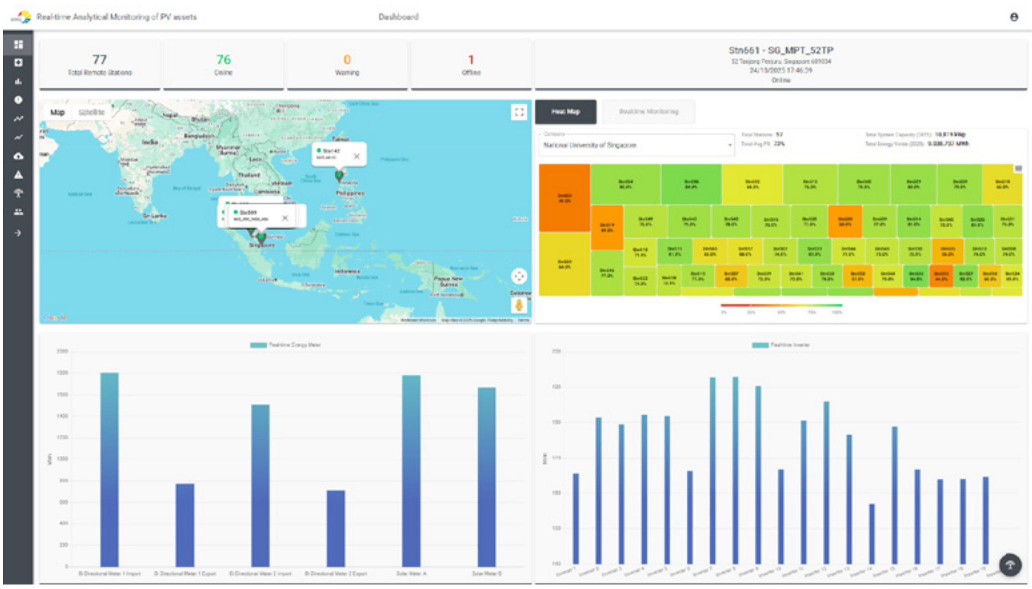
SERIS remote data acquisition station for PV Asset management

Designed for flexibility, SERIS' monitoring solution integrates effortlessly with existing asset management systems, delivering accurate data acquisition, immediate performance validation, and proactive fault detection.

By combining advanced analytics with proven operational expertise, our platform empowers asset owners and operators to maximise energy output, minimise operational costs, and extend the service life of their PV assets, ensuring your investment consistently delivers optimal returns.

- Cloud-based architecture designed for scalability and easy configuration
- Central Data Management – A cloud-based web portal for customers to access the acquired real-time and historical data from PV systems
- 1-minute temporal resolution for various DC and AC parameters, energy generation, inverter performance, and other critical system indicators of a PV system, plus meteorological parameters such as irradiances measured with different devices and inclinations, temperatures (module, ambient), relative humidity and wind speed/ direction
- Energy management and export control, e.g. bidirectional net metering for real-time optimisation of PV generation, load consumption and PV export to the grid
- Evaluation of individual system performance, including regular performance ratio (PR) assessments across the PV fleet
- Advanced algorithms to analyse and detect critical faults and performance anomalies across various components in the system to notify support for targeted troubleshooting
- ± 150 ms time synchronisation with cloud-based time servers
- Automated daily download and data back-up routines with the highest data security standard through a secure virtual private network over 4G/5G connections.
- Submission of live power and irradiance data compliant with requirements from power system operators (PSO), e.g. Singapore's Energy Market Authority (EMA)

Upon a system failure, SERIS engineers and pre-determined client personnel receive a warning (e.g. via SMS), thus enabling a fast reinstatement of the PV system's operation.



SERIS' Real-time PV Assets Management Portal

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ON-SITE PV SYSTEM ASSESSMENTS

On-Site PV System Performance Testing and Commissioning

SERIS provides SAC-SINGLAS-accredited on-site testing and commissioning (T&C) services to ensure that every solar PV system performs as designed. Our services give owners, investors, and regulators the confidence that installations are built to specification, follow best practices, and deliver the energy output they are designed to achieve.

Using ISO/IEC 17025-compliant calibrated equipment, our experts independently verify system quality and performance. Results are normalised to account for real-world conditions such as irradiance and module temperature, and benchmarked against Singapore Standard SS601 and international IEC standards.

Our T&C services include:

- Verification of system installation against design and as-built drawings
- Independent measurement of system power output and efficiency
- String-level and component-level performance checks
- Temperature and irradiance measurements for accurate performance validation
- Accredited reports in compliance with SS601 and IEC 62446

With trusted, internationally recognised reports, SERIS helps ensure PV projects are not only safe and reliable, but also bankable and future-ready.

On-site measurement of PV system performance

On-site inspection / verification of PV system installations

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Thermographic Analysis of PV Systems

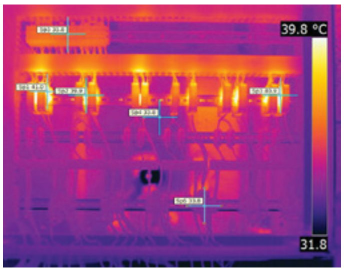
SERIS provides thermographic analysis for photovoltaic (PV) systems at both the system and component levels, allowing early detection of thermal stresses that may indicate underlying issues. Thermal anomalies can compromise system performance or present safety risks, making regular thermographic assessments an essential part of PV system quality assurance.

Our analysis typically focuses on the following areas:

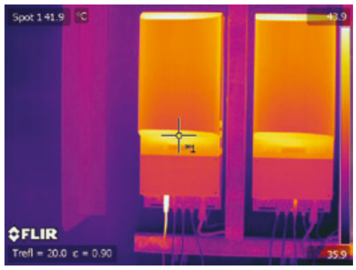
- PV string and module temperature measurements: By monitoring temperature across PV strings and individual modules, we can identify damaged modules, faulty solar cells, or overheating junction boxes, which may reduce energy yield or signal developing failures.
- Component temperature measurements: Elevated temperatures in components can lead to system downtime and pose fire hazards. Thermographic analysis evaluates the operating temperatures of key components, from DC field junction boxes to AC distribution boards, ensuring proper fuse ratings, component selection, and thermal management.
- DC and AC cable temperature monitoring: Hot spots can occur in exposed system elements as well as wiring. Causes include loose connectors, undersized cables, overloaded trays, improper cable routing, or AC cables entering switchgear incorrectly. Detecting these hotspots helps prevent performance losses and mitigate fire risks before they escalate.

Through comprehensive thermographic assessment, SERIS helps PV system owners and operators identify hidden faults, optimise performance, and enhance safety, ensuring reliable and long-term operation of solar assets.

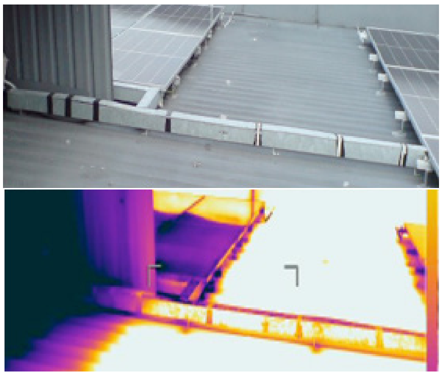
Silicon PV modules in operation, with some solar cells having a significantly increased temperature ("hot spot") due to a bird dropping. Left: Photograph. Right: Thermographic image



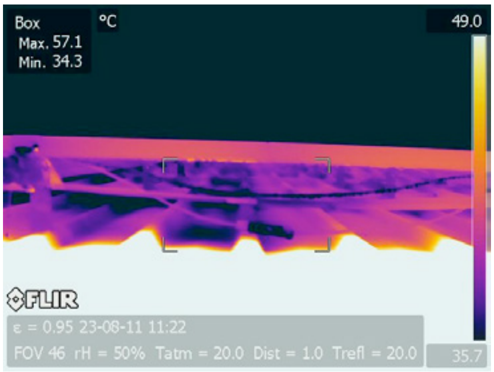
Thermographic image of overheated components in a DC distribution box



