ANNUAL REPORT 2024

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

Table of **Contents**

Feedback from **Key Stakeholders**

National University of Singapore (NUS)

Through ground-breaking research and innovation in solar technology, SERIS continues to accelerate the world's transition to a net-zero energy future. From the development of double- and triple-junction perovskite/silicon tandem solar cells to leading floating solar research, SERIS is redefining solar technology with a commitment to shape a sustainable, renewable and cleaner future for generations to come.

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

National Research Foundation Singapore (NRF)

SERIS has made significant strides in advancing solar energy technologies, particularly through their achievements in developing perovskite and perovskite-silicon tandem solar cells with world-class efficiencies. Its work in solar forecasting, tailored to tropical climates, highlights its contributions to leading-edge solar research and development while innovations in high-efficiency building-integrated photovoltaics and floating solar PV systems enhance Singapore's solar capacity and support the Singapore Green Plan 2030. SERIS is also forging strong regional innovation partnerships to support the growth of renewable energy in Southeast Asia and collectively contribute to a net zero future.

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 plays a vital role in advancing solar energy in Singapore, making significant contributions to the development of sustainable, renewable energy. Their dedication to improving photovoltaic efficiency, promoting urban solar deployment and leading local solar research efforts over the past 16 years reflects their commitment to building a greener future for Singapore.

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 has been a key partner in supporting Singapore's ambition to become a renewable services hub for Asia. As a strong advocate for solar innovation, SERIS conducts advanced research across the solar value chain, particularly in perovskite-silicon tandem technology. SERIS has successfully commercialised its research resulting in the launch of several startups in the solar industry, with the PV DOCTOR being the latest addition. We also congratulate SERIS on the co-founding of the Indonesia Solar Energy Research Centre (ISEREC) with the Indonesian Engineers Association, PII. ISEREC will offer R&D, training, and consultancy services and support the Green Corridor initiative between Singapore and Indonesia.

Mr LIM Wey-Len, Executive Vice President, Singapore Economic Development Board (EDB) and member of the SERIS Supervisory Board

CEO's **Foreword**

The global energy transition is progressing rapidly. As announced by the Global Solar Council (GSC), it took 68 years to reach 1 terrawatt-peak (TW_p) of installed solar photovoltaic (PV) capacity in 2022, whereas only two years were needed to add the next 1 TW_p by 2024. The GSC also stated that an additional 4 TW_p of PV will likely be deployed by 2030. Solar energy is largely unconstrained by resource availability and raw materials, and has very low environmental and social impacts. Solar PV is particularly well suited for the tropical sunbelt, which is blessed with an abundant solar resource year-round that shows only small seasonal variability. SERIS expects that PV will be the leading renewable energy source in Southeast Asia by 2040, as its generation costs (LCOE) and rate of growth far undercut all alternatives. The abundance of low-cost PV electricity will also contribute towards decarbonising the "electrification of almost everything" (transport, heating/cooling, industry), paving the way for a net-zero Southeast Asia (and other regions) by 2050.

Singapore is taking important steps in this direction, and SERIS expects that the City-state will eventually rely largely on solar electricity generated within its own territory and imported solar power via electric cables from neighbouring countries. In the first half of 2024, the total installed PV capacity passed 1.3 gigawatt-peak (GW_p), and the nation is well on track to reach its 2030 PV target of at least 2 GW_p. SERIS is also supporting Singapore's plans to import GW-scale solar electricity from Indonesia as part of the "Green Corridor" project. In 2024, SERIS - in collaboration with PII Indonesia (the equivalent to the Institute of Engineers and the Professional Engineers Board) - launched the "Indonesia Solar Energy Research Centre" (ISEREC) to build up training and R&D capabilities for these multi-billion-dollar investments.

SERIS' mission is to develop and commercialise solar technologies suited for urban and tropical applications, and support industry development and solar adoption in the energy transition. A major challenge for PV deployment in Southeast Asia is the land scarcity, and in particular so in Singapore. SERIS addresses this by researching technologies that allow multiple use of spaces, for example Building-integrated PV (BIPV), Floating solar, Agrivoltaics (dual use of PV and crop growing) and solar canopies (PV systems over-arching existing infrastructures such as car parks or flood canals). At the same time, the space limitation also means that the installed PV panels should have very high efficiencies of 23% or more, to maximise solar energy production per m^2 and year. Such high-performance panels are now commercially available, for example from our Singapore-based industry collaboration partner REC Solar. SERIS also works on innovative technologies for integration of the intermittent solar generation into electric power systems and their techno-economic assessments (i.e., levelised cost of integration, LCOI). Making solar inverters an active part of the grid (e.g. using fault ride through capabilities), hybrid energy storage systems (e.g. using batteries and pumped hydro), and solar forecasting are examples for suitable technologies to manage variable solar PV generation, as they address a variety of possible grid impacts and can be used on different time scales (from minutes to days/ weeks ahead).

SERIS is presently in its fourth funding cycle, which runs for 5 years (FY22 - FY26) and provides core funding for 3 flagship projects (Perovskite on silicon tandem solar cells, BIPV modules & systems, Floating PV systems) and the development & testing of several "Urban Solar" deployment options.