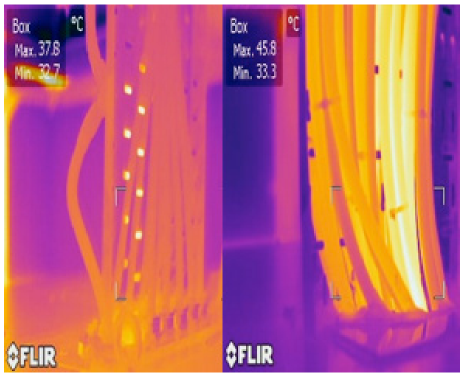
Thermographic analysis showing the overheating of a DC cable and a connector



The main drop-down cable trunking (from the roof to the inverter at ground) is overheating due to packed cable trays (too many cables) in the trunking. Top: Photograph showing how the trunking is bulging. Bottom: Thermographic image



Thermographic investigation demonstrating the overheating of two DC connectors that are in contact with the metal roof



Thermographic picture of AC cables entering the electric switchgear
Left: Thermographic image of cables with proper cable glands and cable routing.
Right: Thermographic image of AC cables entering the switchgear as a bundle, leading to overheating due to improper setup

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SPECIALISED SERVICES

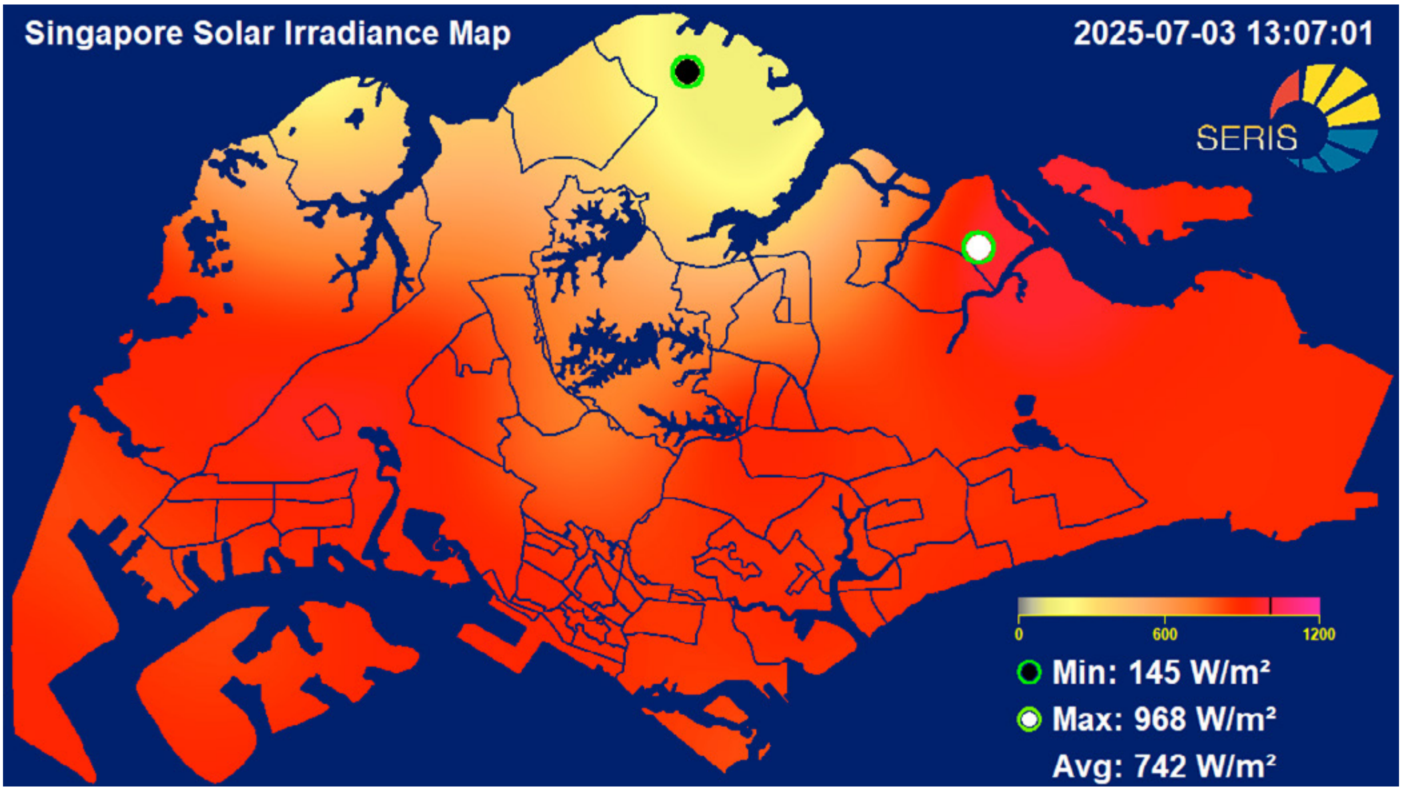
Real-Time Monitoring System of Meteorological Parameters

SERIS operates a network of 25 irradiance stations in Singapore measuring global horizontal irradiance (GHI) across the city-state on a ~5 km x 5 km grid, enabling a live (i.e., real-time) solar irradiance map for Singapore based on actual irradiance measurements. The live irradiance map developed by SERIS can be seen at www.solar-repository.sg/solar-irradiance-map. A screen snapshot is shown below.

10 of these 25 stations are fully equipped meteorological stations, which also measure the following additional parameters:

- Global diffuse horizontal irradiance
- Ambient temperature and relative humidity
- Wind speed and direction
- Air pressure

Features of the real-time monitoring system are 1-second temporal resolution, automated daily downloads, graphical user interfaces, and precise time synchronisation. The system is very flexible and thus can also be applied to other data acquisition needs (e.g. building monitoring systems, BMS).



Snapshot of a typical irradiance distribution in Singapore

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Real-time Sensor & Control System for Agrivoltaics

SERIS has set up two testbeds at the Yuhua Agritech Solar (YAS) Living Lab for the combination of agriculture and PV power generation (also known as "Agrivoltaics"). The objective of this project is to design the Next Generation Solar & Agri-Tech (NGSAT) system which can balance crop yield, energy generation & energy consumption in an urban farming set-up while minimising waste. The system includes special features with various sensors which are the basis for developing a self-learning algorithm that will allow to fully automate future agrivoltaic systems.

For these testbeds, SERIS has designed a unique type of PV module which mimics rotatable louvers to track the sun during the day to maximise solar energy generation but also to manage and possibly harvest rainwater. With this innovation, the traditional meshes used in outdoor farms can likely be replaced by rotatable PV modules which then provide both shading and power generation. Numerous sensors are deployed in the testbed, as described below.

- Meteorological data such as irradiance measured with different devices and at different inclinations, temperatures (module, ambient), relative humidity, and wind speed/direction are collected with 1-minute time resolution. These data are used to evaluate the energy yield of the testbeds, and also as input parameters to the self-learning algorithm which then sends signals to the stepper motor to move the rotatable solar modules in real-time.
- Various DC and AC parameters of the two PV systems are collected from the inverters and the energy meters to evaluate the net energy consumption of the testbeds.
- Geolocation and date-time data are used to calculate the default sun angle at different times of the year during the day, and the developed algorithm uses this information to set the position of the rotatable solar modules to track the sun for maximised solar power generation, unless other signals (e.g. heavy rainfall, insufficient light for the plants) suggest other positions.
- pH level sensors, water temperature sensors, humidity sensors, IEC (integrated electric conductor) sensors, and PAR (photosynthetically active radiation) sensors on the growing area for optimum growth and nutrient control of the plants.
- Proximity sensors at each rotating PV module are deployed to prevent overturning of the gear beyond its start and stop positions. To avoid drifts, the default positions are automatically calibrated every night.

The automated operations and remote monitoring & control are implemented in a cloud-based platform using software designed in LabVIEW. The activities and measurements are displayed in numerical and graphical form in SERIS' PV System Monitoring Lab, providing visualisation of the PV energy generation and plant health in real-time as well as triggering alarms in case of emergencies.

The SERIS Agrivoltaics testbeds have a unique type of PV module which mimics rotatable louvers to track the sun during the day to maximise solar energy generation.

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Glare Analysis of PV Installations

With increasing deployment of solar PV systems, potential glare from the glass surfaces of the PV modules has raised some concerns. Although PV modules are designed to reflect as little sunlight as possible, glare can still occur in some situations. Hazards caused by improperly sited PV modules may include distraction and/or temporary disability (flash blindness). These potential hazards are even more crucial at locations where glare might affect operational safety, such as at airports.

To address these challenges, SERIS has developed an in-house capability to analyse the effects of glare at several observation points using commercially available glare assessment tools. This capability has been developed from a knowledge base that has its origin in SERIS' involvement in government-initiated studies on glare from particular PV installations in Singapore. SERIS has also previously advised both the Building & Construction Authority (BCA) and the Urban Redevelopment Authority (URA) regarding actual glare cases arising from PV installations. In addition, close engagement with the Civil Aviation Authority of Singapore (CAAS) was established concerning solar PV projects at or near Changi and Seletar airports.

SERIS' track record in glint and glare consultations for PV installations:

1. Publications:
   i. Diminishing the glare that obscures, September 2015, PV Tech
   ii. Circular Nr. URA/PB/2017/01-DCG, 24 January 2017, Urban Redevelopment Authority, Singapore

2. Project references for glint and glare analysis involving commercially available glare assessment tools:
   i. Singapore – 149 locations
   ii. Malaysia – 29 locations
   iii. Cambodia – 1 location
   iv. Kingdom of Saudi Arabia – 1 location

With experience gained from glare-related projects under the SolarNova programme, coupled with extensive experience in PV systems, SERIS is able to provide glare analysis and recommend mitigation measures for developers concerned about potentially introducing glare through their PV system installations. This is conducted in close cooperation with various stakeholders (see Table 1), using the framework outlined in Fig. 1.

Table 1: Interactions with stakeholders in a typical glint and glare analysis (Example: Proposed installation near an airport)

** ATCT: Air Traffic Control Tower*

Stakeholder	Engagement
EPC Contractor	Provision of relevant PV layout diagrams
Building Owner	Provision of relevant building plans
Airport operator	Information on the height and number of ATCT(s)*, runway threshold(s) and the inbound flight path(s)
Government Regulator/ Authority	Discuss results from assessment and provide mitigation measures (if needed)

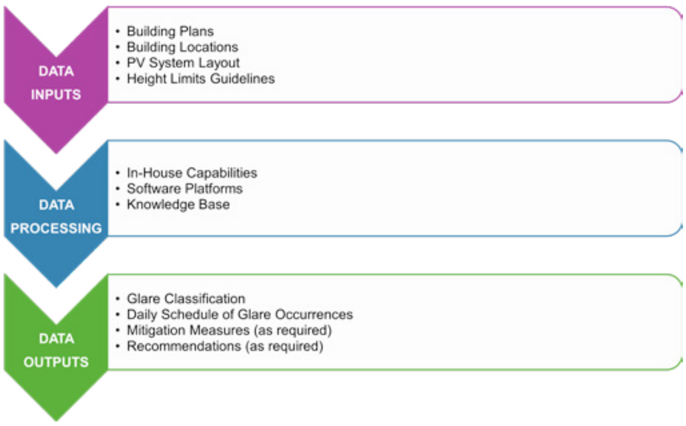

Fig. 1: Glare analysis framework at SERIS. Customised solutions can be designed to suit the needs of individual clients

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A typical setup for a glare analysis project: ATCTs and flight paths considered for glare analysis for a PV installation within Changi Airport, Singapore

TECHNICAL CONSULTING

SERIS offers a wide range of technical consulting services. They are based on the institute's activities in application-oriented research and development, ensuring that state-of-the-art methods and know-how are applied in their provision.

Selected topics for technical consulting include:

- Solar cells
- PV modules
- PV systems
- PV cell and module measurement procedures and measurement uncertainties
- Classification of solar simulators (IEC 60904-9 standard)
- Building-integrated / building-attached PV (BIPV/BAPV)
- Floating Solar
- Agrivoltaics
- Feasibility studies
- Technical due diligences
- Solar potential assessment
- Pre-qualification for government programmes (e.g. Solar Nova)
- Manpower training (PV cells, modules, systems)

OUTREACH ACTIVITIES

CONFERENCES, PUBLIC SEMINARS, WORKSHOPS AND WEBINARS CO-ORGANISED BY SERIS

18th Global Advanced PV Technology Conference, at the SNEC PV+ 18th (2025) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition, Shanghai, China, 10-13 June 2025

SERIS co-organised the 18th Global Advanced PV Technology Conference at the world's largest PV tradeshow in 2025, the SNEC PV+ 18th (2025) International Photovoltaic (PV) Power Generation and Smart Energy Exhibition & Conference in Shanghai, China. The Conference covered a wide scope of PV technologies, ranging from silicon feedstock, PV materials, silicon solar cells, perovskite solar cells, HIT/HJT, TOPCON and BC solar cell technologies, modules, systems and quality assurance to smart grid technologies. The program consisted of plenary sessions and 7 oral sessions, where PV experts from around the world shared the latest research findings with attendees via oral presentations (plenary, invited and regular talks). The speakers included scientists from well-known universities and research institutes from around the world, as well as CTOs and technical experts from world-leading solar companies.

SERIS CEO and Conference Chairman Prof Armin ABERLE welcomed all participants at the Opening Ceremony of SNEC 2025. Photo credit: Asian Photovoltaic Industry Association (APVIA)

Dr Thomas REINDL, Deputy CEO of SERIS, presented an invited talk on "Current status and outlook of Floating Solar" at the SNEC 18th Global Advance PV Technology Conference. Photo credit: Asian Photovoltaic Industry Association (APVIA)

Public Seminar: "30-40% Efficient Solar Technologies based on Perovskites: Dream or Reality?" at the National University of Singapore, 27 March 2025

As part of a scientific exchange with SERIS, a delegation from Helmholtz Centre Berlin (HZB) and Humboldt University Berlin (HUB) visited Singapore in March 2025. SERIS leveraged on the visit and organised a public seminar which gathered selected speakers and panellists from the overseas delegation, SERIS and from the local PV industry. The topics presented and discussed ranged from the need of ultra-high efficient solar technologies for Singapore to the latest advancements in tandem technologies and how to move to mass production. This free public seminar was well received by about 100 attendees from the local PV community, who gained insights from some of the leading researchers and technologists in the field (including "world record holders") about the path towards 30-40% efficient solar technologies.

Dr Thomas REINDL, Deputy CEO of SERIS, welcomed all participants at the Public Seminar held at the National University of Singapore

Prof Armin ABERLE, CEO of SERIS, presented a talk on "Industrial tandem solar cells: Bundling resources in a Corporate Laboratory" at the public seminar.

Public Seminar: "Status and Outlook for Standards for Solar PV" at the Nanyang Technological University @one-north, Singapore, 15 May 2025

Supported by SERIS and NTU-SDO, a public seminar was held where global experts from IEC (International Electrotechnical Commission) and local industry experts shared on the latest developments in solar PV technologies and discussed on key technical standards required to support the implementation and deployment of these systems. The seminar also includes a panel discussion session on the benefits and challenges of developing and adopting solar PV standards. Attendees were from the public and private sectors interested in understanding the status and future outlook of standards for Solar Photovoltaic Systems, including representatives from industry, academia, government agencies, financiers, insurance companies.

About 100 registrants from the local solar PV community attended the public seminar and the networking session sponsored by Sembcorp Industries.

The public seminar was well attended by about 100 registrants from the local solar PV community.

The panel discussion session "How to ensure high-quality PV systems through standards and proper training" was moderated by Dr Thomas REINDL, Deputy CEO of SERIS

Public Seminar: "Practical Innovations in Solar PV Quality Assurance and Asset Management" at the National University of Singapore, 19 Aug 2025

Solar PV systems are "low" maintenance (compared to wind assets that have moving parts), but they are not "no" maintenance, as many assume. For the case of Singapore, they are also deployed much more distributed than centralised solar farms in other regions and often in locations difficult to access. In consequence, in Singapore, the current installed capacity of 1.6 GWp is distributed across 11k (!) individual installations (mostly rooftops).