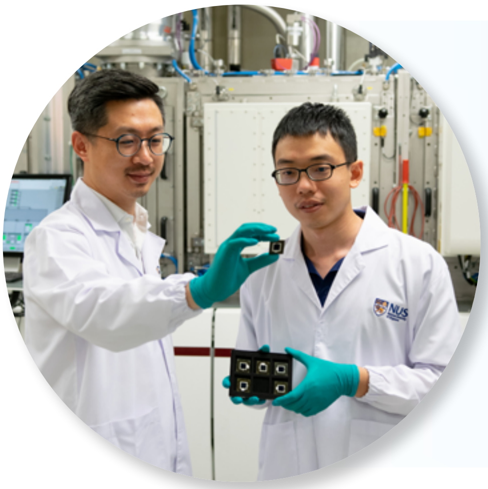
Notable SERIS achievements in 2024 include 33.2% efficiency for a dual-junction perovskite-silicon tandem solar cell (area 1 cm^2), 29.1% for a triple-junction perovskite-perovskite-silicon cell (1 cm^2), 25.5% for a single-junction perovskite cell on glass (1 cm^2), and efficiencies of 25% and 20% for perovskite-silicon tandem cells with active areas of 16 and 244 cm^2. These results make SERIS one of the top-3 labs in the world for perovskite-silicon tandem solar cells, for both small and large-area (full wafer) tandems. We also converted these tandem cells into glass-glass mini-modules, achieving 1-cell mini-module efficiencies of 30% and 16.2% for active module areas of 1 and 244 cm^2. Good progress was also made in 2024 with the REC@NUS Corporate Laboratory project that targets 30% efficient very large-area (440 cm^2) perovskite-silicon tandem cells. SERIS has also started to showcase its aesthetic solar PV modules (known as the "Peranakan" modules) in other design and form factors. The "Singapore flag made of solar panels" was part of the National Day Parade celebrations, while the SIEW and ACES logos were shown as PV modules during the Singapore International Energy Week 2024. SERIS also developed an innovative and disruptive floating solar technology (iFloat Solar), which won a Sustainability Open Innovation Challenge award. Our latest spin-off, the PV DOCTOR™, an asset performance management and smart O&M company, was launched during the Asia Clean Energy Summit in October. Within less than 6 months, it signed up more than 3% of Singapore's installed PV capacity as new clients. In February 2024, SERIS' leading-edge solar forecasting system went live at Singapore's Power System Operations Centre and is supplying real-time forecasting data for grid operations and market settlement.

I would like to thank all SERIS staff, adjunct researchers and students for their hard work and achievements throughout the year. SERIS sincerely thanks all its supporters and industry partners and over the past 12 months, especially the National University of Singapore (NUS), the National Research Foundation Singapore (NRF), the Energy Market Authority of Singapore (EMA), the Singapore Economic Development Board (EDB), our Supervisory Board, our International Advisory Panel, and other collaborators in the public and private sectors.

Although humanity's carbon emissions are still rising, there is hope that the clean energy transition will soon reverse this dangerous global trend and pave the way for a net-zero energy future for all. The prospects are bright - let the Sun shine and do its magic!

Prof Armin ABERLE
SERIS CEO, 12 Dec 2024

Highlights **2024**



March

New triple-junction tandem solar cell with world-record efficiency

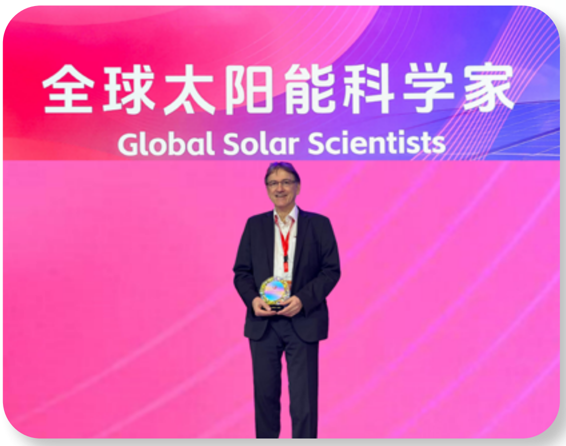
A novel triple-junction perovskite-Si tandem solar cell with a certified world-record power conversion efficiency of 27.1% across a solar energy absorption area of 1 cm^2, representing the best-performing triple-junction perovskite-Si tandem solar cell thus far, was reported in the Nature journal.

This solar cell was fabricated using cutting-edge technologies and equipment at the Solar Energy Research Institute of Singapore (SERIS) in NUS. This ground-breaking invention by a team of scientists from NUS and SERIS, led by Assistant Professor Hou Yi, sets a new course for the further development of perovskite-based triple-junction solar cells, which has a potential theoretical efficiency exceeding 50%.

April

SERIS' Agrivoltaics project at the Yuhua Agritech Solar (YAS) Living Lab was featured in The World IP Day 2024 co-organised by the Intellectual Property Office of Singapore (IPOS) and the Ministry of Sustainability and Environment (MSE)

The World IP Day is a global celebration that recognises the role of IP in encouraging innovation and creativity. The theme this year focused on the relationship between IP and the Sustainable Development Goals. As part of this celebration, a media outreach was organised at Singapore's YAS Living Lab (located on an HDB rooftop carpark), an innovation hub that fosters innovation and experimentation in solar PV and soil-less Agritech in an urban farming concept. Two of the testbeds set up by SERIS, in collaboration with V-plus Agritech and Arianetech, were featured. Both testbeds have rotatable PV modules to track the Sun to maximise crop yield. There is also an aquaponic system that circulates nutrients from fish waste to the growing towers of crops. Read more about SERIS' Agrivoltaics project in the R&D chapter of this SERIS Annual Report.