Co-organised by SERIS and PV Doctor, this public seminar gathered experts from industry and academia to share the latest innovations and developments in solar PV quality assurance and asset management. The roles that digital twins and AI can play and whether robotics will make on-site personnel obsolete over time were also discussed. The program also explore the future of PV quality assurance and asset management with the aim to safe-guard investment and ROI of solar PV systems.

About 120 registrants from the local solar PV community attended the public seminar and the networking session.

Dr André Nobre, Co-Founder & Managing Director of PV Doctor Pte. Ltd., was one of the Plenary speakers at the seminar.

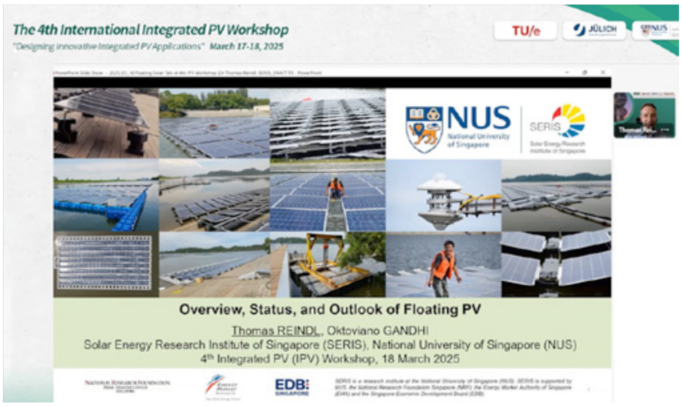
The seminar speakers are all present or former SERIS staff, who are well-respected PV experts in academia and industry.

4th International Integrated-PV Workshop (IPV), 17-18 Mar 2025

The 4th IPV workshop was jointly organised by Eindhoven University of Technology (TU/e), Forschungszentrum Jülich, the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) and Solarbe Global.

Building on the success of previous international IPV Workshops in 2022, 2023 and 2024, the 4th IPV workshop brought together designers, industry leaders, academic researchers, social scientists, architects, and other technical experts to explore the latest trends, research, designs and advancements in IPV technologies. This workshop helped to foster an inspirational environment for interdisciplinary discussions and cutting-edge knowledge exchange.

The 4th IPV workshop was Live broadcast via SolarBe's website and WeChat. The workshop gathered around 2800 individual online attendees over the 2 days, with a maximum of close to 700 concurrent attendees in a single session.



Dr Thomas REINDL, Deputy CEO of SERIS, delivering his online talk on "Overview, Status and Outlook of Floating PV".

SERIS Research Fellow, Dr Tianyi CHEN, gave a talk on the "Research perspective building information modelling (BIM) for building integrated photovoltaics (BIPV)

Webinar: Renewable Energy Futures
Floating Solar PV Potentials in Malaysia and Operators' Experiences, 20 Feb 2025

SERIS co-hosted this free webinar with the Society of Floating Solutions (Singapore). The webinar offered valuable insights into the energy transition toward renewables, water resource management, climate change adaptation, and the expanding role of floating structures as enabler to support these trends. Dr Thomas Reindl, Deputy CEO of SERIS, delivered a keynote talk which examined the region's - particularly Malaysia's - prospects for floating solar PV adoption and its broader implications. The other presentations were from three floating solar PV operators, which highlighted their experiences in energy generation, synergies with other systems, technological advancements, and sustainable development.

The webinar gathered more than 100 attendees from Southeast Asian countries. About half of the participants were solar developers, EPCs and consultants, while the rest from academic institutions, PV manufacturers & related industries.

SERIS' PARTICIPATION AT CONFERENCES & EXHIBITIONS

SIEW Energy Showcase at the 2025 Singapore International Energy Week, Singapore, 27-31 Oct 2025

SERIS is a supporting organisation of SIEW. To celebrate Singapore's 60th year of independence, SERIS manufactured a special "SG60 edition" of the SIEW logo for the SIEW Energy Showcase. Fabricated from solar cells and modules using SERIS-developed building-integrated photovoltaics (BIPV) technology, these prototypes demonstrate how solar panels can be both functional and visually appealing.

Asia Clean Energy Summit (ACES) Conference & Exhibition, Singapore, 28-29 Oct 2025

SERIS set up a 9-sqm booth to showcase a selection of its innovations in PV cells, modules and systems. Visitors had the opportunity to learn about several SERIS projects, such as next-generation photovoltaic technologies, "PV pixel" suitable for BIPV application, and real-time operational solar power forecasts tailored for tropical Singapore and the Asia-Pacific region. Another highlight of the booth were several flexible thin-film perovskite solar panels by SERIS' collaboration partner, Shanghai Geoharbour Group.

SERIS researchers sharing with visitors about the innovative projects on showcase at the SERIS booth at ACES 2025

High-efficiency, flexible thin-film perovskite solar technology at the SERIS booth at ACES 2025. The thin-film modules are like foil and hence ultra-lightweight. This opens fundamentally new possibilities of deployment (e.g., in large over-arching canopies). They can also be made in different levels of transparency for window applications.

Dr Thomas Reindl, Deputy CEO of SERIS, moderating the panel discussion on "Scaling solar to net-zero" at the Solar and Storage track at ACES 2025 (image credit: SEAS)

Dr SUN Huixuan, Research Fellow from SERIS, giving a talk on "3D Glare assessment of solar PV installations in dense urban environments" at the Tech-Talk session at ACES 2025 (image credit: SEAS)

OUTREACH ACTIVITIES TO NON-SCIENTIFIC COMMUNITIES

SERIS regularly engages in outreach activities targeting non-scientific communities and schools to increase the awareness of solar energy research in Singapore. Our researchers conduct talks and organise laboratory tours for students and visitors from Singapore and abroad to demonstrate solar research capabilities at SERIS, and to inform about the progress of solar energy research in Singapore. Below is a collection of photos from selected activities organised by SERIS in 2025. A full list of our outreach activities can be found in the Facts and Figures chapter of this annual report.

Assembly talk at Chua Chu Kang Secondary School, 17 Feb 2025

SERIS researcher Stella Hadiwidjaja was invited by Chua Chu Kang Secondary School Singapore to share with the students on the topic of solar energy research and essential skills required for careers in research, science or engineering at the school's assembly session.
(Photo credit: Chua Chu Kang Secondary School Singapore)

NUS Career Fest 2025, Singapore, 19 Feb 2025

SERIS staff sharing with NUS undergraduates and postgraduates about internship opportunities and sustainability-related careers in SERIS. This annual event was organised by the NUS Centre for Future-ready Graduates.

Visit by SEAS members, 25 Mar 2025

Dr Thomas REINDL, Deputy CEO of SERIS, hosted the visit of SEAS members

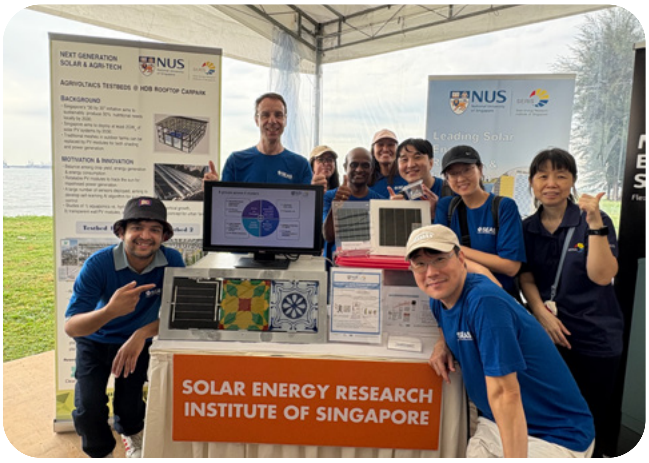
Visits by teachers and students from Bukit Panjang Government High School, 2 & 3 Apr 2025

SERIS researcher Dr WANG Puqun showing the students different solar cell technologies analysed at SERIS' PV Devices Characterisation laboratory

Visit by GAV Biotechnology Group, 30 May 2025

SERIS' Senior Business Development Manager Eddy BLOKKEN hosted a group of overseas students from University of Texas in Austin, TX.

Outreach at SEAS Beach Clean-up event, 23 Aug 2025

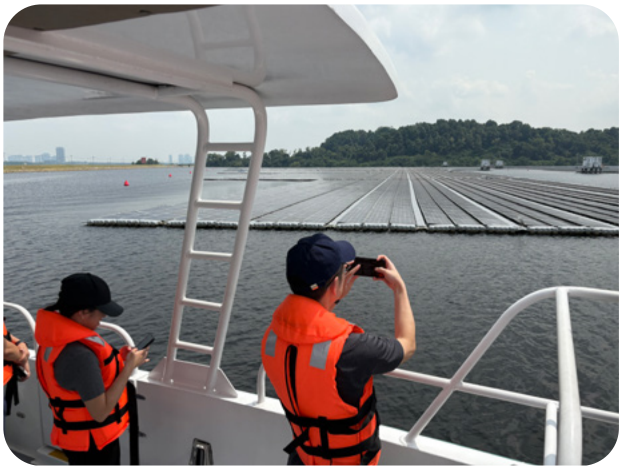


SERIS set up an educational booth at the Beach Clean-up event to promote the awareness that Solar Energy is a promising form of Renewable Energy for Environmental Sustainability. Several key solar R&D projects conducted by SERIS were also displayed at the booth.

SERIS researchers joined the event to collect a total of 114 kg of trash along the coastline. The event organised by the Sustainable Association of Singapore (SEAS) was well attended by 177 dedicated volunteers from SEAS members and the public.

NUS Sustainability CONNECT 2025, Sep 2025

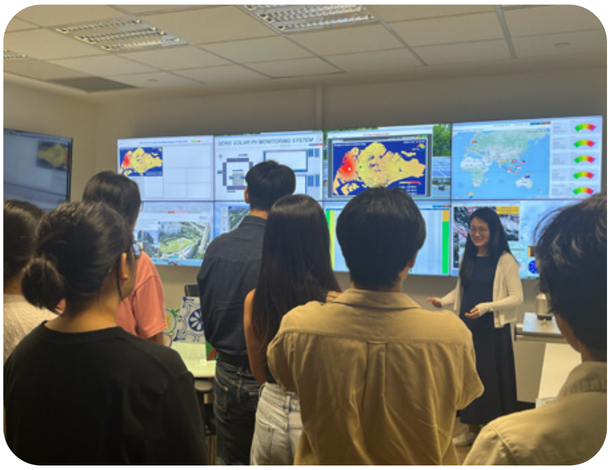
2 Sep 2025: SERIS collaborated with the NUS College of Design and Environment to organise a visit to the PV installation at the rooftop of the NUS-SDE3 building



26 Sep 2025: SERIS collaborated with Sembcorp to organise a visit to the Sembcorp Tengeh Floating PV solar farm

Visit by Student delegation from the NUS Environmental Study Program, 7 Nov 2025

Dr LIN Fen, Deputy Director of SERIS' Solar Energy Systems Cluster, hosted the students and gave a talk on the challenges of PV deployment.



SERIS Research Fellow, Dr Lucia XU, conducted a guided tour of the SERIS PV system monitoring laboratory

FACTS AND FIGURES

AWARDS AND ACHIEVEMENTS

Mar: SERIS' project on 'Advanced Photoluminescence Imaging for Tandem Solar Cells', presented by students Alvin Liu En Yu, Lemuel Tan and Chen Tingyu from Hwa Chong Institution as their project work during their attachment to SERIS, won the Gold Award at the Singapore Science and Engineering Fair 2025. The students were supervised by SERIS' Senior Research Fellow, Dr Biplab Ghosh for this project work. Following this, Hwa Chong Institution has nominated the students to present the project at the Korean Science Academy Science Fair 2025 (see also July).

Mar: SERIS' Deputy CEO Dr Thomas Reindl, receives appreciation certificate from the Standards Development Organisation (SDO) of Enterprise Singapore, in recognition of his invaluable leadership in the development of Technical Standards (TR 117:2024 – Photovoltaic (PV) systems) in Singapore. Dr Reindl is a member of the SDO Working Group on Solar Photovoltaic Energy Systems.

Apr: Assistant Prof Hou Yi wins the CDE Young Researcher Award 2025 and the CDE Design and Technology Innovation Award 2025. This award recognises faculty who have demonstrated excellence in research and is given out annually. The CDE Young Researcher Award is conferred to researchers 40 years old and below, based on their impact and promise in research. The Design and Technology Innovation Award recognises faculty for their outstanding achievements in innovation and research translation.

May: Dr Carlos Clement, Head of Building Integrated Photovoltaics at SERIS, has been awarded a Certificate of Appreciation by the Singapore Civil Defence Force (SCDF) in recognition of his significant contributions to the ongoing revision and enhancement of Singapore's Fire Code, supporting industry readiness. Dr Clement currently serves as a member of the Working Group on Roof-mounted Solar Photovoltaic (PV) Installations.

Jul: SERIS' project on 'Advanced Photoluminescence Imaging for Tandem Solar Cells', by students Alvin Liu En Yu, Lemuel Tan and Chen Tingyu from Hwa Chong Institution (HCI) as their project work during their attachment to SERIS, represented HCI and Singapore in the Korean Science Academy Science Fair (KSASF) held at Busan, Korea, from 1-4 July 2025. They have received the 'Innovative Research' award after a round of poster presentation and oral presentation.

Sep: At the NUS University Award ceremony, Assistant Prof Hou Yi from the Department of Chemical & Biomolecular Engineering and SERIS received the NUS Young Researcher Award for conducting groundbreaking research in the field of renewable energy, particularly in perovskite solar cell technology. He has received global acknowledgement for his work, including his inclusion in the MIT Innovators Under 35 list for the Asia-Pacific region. His recognition as a Clarivate Highly Cited Researcher in the Cross-Field category from 2022 to 2024 further highlights his exceptional impact on his field.

Oct: SERIS researcher Soe Pyae participated and contributed to a group project for the NUS Intermediate AI Competency Course (AICC) course. The project received the Intermediate AICC Project Excellence Award from the NUS Learning & Development Academy.

Nov: The poster entitled "Tandem cells for BIPV: Predicting colour-induced inter- & intra-cell current mismatch for 2-T tandem modules" won a Best Poster Presentation Award at the 36th International Photovoltaic Science and Engineering Conference (PVSEC-36), Thailand, 9-14 Nov 2025. The poster was co-authored by Wilson Moyer, Stella Hadiwidjaja, Priscille Koehl, and Dr Carlos Clement from the Solar Energy Research Institute of Singapore (SERIS, NUS).