June

Prof Armin Aberle honoured with a Global Solar Scientist Award by the Global Solar Council and the Asian Photovoltaic Industry Association at the SNEC PV 17th (2024) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition in Shanghai, China

Prof Armin Aberle, CEO of SERIS, was recognised as one of the Global Solar Scientists who have made outstanding contributions to the development of the photovoltaic industry over the past 2-3 decades. In his 38-year career in 3 continents (Europe, Australia, Asia), Prof Aberle has been a prolific researcher, educator, mentor and leader in the global solar PV community. His research covers the full spectrum from fundamental materials and device research to the industrial evaluation of novel PV technologies at the pilot line level and their transfer to industry. He supervised more than 60 PhD students to successful completion of their degrees. He published more than 500 scientific-technical papers which have received more than 19,000 citations (h-index 65).

Highlights **2024**

July

iFloat Solar Pte Ltd, a newly proposed start-up company and partner of SERIS, received an award at the Singapore Open Innovation Challenge (SOIC) 2023 organised by Enterprise Singapore

Dr Thomas Reindl won the award in the category Floating Solar at the SOIC 2023 Award Ceremony for the innovative floating PV module and system deployment approach which has the potential to revolutionise the way how floating PV systems are designed and implemented in the future. The Sustainability Open Innovation Challenge 2023 saw almost 400 entries from 80 countries to address 21 challenge statements and an open category.

NUS-SERIS signs a Memorandum of Understanding (MoU) with Pandit Deendayal Energy University (PDEU) to execute Research and Academic Collaborations in the Renewable Energy Sector

SERIS CEO Prof Armin Aberle (right) and the Director General of PDEU Dr S. Sundar Manoharan (left) agreed on mutual collaborations and to leverage on the expertise and skill sets of both organisations to execute the projects at PDEU and NUS-SERIS.

August

SERIS and REC Solar created a Singapore flag made of solar panels to celebrate Singapore's National Day 2024

This Special Edition of the Singapore Flag was made with 396 half-cut bifacial monocrystalline heterojunction solar cells (provided by REC Solar) using gap-less technology, the same advanced cell technology as in REC's award-winning Alpha panels. SERIS' patented glass colouring technology was applied to the glass lamination on top of the solar cells to produce the seamless appearance of the Singapore Flag. The flag-developed, designed and produced in Singapore-demonstrates the sheer endless opportunities for Building-integrated photovoltaics (BIPV) in Singapore as part of the SG Green Plan 2030.

The special edition flag was displayed at the National Day Parade (NDP) "Heartland Exhibition" at Bishan on 10 August 2024.

Highlights **2024**

October

Official launch of the Indonesia Solar Energy Research Centre (ISEREC)

SERIS and PII (the Institution of Engineers Indonesia), officially launched the Indonesia Solar Energy Research Centre (ISEREC) on 2 October 2024. ISEREC aims to establish world-class research and development activities on solar photovoltaic (PV) technologies in Indonesia, involving local and international institutions, companies and other non-governmental organisations. A brief report on the official launch of ISEREC can be found on page 8 of this Annual Report.

Commissioning of NUS Campus-wide solar PV systems

Image credit: ENGIE South East Asia

NUS has made a significant leap towards a sustainable future with the commissioning of a campus-wide solar photovoltaic (PV) installation project, with 9.2 MW_p of solar panels on over 60 buildings across NUS' Kent Ridge Campus and University Town. SERIS was involved in designing and deploying the monitoring solution for the entire Campus project, providing real-time monitoring with analytical solutions for PV asset management, and submission of live power and irradiance data compliant with the requirements from the power system operator (PSO).

SERIS showcases the versatility of Building-integrated photovoltaics (BIPV) technology at SIEW 2024 and ACES 2024

Image credit: Courtesy of Energy Market Authority of Singapore

NUS-SERIS presented the special edition of the SIEW logo (left) and the ACES logo (right) - made of solar cells and modules at the Singapore International Energy Week (SIEW) and the Asia Clean Energy Summit (ACES). SERIS showcased its innovations in solar energy research to Deputy Prime Minister and Minister for Trade and Industry, Mr Gan Kim Yong (middle in left photo) at SIEW and to Senior Minister of State, Ministry of Culture, Community and Youth & Ministry of Trade and Industry, Ms Low Yen Ling, and to Mr Chua Shun Loong, Assistant Chief Executive, Energy Market Authority of Singapore (left in right photo) at ACES.

ISEREC signs a Memorandum of Understanding (MoU) with the Sustainable Energy Association of Singapore (SEAS)

Establishing training programmes to build up a skilled workforce for the solar value chain in Indonesia is a crucial element and one of objectives of ISEREC. For that, ISEREC and SEAS have agreed to collaborate and cooperate in the areas of capacity building and "train the trainer" programmes for solar PV, in conjunction with the Singapore Institute of Technical Education (ITE). SERIS Deputy CEO, Dr Thomas Reindl, Co-CEO of ISEREC, signed an MOU with SEAS at the Asia Carbon Summit (ACS) Launch Ceremony, which was graced by Guest-of-Honour, Dr Amy Khor, Senior Minister of State, Ministry of Sustainability and the Environment, Ministry of Transport.