MEDIA COVERAGE

22 Jan 2025: Around 10% of the world's inland reservoirs could host 22 TW of floating PV. PV Magazine

22 Jan 2025: Around 10% of the world's inland reservoirs could host 22 TW of floating PV. FinanzNachrichten.de

28 Jan 2025: 22 TW FPV can be hosted on just 10% of world's inland reservoirs: research. TAIYANGNEWS

9 Feb 2025: The world finds 22,000 GW of energy… in water: It's all over the planet. Ecoportal.net

4 Apr 2025: PV module recycling tech based on electrohydraulic shockwave fragmentation. PV Magazine

4 Apr 2025: PV module recycling tech based on electrohydraulic shockwave fragmentation. Energy Hub

4 Apr 2025: PV module recycling tech based on electrohydraulic shockwave fragmentation. FinanzNachrichten.de

4 Apr 2025: PV Doctor launches in Singapore, ushering in new era for solar asset management. SolarQuarter

7 Apr 2025: SERIS launches solar asset management spinoff. PV Magazine

9 Apr 2025: Launch of the "PV Doctor" - the future of solar PV asset performance management. Newswise

9 May 2025: "绿动新加坡"下周五启动 公众可参观平日不开放设施. Zaobao news

9 May 2025: Guided ferry tour of Southern Islands, mushroom cultivation among Go Green SG 2025 activities. The Straits Times

20 May 2025: Quantified Energy secures Series A funding led by Vertex Ventures Southeast Asia & India to accelerate solar inspection technology innovation and global expansion. Vertex Ventures

20 May 2025: Singapore's Quantified Energy secures Series A funding led by Vertex Ventures Southeast Asia & India. TNGlobal

20 May 2025: Singapore's Quantified Energy raises Series A funding led by Vertex Ventures Southeast Asia & India. Starup Rise Asia

21 May 2025: Deals in brief: CrediLinq secures Series A funding, Vertex Ventures backs Quantified Energy, Ringkas raises 5.1 million, and more. KrASIA

21 May 2025: Quantified Energy ends funding round for solar drone tech expansion. Singapore Business Review

3 Jun 2025: Quantified Energy obtained Series A funding from Vertex Ventures Southeast Asia & India. Incubees

12 Jun 2025: 我国加紧推进屋顶安装太阳能板 促进环保和节能减排. Zaobao news

26 Jun 2025: SERIS achieves world record efficiency of 26.7% for perovskite-organic tandem solar cell. PV Magazine

26 Jun 2025: Researchers achieve record-setting perovskite tandem solar cell with novel NIR-harvesting molecule. Tech Xplore

17 Jul 2025: The "PV Doctor" surpasses 0.5 GWp and 1,000 assets under management across 15 countries and 5 continents. PV Magazine

6 Sep 2025: 德光岛拟建93兆峰瓦浮动太阳能系统 预计逾六年完成. Zaobao news

10 Nov 2025: "PV Doctor" – the new Gigawatt player in the PV industry. PV Magazine

18 Nov 2025: Climate science in Singapore focuses on tropical priorities. University World News

5 Dec 2025: Offshore solar could achieve LCOE of less than $0.06/kWh in Thailand, Malaysia. PV Magazine

PRESS RELEASES / JOINT PRESS RELEASES

2 Apr 2025: Launch of the "PV Doctor" - the future of solar PV asset performance management

26 Jun 2025: Boosting solar efficiency: NUS researchers achieve record-setting perovskite tandem solar cell with novel NIR-harvesting molecule (NUS Press Release)

15 July 2025: The "PV Doctor" surpasses 0.5 GWp and 1,000 assets under management across 15 countries and 5 continents

20 Aug 2025: "PV Doctor" appoints esteemed International Advisory Panel (IAP) to enhance strategic guidance, support regional expansion and outreach

6 Nov 2025: "PV Doctor" – the new Gigawatt player in the PV industry

PARTICIPATION IN NATIONAL AND INTERNATIONAL ORGANISATIONS

Editorial Boards of journals

- Progress in Photovoltaics, Wiley, UK (Prof Armin ABERLE, member of the Editorial Board)
- Solar RRL, Wiley-VCH Verlag, Germany (Prof Armin ABERLE, member of the Editorial Board)
- Renewables: Wind, Water and Solar, Springer, Germany (Dr Thomas REINDL, member of the Editorial Board)
- IEEE Journal of Photovoltaics (Asst. Prof HOU Yi, member of the Editorial Board)

Committees

- International Advisory Committee for the Asia-Pacific Forum on Renewable Energy (AFORE 2025) (Dr Thomas REINDL, member)
- Academic Committee of the Asian Photovoltaic Industry Association (APVIA) (Prof Armin ABERLE, Executive Chairman)
- Advisory Committee, National Center for Photovoltaic Research and Education (NCPRE), Indian Institute of Technology (IIT) Bombay (Prof Armin ABERLE, member)
- International Advisory Committee of the Institut Photovoltaique d'Ile-de-France (IPVF) (Prof Armin ABERLE, member)
- International Advisory Committee of the International Photovoltaic Science and Engineering Conference (PVSEC) (Prof Armin ABERLE, member)
- Technology expert for International Technology Roadmap for Photovoltaics (ITRPV) (Prof Armin ABERLE)
- Organising Committee of the SNEC PV+ 18th (2025) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2025), 18th Global Advanced PV Technology Conference (Prof Armin ABERLE, Chairman)
- 3rd Korea-Singapore Joint Photovoltaic Symposium 2025 (Prof Armin ABERLE, Co-organising Chair)
- International Advisory Board of the 6th Edition of the International Conference on Micro/Nanoelectronics Devices, Circuits, and Systems (MNDCS) (Prof Armin ABERLE, member)
- International Scientific Committee of European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2025) (Dr Thomas REINDL, member)
- The Power and Industry Decarbonisation R&D (PID) Steering Committee (SC), Ministry of Trade and Industry Singapore, MTI (Dr Thomas REINDL, Standing Attendee)
- Steering Committee of the 4th Integrated PV (IPV) Workshop (Dr Thomas REINDL, member)
- Executive Committee of the International Energy Agency, Photovoltaic Power Systems Programme (IEA-PVPS), SERIS is PVPS sponsor member, represented by Dr Thomas REINDL and Eddy BLOKKEN as members of the ExCo
- Member of the "2nd External Advisory Panel for Environmental Sustainability" of the Singapore Ministry of Defence (Dr Thomas REINDL, invited member)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 13 (Dr Jaffar Moideen YACOB ALI, Dr Oktoviano GANDHI, attendees)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 15 (Dr Carlos CLEMENT, attendee)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 19 (Rachel TAN, attendee)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/WG 2 and IEC-TC82/WG 6 (Aziz NAIRI, member)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/JWG 11 (Dr Thomas REINDL, member)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/WG 3 and IEC-TC82/WG 6 (Dr Thomas REINDL, member)
- National IEC Mirror Committee TC 1 WG10 ("Solar PV Product & Accessories"), Enterprise Singapore (Aziz NAIRI, co-convenor)
- National IEC Mirror Committee TC 3 WG6 ("Solar PV Systems"), Enterprise Singapore (Dr Thomas REINDL, co-convenor)
- Enterprise Singapore, "Environment and Resources Standards Committee" (ERSC) (Dr Thomas REINDL, invited member)
- Enterprise Singapore, Technical Committee TC3 on "Energy Systems" (Dr Thomas REINDL, invited member)
- Clean Energy Committee of the Sustainable Energy Association of Singapore (Eddy BLOKKEN, member)
- "Roof-mounted solar PV installation working group" working group organised by SCDF, Singapore (Dr Thomas REINDL, Dr Carlos CLEMENT, members)
- APEC Engineer and the International Professional Engineer and Institution of Engineer, Malaysia (IEM) (Rachel TAN, member)
- ASEAN Chartered Professional Engineer (Rachel TAN, member)
- Professional Engineers Board, Singapore (Rachel TAN, member)

SERIS MEMBERSHIPS / PARTNERSHIPS

- Asian Photovoltaic Industry Association (APVIA)
- International Solar Energy Society (ISES) – Silver Institution Membership
- Sustainable Energy Association of Singapore (SEAS)
- Southeast Asia Energy Transition Think-Tank Collaboration Network (SETC)

VISITORS

17 Feb 2025: Visit by President of ProdBank Pte Ltd and by CEO of Beijing Oriental Senter Decoration and Engineering Ltd

24 Feb 2025: Visit by students from NTU Clean Energy Club, Singapore

26 Feb 2025: Visit by staff of ITE College East and German Partner

25 Mar 2025: Visit by SEAS members

2 & 3 Apr 2025: Visit by students from Bukit Panjang Government High School, Singapore

4 Apr: Visit by delegation from the Energy Market Authority of Singapore

28 Apr: Visit by students and teachers from ITE College East, Singapore

7 May: Visit by delegations from the Solar Farm Corporation, Taiwan

27 May: Visit by delegation from Vidacity Singapore

28 May: Visit by students and teachers from Chua Chu Kang Secondary School, Singapore

30 May: Visit by students from GAV Biotechnology Group

9 Jun: Visit by delegation from Jiangsu Government China

3 July: Visit by Professor of Optoelectronic Materials from the University of Twente, Netherlands

3 July: Visit by delegation from 12th International Conference on Industrial Ecology (ISIE2025)

9 July: Visit by lecturers from ITE College East, Singapore

9 July: Visit by high-level delegation from Envcares Eco Impact Network

31 July: Visit by delegation of Chinese Microelectronics students Zhejiang province, China

21 Aug: Visit by delegation from Ngee Ann Polytechnic, Singapore

4 Sep: Visit by Founder and President of Linyang Group, China

17 Oct: Visit by a high-level delegation from the State-owned Assets

Supervision and Administration Commission of Shanxi Province (Shanxi SASAC), China

23 Oct: Visit by delegation from the Institution of Mechanical Engineers Universiti Teknologi PETRONAS Student Chapter (IMechE-UTP-SC), Malaysia

29 Oct: Visit by a high-level delegation from China Three-Gorges Corporation, China

31 Oct: Visit by CEO of Shanghai Geoharbour Group, China

5 Nov: Visit by students from Nanyang Girls High School, Singapore

7 Nov: Visit by students from ENV3206 modules, National University of Singapore

21 Nov: Visit by Director of the Indian Institute of Technology, Delhi, India

CONFERENCES / WORKSHOPS CO-ORGANISED OR SUPPORTED BY SERIS

17-18 Mar 2025: 4th Integrated PV (IPV Workshop), online

10-13 Jun 2025: 18th Global Advanced PV Technology Conference at the SNEC PV+ 18th (2025) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition, Shanghai, China

28-30 Oct 2025: Asia Clean Energy Summit (ACES 2025), Singapore

TEACHING / GUEST LECTURES AT UNIVERSITIES

Prof Armin ABERLE, for Electrical and Computer Engineering Course EE4438 Solar Cells and Modules, AY24/25 Semester 2, National University of Singapore (NUS)

PATENT APPLICATIONS IN 2025

Huixuan SUN, Thomas REINDL, Yu Hong CHIA, Soe PYAE, Ji ZHANG. Advanced 3D glare assessment tool. Non-provisional, Singapore, application number 10202500790P, filing date 26 Mar 2025

Carlos Enrico Cobar CLEMENT, Rupendra ARYAL, Shin Woei LEOW. Interlocking mismatch-resistant architectural tiles for building integrated photovoltaics. Non-provisional, Singapore, application number 10202500801T, filing date 26 Mar 2025

PUBLICATIONS

Journal papers

Wei, Z., Zhou, Q., Niu. X. et al. Surpassing 90% Shockley–Queisser V_{OC} limit in 1.79 eV wide-bandgap perovskite solar cells using bromine-substituted self-assembled monolayers. Energy Environ. Sci., 2025,18, 1847-1855

Padhamnath, P., Nalluri, S., Kuśmierczyk, F. et al. Electrohydraulic fragmentation processing enabling separation and recovery of all components in end-of-life silicon photovoltaic panels. Solar Energy, 2025, 289, 113329

Padhamnath, P., Nalluri, S., Kuśmierczyk, F. et al. Development of PV panel recycling process enabling complete recyclability of end-of-life silicon photovoltaic panels. Solar Energy Materials and Solar Cells, 2025, 286, 113571

Luo, R., Jia, X., Niu, X. et al. Machine learning-driven insights for phase-stable $FA_xCs_{1-x}Pb(I_yBr_{1-y})_3$ perovskites in tandem solar cells. JACS Au, 2025, 5, 4, 1771-1780

Spaans, E., Venkataraj, S., Singh, K. et al. Optical losses in silicon heterojunction solar cells: analysis of record-efficiency devices and practical limits based on ray-tracing simulations. EES Solar, 2025,1, 157-171

Lee, L.K., Li, N., Wang, X. et al. Oxygen-dependent sputtered NiO_x for high-performance perovskite solar cells and minimodules. ACS Materials Letters, 2025, 7(5), 1698-1706

Saw, M.H., Heng, S.L., Leow, S.W. et al. Reliability of floating photovoltaics (FPV): evaluating the effects of hydrodynamic mechanical loads on photovoltaic modules. Japanese Journal of Applied Physics, 2025, 64(4)

Zhao, X., Huang, C., Birgersson, E. et al. Accelerating device characterisation in perovskite solar cells via neural network approach. Applied Energy, 2025, 392(C)

Jia, Z., Guo, X., Yin, X. et al. Efficient near-infrared harvesting in perovskite–organic tandem solar cells. Nature, 2025, 643, 104-110

Wang, YD., Jia, Z., Liu, S. et al. Regulating wide-bandgap perovskite face-on stacking in hybrid-deposited perovskite/organic tandem solar cells. Nat. Commun. 2025, 16, 6142

Luo, C., Zhou, Q., Wang, K. et al. Engineering bonding sites enables uniform and robust self-assembled monolayer for stable perovskite solar cells. Nat. Mater., 2025, 24, 1265-1272

Luo, C., Gu, H., Zhang, B. et al. Perovskite tandems: the next big leap in photovoltaic technology. Advanced Materials, 2025, https://doi.org/10.1002/adma.202508331

Alvianto, E., Wang, Y., Lin, S. et al. Industry-compatible fully laminated perovskite-CIGS tandem solar cells with co-evaporated perovskite. Advanced Materials, 2025, https://doi.org/10.1002/adma.202505571

Dong, Z., Hu, J., Guo, X. et al. Intermediate phase evolution for stable and oriented evaporated wide-bandgap perovskite solar cells. Nat. Mater. (2025), https://doi.org/10.1038/s41563-025-02375-8

Rodríguez-Gallegos, C.D., Gandhi, O., Sun, H. et al. Global assessment of offshore floating photovoltaics: technical potential, cost-competitiveness, and deployment pathway. Energy Environ. Sci., 2025, Advance Article, https://doi.org/10.1039/D5EE04460J

Li, N., Niu, X., Dong, Z. et al. Optimal perovskite vapor partitioning on textured silicon for high-stability tandem solar cells. Science 390, eadz3698 (2025). DOI: 10.1126/science.adz3698

Conference papers / proceedings

Padhamnath, P., Arcebal, J. D. D., Dasgupta, S., De Luna, G., Rohatgi, A., & Aberle, A. G. (2025). Investigation of contact properties and device performance for bifacial double-side textured silicon solar cells with polysilicon based passivating contacts. SiliconPV Conference Proceedings, 2. https://doi.org/10.52825/siliconpv.v2i.1295

Padhamnath, P., De Luna, G., Zhong, R., Arcebal, J. D., Rohatgi, A., & Aberle, A. G. (2025). Investigation of the Impact of the Wafer Resistivities on double-side passivated contact silicon solar cells. SiliconPV Conference Proceedings, 2. https://doi.org/10.52825/siliconpv.v2i.1271

Xu, X., Nobre, A.M., Han Cao, H., Xu, Y., Peters, I.M., Reindl, T. Detailed analysis of degradation rates of operating PV assets in tropical climate conditions. Proceedings of the 42nd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Spain, 22-26 Sep 2025

Bourgeois, A., Hadiwidjaja, S., Nicot-Senneville, Z., Ye, J., Choi, K.B., Zhou, Q., Hou, Y. Elucidating the process of accurate spectral calibration for tandem I-V measurement using multi-lamp light sources. Proceedings of the 42nd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Spain, 22-26 Sep 2025

Yagli, G.M. Development and validation of image-to-irradiance conversion implemented on Himawari-9 satellite images. Proceedings of the 36th International Photovoltaic Science and Engineering Conf (PVSEC-36), 9-14 Nov 2025, Thailand (in press)

Technical papers

Rodriguez, C., Gandhi, O., Sun, H.X. Global floating PV potential in inland reservoirs: a comparison of different technologies. PV Tech Power vol. 42, Apr 2025

Selj, J., Wieland, S., Tsanakas, I. (2025). Selj, J., Jahn, U., Maugeri, G. (Eds.), Floating Photovoltaic Power Plants: A Review of Energy Yield, Reliability, and Maintenance (Report No. T13-31:2025). IEA PVPS Task 13.