Image credit: SEAS

Official Launch of the **Indonesia Solar Energy Research Centre (ISEREC)**

The Solar Energy Research Institute of Singapore (SERIS) and Persatuan Insinyur Indonesia (PII), the Indonesian Institution of Engineers and Professional Engineers Board, officially launched the Indonesia Solar Energy Research Centre (ISEREC) on 2 October 2024 in Jakarta at the Auditorium of the Ministry of Public Works, Republic of Indonesia. The research centre is a collaboration to establish world-class research and development on solar photovoltaic (PV) technologies in Indonesia, involving local and international institutions, companies and other non-governmental organisations. Based in Jakarta, Indonesia, ISEREC is jointly led by two Co-CEOs – Prof Michael Goutama, Director International Affairs of PII, and Dr Thomas Reindl, Deputy CEO of SERIS, NUS.

ISEREC will play an important role in accelerating the development of solar energy in Indonesia, and also help to strengthen the country's position as a leader in renewable energy technology & innovation. The centre aims to be a driving force for the future of sustainable energy in Indonesia and in the world.

The key objectives of ISEREC include:

(1) **Education:** Support PhD and post-doctoral programs in solar technology through student exchanges and joint professional development programs. This should foster the collaboration with leading global universities and research institutes.
(2) **Research & Development:** Develop and implement research programmes and projects that are targeted to enable the large-scale adoption of solar PV and associated technologies (e.g. energy storage systems, ESS) in Indonesia.
(3) **Technology:** Build competencies in PV technology to support the establishment of a local PV supply chain industry "from sand to systems" and establish highest quality standards.
(4) **Training:** Establish training programmes to build up a skilled workforce required for the PV supply chain, from manufacturing to engineering, system design & deployment, and operation & maintenance (O&M).
(5) **Consulting:** Support companies in the development and application of PV technologies in Indonesia.

Contact person: Dr Thomas REINDL (thomas.reindl@nus.edu.sg)

The official launch of ISEREC was held in conjunction with the First International Conference on "Building of Large Green Corridors" in Jakarta, Indonesia, on 2 October 2024.

ISEREC Co-CEO Prof Michael Goutama, delivering a speech at the official launch ceremony of ISEREC in Jakarta, Indonesia. (Image credit: SEAS)

The launch ceremony was graced by several VVIPs including the Minister of Public Works of the Republic of Indonesia, H.E. Ir. Mochamad Basuki Hadimoeljono, the Deputy Minister Coordinating Ministry for Economic Affairs of the Republic of Indonesia, Dr. Ali Murtopo Simbolon, the President of PII, Dr. Danis Hidayat Sumadilaga and the Chairman of the Sustainable Energy Association of Singapore (SEAS), Er. Edwin Khew. (Image credit: SEAS)

SERIS key numbers in **CY 2024**

(as of 30 Nov 2024, unless otherwise stated)

PEOPLE

118
Staff, Adjuncts & Students

68
With university degrees

RESEARCH HIGHLIGHTS

33.2% efficiency for dual-junction perovskite-silicon tandem solar cell (area 1 cm^2)

29.1% efficiency for triple-junction perovskite-perovskite-silicon tandem solar cell (area 1 cm^2)

25.5% efficiency for single-junction perovskite solar cell on glass (area 1 cm^2)

INDUSTRY INCOME

~SGD
2 Million
(FY 2024, projected)

PV PROJECTS

>20 locations (glare analysis) in Singapore assessed

~2.0 GW_p feasibility studies / consultancies conducted on floating solar thus far

~100 MW_p PV systems monitored across 300+ sites in 8 countries in Asia

PUBLICATIONS

18
Journal & 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 to IEC 60904-2.*

SCIENTIFIC OUTREACH

>30 talks & posters presentations at conferences, symposium, workshops & webinars

~4 seminars hosted at SERIS

LINK WITH ACADEMIA, INDUSTRY, GOVERNMENT BODIES

~30 memberships in technical and/or advisory committees

VISITS

Hosted
>20
visits from schools and companies

of which
>10
VIP visits

MEDIA REPORTS*

>20 on TV news, radio, newspaper & trade magazine

>30 on social media platform

** that mentions SERIS*

Industry **Feedback**

INSEAD Executive Education

It was a privilege to visit the Solar Energy Research Institute of Singapore (SERIS) and to learn about the pioneering work being done there. I was captivated and gained valuable insights into solar energy advancements and SERIS' role in addressing climate change.

The innovative approaches and sustainability initiatives at SERIS are not only contributing to the energy sector but also inspiring a broader commitment to green solutions and climate resilience.

We were particularly impressed by the practical applications of your research and the strategic direction. The visit highlighted the importance of embracing change and innovation, fostering a deeper appreciation for the impact of renewable energy technologies.

We are excited about the potential for future collaboration and furthering our shared goals in sustainable development.

Prof Gabriel SZULANSKI
INSEAD Programme Director

mapletree logistics

We are pleased to commend the remarkable collaboration between Mapletree Logistics Trust and Solar Energy Research Institute of Singapore (SERIS) on their recent photovoltaic (PV) monitoring and installation initiative. This partnership exemplifies an outstanding commitment to reducing carbon emissions and promoting sustainable green initiatives. The project involved the strategic installation and monitoring of PV systems across several logistics facilities within Asia, significantly enhancing our energy efficiency.

We have observed a substantial reduction in traditional energy consumption, which contributes to our sustainability goals and helps mitigate our carbon footprint. The expertise and innovation demonstrated by SERIS in their cutting-edge PV monitoring solution have been pivotal in ensuring optimal energy harnessing from our solar installations. Meanwhile, Mapletree Logistics Trust's excellence in execution and facilities management has ensured seamless integration with our existing infrastructure, maximising the benefits of this green initiative.

Overall, this collaboration not only advances our commitment to environmental responsibility, but also sets a benchmark for future sustainable projects within the industry. We look forward to seeing continued progress in this vibrant partnership and the positive impact it will have on the environment.

Mr SOH Wee Cheng
Senior Manager
Mapletree Investments Pte Ltd - MLT

DEFENCE COLLECTIVE SINGAPORE

Singapore Discovery Centre by DEFENCE COLLECTIVE SINGAPORE

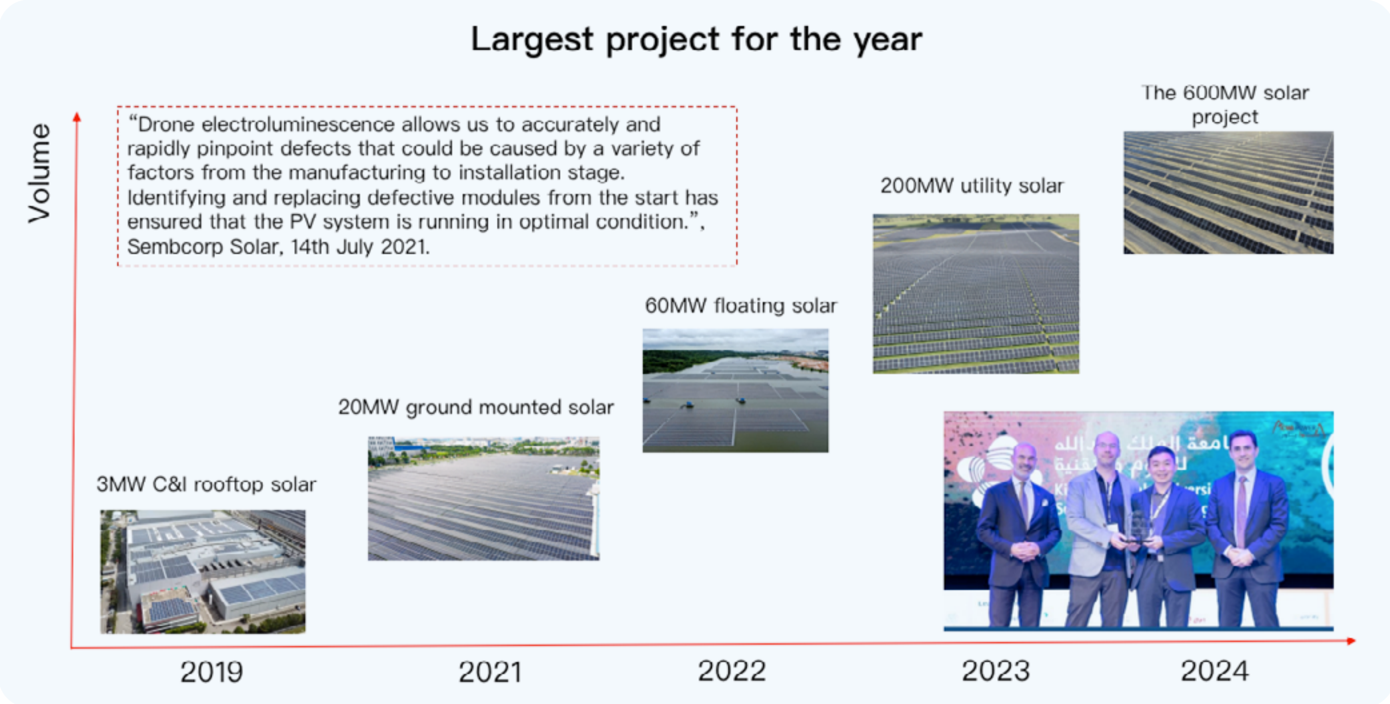
The Singapore Discovery Centre (SDC), part of Defence Collective Singapore, is proud to partner with SERIS to advance our renewable energy initiatives. With an installed solar PV capacity of 1.56 MW_p, SERIS' expertise in PV testing, commissioning, and optimisation through the PV Doctor service has been instrumental in enhancing the yield and efficiency of our solar assets.

This collaboration has enabled SDC to achieve key milestones, including becoming Singapore's first positive energy museum, while also engaging the public in sustainability awareness through initiatives like the Sustainability Festival. We extend our heartfelt appreciation to SERIS for their expertise and dedication, which supports our alignment with the Singapore Green Plan 2030 and drives innovation in environmental stewardship.