Friesen, G., Micheli, L. (2025). Friesen, G., Micheli, L., Jahn, U. (Eds.), Optimisation of Photovoltaic Power Systems for Different Climates (Report No. T13-32:2025). IEA PVPS Task 13. https://doi.org/10.69766/QSYC8858

TALKS AT CONFERENCES, WORKSHOPS AND SEMINARS

(Speaker's name underlined)

Reindl, T. Floating solar and its potential for powering remote islands. IEEE iDEAS 2025, Indonesia, 06-09 Jan 2025 (invited keynote)

Hou, Y. Unlocking the potential of perovskite solar cells: from single-junction to tandem. Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics (IPEROP25), Japan, 20-21 Jan 2025 (invited)

Chen, J., Hou, Y. Elucidating and resolving the bonding-degradation trade-off at heterointerfaces for increased efficiency and durability of perovskite solar cells. Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics (IPEROP25), Japan, 20-21 Jan 2025

Dong, Z., Guo, X., Hou, Y. Thermostable perovskite solar cells enabling operational lifetime over 25 years. Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics (IPEROP25), Japan, 20-21 Jan 2025

Guo, X., Jia, Z., Dong, Z., Hou, Y. Suppressing halide phase segregation in wide-bandgap perovskite for perovskite-organic tandem solar cells. Asia-Pacific International Conference on Perovskite, Organic Photovoltaics and Optoelectronics (IPEROP25), Japan, 20-21 Jan 2025

Hadiwidjaja, S. SERIS presentation at Total Defence Day 2025. Chua Chu Kang Secondary School, Singapore, 17 Feb 2025 (invited)

Chen, T. Research perspective BIM for BIPV. 4th International Integrated PV Workshop, 17-18 Mar 2025 (virtual, invited)

Reindl, T. Overview, status and outlook of floating PV. 4th International Integrated PV Workshop, 17-18 Mar 2025 (virtual, invited)

Reindl, T. Welcome address. NUS Public Seminar - 30-40% Efficient Solar Technologies based on Perovskites: Dream or Reality? Singapore, 27 Mar 2025 (Host, moderator for panel discussion)

Hou, Y. The path towards tandem and triple-junction perovskite solar cells. NUS Public Seminar - 30-40% Efficient Solar Technologies based on Perovskites: Dream or Reality? Singapore, 27 Mar 2025 (invited)

Aberle, A. Industrial tandem solar cells: Bundling resources in a Corporate Laboratory. NUS Public Seminar - 30-40% Efficient Solar Technologies based on Perovskites: Dream or Reality? Singapore, 27 Mar 2025 (invited)

Lin, F., Liu, T., Reindl, T. Agrivoltaics in Singapore and beyond: unlocking potential in ASEAN. ADB Emerging Areas Knowledge Sharing Series: Sun-Powered Futures, webinar, 27 Mar 2025 (virtual)

Lin, F., Reindl, T. Harnessing urban solar power: innovations and challenges in PV technology. Practical insights into solar photovoltaic safety for the built environment, webinar, 27 Mar 2025 (virtual)

Hou, Y. Can efficiency, stability and commercial viability be combined in perovskite-based tandem solar cells? MRS 2025 Spring, USA, 7-11 Apr 2025

Wei, Z., Zhou, Q., Niu, X., Aberle, A.G., Yin, X., Hou, Y. Surpassing 90% Shockley-Queisser V_{oc} Limit in 1.79 eV wide-bandgap perovskite solar cells using bromine-substituted self-assembled monolayers. MRS 2025 Spring, USA, 7-11 Apr 2025

Zhou, Q., Hou, Y. Rationalising perovskite crystal growth on industrial Cz silicon wafers for efficient tandem solar cells. MRS 2025 Spring, USA, 7-11 Apr 2025

Reindl, T., PV market overview & technology update. Intersolar Europe, Germany, 6-9 May 2025 (invited)

Lin, F., Gandhi, O., Sun, H.X., Reindl, T. An overview of floating PV Potential in Indonesia & Southeast Asia. SFSS - SERIS Joint Webinar: Floating Solar PV Systems in Indonesia, Webinar, 15 May 2025 (invited)

Aberle, A. Progress with perovskite-silicon tandem solar cells at SERIS. SNEC PV+ 18th Global Advanced PV Technology Conference, China, 10-13 Jun 2025 (plenary)

Reindl, T. Floating solar: current status and outlook. SNEC PV+ 18th Global Advanced PV Technology Conference, China, 10-13 Jun 2025 (invited)

Hadiwidjaja, S., Dahiya, V., Sharma, R., Ghosh, B., Kyaw, Z.W., Soe, P., Aung, M.K., Khup, D., Nalluri, S., Ye, J., Aberle, A. Long-term outdoor performance of large-area perovskite-silicon 2-terminal tandem mini-modules in a tropical climate. SNEC PV+ 18th Global Advanced PV Technology Conference, China, 10-13 Jun 2025

Wang, P., Hadiwidjaja, S., Ungur, E., Choi, K.B., Aberle, A. Fast lifetime imaging for perovskite solar cells using modulated optical excitation. SNEC PV+ 18th Global Advanced PV Technology Conference, China, 10-13 Jun 2025

Pyae, S. How PV monitoring powered by cRIO and LabVIEW is critical for seamless integration and effective management of PV performance assets. NI Days Singapore 2025, Singapore, 25 Jun 2025 (keynote)

Pyae, S. SERIS' real-time PV performance assets management portal. NI Days Singapore 2025, Singapore, 25 Jun 2025

Pyae, S. Beyond Solar PV: SERIS' asset management platform. Public Seminar: Practical Innovations in Solar PV Quality Assurance and Asset Management, Singapore, 19 Aug 2025 (invited)

Xu, X. PV asset performance in tropical climates: analysing degradation trends, generation output, and soiling impacts. Public Seminar: Practical Innovations in Solar PV Quality Assurance and Asset Management, Singapore, 19 Aug 2025 (invited)

Lin, F., Gandhi, O., Sun, H.X., Vinayagam, L., Reindl, T. From niche to necessity: The rise of floating solar in Asia and beyond. 3rd Korea-Singapore Joint PV Symposium, South Korea, 1-3 Sep 2025 (invited, plenary)

Clement, C. BIPV innovations: the next frontier for mega-cities. 3rd Korea-Singapore Joint PV Symposium, South Korea, 1-3 Sep 2025 (invited)

Kim, RT. Progress with perovskite-silicon tandem solar cells at SERIS. 3rd Korea-Singapore Joint PV Symposium, South Korea, 1-3 Sep 2025 (invited)

Xu, X., Nobre, A.M., Cao, H., Xu, Y., Peters, I.M, Reindl, T. Detailed analysis of degradation rates of operating PV assets in tropical climate conditions. 42nd European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Spain, 22-26 Sep 2025

Reindl, T. Roundtable discussion - Always on: Storage solutions as a pathway to 24/7 clean energy. Reuters Events: Energy Asia 2025, Singapore, 13 Oct 2025 (invited)

Reindl, T. Panel discussion: Scaling solar for net-zero: Pioneering Asia's energy transition with renewable leadership. Solar and Storage Track at the Asia Clean Energy Summit 2025, Singapore, 29 Oct 2025 (invited, moderator)

Sun, H.X., Pyae, S., Reindl, T. 3D glare assessment of solar PV installations in dense urban environments. TechTalk at the Asia Clean Energy Summit 2025, Singapore, 29 Oct 2025

Choi, K.B., Wang, P. Path to high-efficiency solar cell devices: Perspectives from simulation and characterisation aspects in a PV research institute. 2025 MI Green Power Innovation Conference, China, 29-31 Oct 2025 (invited)

Sharma, R., Aberle, A. Cell to module transition for 2T perovskite-silicon tandems. Transatlantic Alliance of Excellence for PV Innovation (TEAM PV), Germany, 3-6 Nov 2025 (invited)

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