Mr LIM Chin Seang
Director Infrastructure and Sustainability
Defence Collective Singapore

SERIS Spin-Offs – **Status & Progress**

Quantified Energy Labs Pte Ltd (QE-Labs)



QE-Labs' innovative solutions are gaining significant traction

Quantified Energy Labs (QE-Labs) is a SERIS/NUS spin-off established in 2021 by researchers from the PV Modules Cluster. The company is dedicated to ensuring the sustainable growth of the global solar industry. QE-Labs achieves this goal through:

- Advanced AI and computer vision to diagnose PV system health issues
- Autonomous UAVs and robotics to enhance field operation productivity
- Digital solutions that empower users to navigate solar investment risks

Key Innovations and Contributions

QE-Labs is at the forefront of re-defining solar PV inspections with its ground-breaking autonomous drone electroluminescence (EL) mapping solution. This technology provides lab-quality inspections of PV modules directly in the field without moving them from their installed position, ensuring early and accurate detection of defects. EL is the "gold standard" for quality control in PV factories, and its application in the field ensures long-term reliability and optimal performance of PV modules and systems. To expand accessibility, during the Intersolar exhibition in Munich, Germany in June 2024, QE-Labs has released a new-generation EL camera compatible with the widely used DJI M300 drone. By applying this powerful inspection method across all stages of the PV lifecycle, QE-Labs provides detailed insights that maintain system integrity, reduce energy losses, and support informed decision-making.

Our Growth and Achievements

As a problem-oriented data-driven deep-tech start-up, QE-Labs focuses on growth and innovation within the global solar PV industry. With headquarters in Singapore, an operational center in Malaysia, and subsidiaries in key markets such as China and the EU (Germany), QE-Labs sustains a strong global presence to support its clients worldwide. In 2024 QE-Labs successfully completed the largest solar inspection project to date, reaching a massive 600 MW_{dc} - 200 times the annual record set by us in 2019.

Awards and Recognition

QE-Labs' innovation has been recognised globally. In 2024, the company has won the ACWA Power Innovation Challenge in Saudi Arabia and received an award for Excellence in Innovation from EDPR APAC.

For further information please contact:
Dr Yan WANG, CEO and Co-founder of QE-Labs,
yan.wang@qe-labs.com

SERIS Spin-Offs – **Status & Progress**

The PV DOCTOR™

We listen, we analyse, we cure

The PV DOCTOR™ provides an advanced and comprehensive range of asset management services for photovoltaic (PV) system owners across Asia. The company had its "soft launch" in October 2024 and now provides services directly to industry customers. In just nine months, the team has on-boarded close to 100 MW_p of PV assets across more than 300 sites in 8 countries (Singapore, Southeast Asia and India).

PV DOCTOR™ is an Asset Performance Management (APM) company which aims to commercialise the know-how and services developed in the "Smart O&M" Group at SERIS. It also leverages the vast experiences with PV systems (design, implementation, operation, trouble-shooting, maintenance) which SERIS has gathered over the past 15 years in Singapore and the region.

The importance of monitoring of solar PV systems on a daily basis (and ideally in real time) cannot be overstated, given the number of PV assets that are underperforming in the world (a global assessment by a consulting company estimates annual losses of USD 4.6 billion worldwide). Poorly operating PV systems can also pose safety and/or fire risks, which must be mitigated.

The analogies with the medical world are striking (therefore the company name) and the graphic below provides an overview of the comprehensive "medical" services of the PV DOCTOR™.

Generally, the PV DOCTOR™ has identified three types of PV assets, depending on their level of monitoring:

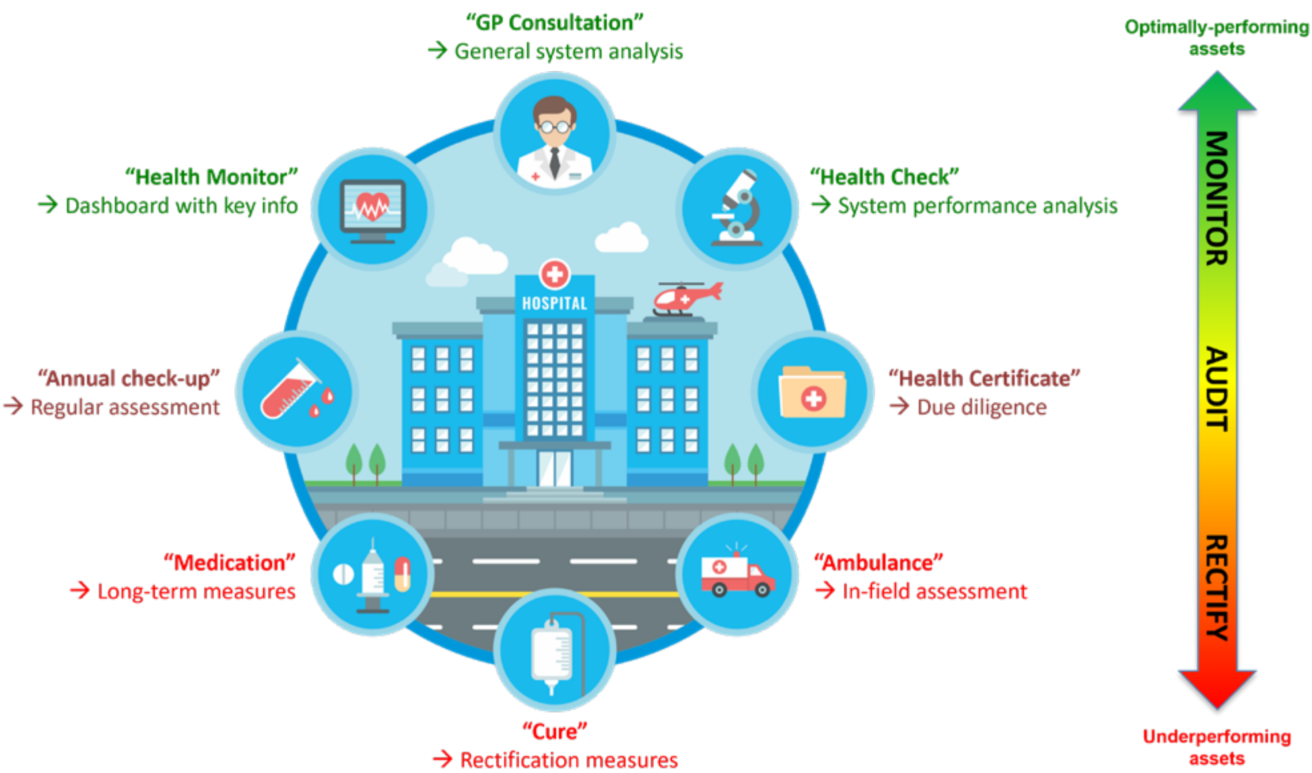
i. "Abandoned" systems:
PV installations with no or little monitoring, sometimes even without any maintenance routines (which even poses safety and potentially fire risks).

ii. Partially monitored systems:
Systems are checked for performance, however very infrequently (e.g. monthly or quarterly). This leads to non-optimum performance, as power trips or faults would only be detected with delays of weeks or even months.

iii. Fully monitored systems:
Typically belonging to professional developers or investors. In these cases the PV DOCTOR™ is typically engaged for daily performance assessments, for which the in-house teams nor the maintenance contractors are not trained. Also, clients with "perfect" monitoring systems often require expert assistance to "make sense" out of the vast amount of data. This also to identify key learnings for future better optimised PV system designs.

The PV DOCTOR™ team is ready to serve the needs of its clients.

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



Overview of the services offered by the PV DOCTOR™ spin-off for the asset management of PV systems. Image source: SD Global Tech.

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 huge demand for renewable energy generation and carbon emission reductions, especially in the building industry.

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.

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

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).

Fig. 2: Coloured BIPV modules that mimic building materials, seamlessly integrating into the built environment

Power Facade has been awarded the EMA-Shell Partnership Start-up Grant by the Energy Market Authority (EMA) to deliver solutions that will promote and improve the clean energy sector in Singapore. This grant will support fine-tuning of its products in 2025. SERIS is a collaborator of Power Facade in this grant.

For further information please contact:
Power Facade Pte. Ltd.
Dr ZHANG Qianning, CEO and Co-founder
(qianning.zhang@powerfacade.net)
Dr CHEN Tianyi, Co-founder
(tianyi.chen@powerfacade.net)

INSTITUTE IN BRIEF

Introduction

Founded in 2008, the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) is the City-state's national institute for applied solar energy research and a global leader in solar research and development. 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 contributes actively to Singapore's and the region's need for solar adoption and industry development, and also supports the government's pledge to reduce the nation's carbon emissions. Since November 2022 the institute hosts the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics. This 5-year project aims to develop and commercialise disruptive PV technologies based on perovskite-silicon tandem solar cells. In October 2024, as an expansion of its activities, SERIS - in collaboration with PII (the Institution of Engineers Indonesia) - officially launched the Indonesia Solar Energy Research Centre (ISEREC). ISEREC aims to establish world-class research and development on PV technologies in Indonesia, involving local and international institutions, companies and other non-governmental organisations. ISEREC also supports the Green Corridor project that aims to export solar electricity from Indonesia to Singapore.

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 (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), grid-tied solar PV system measurement (for insulation resistance test voltages up to 1000 V) and SERIS' Solar Cell Measurement Laboratory 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 also a sponsor member of the IEA PVPS programme and is actively involved in 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 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)

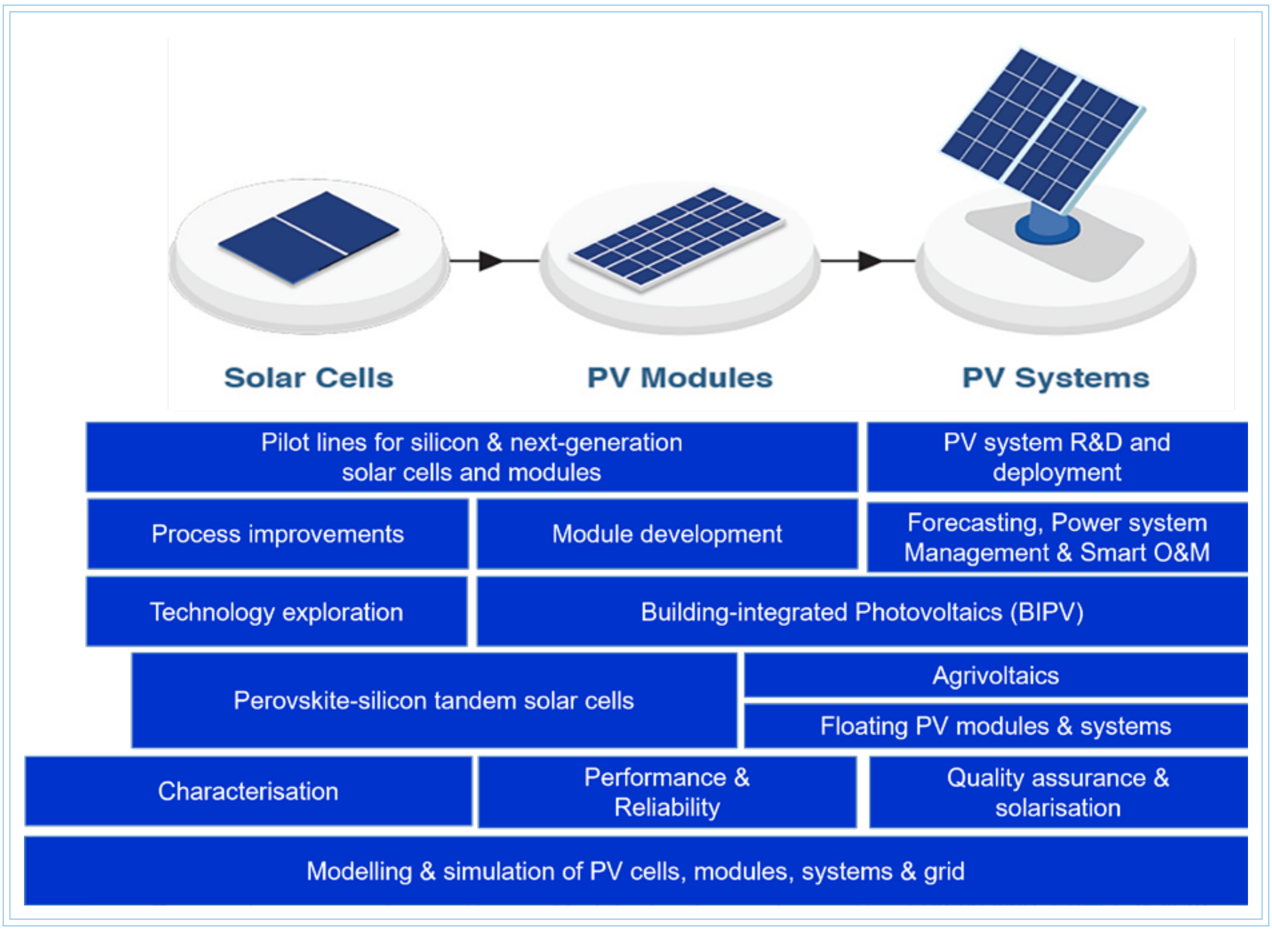
Collectively, these four research clusters operate and support SERIS' three main business areas:

- Solar cells
- PV modules
- PV systems

In each business area, SERIS generates innovations for the solar industry ecosystem and the public sector. The institute's application-oriented research and development is 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 also globally.

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 thin-film solar cells
- Perovskite-silicon tandem solar cells



SERIS' three main business areas and associated R&D activities

Finances

For Financial Year (FY) 2024, 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 14.7 million. The core funding is complemented by grants from public competitive R&D programmes and funds from industry contracts of approximately SGD 9.6 million and SGD 2.0 million, respectively. These are projected amounts, as FY 2024 will end on 31 March 2025. The breakdown of the projected SERIS funding of SGD 26.3 million for FY 2024 is displayed in Fig. 1.

Figure 2 shows the breakdown of the projected SERIS expenses of SGD 28.1 million in FY 2024: SGD 9.7 million for manpower, SGD 8.7 million for equipment, SGD 7.6 million for operating expenses, and SGD 2.1 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 10 financial years is shown in Fig. 3.

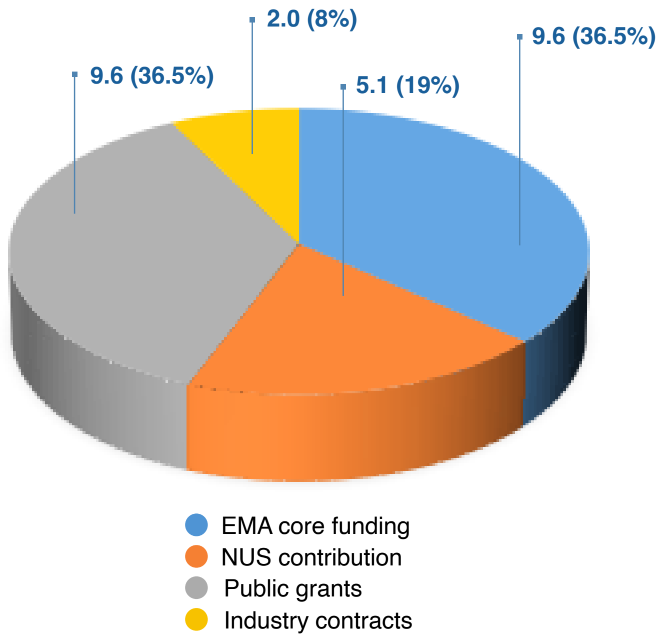


Fig. 1: Projected SERIS funding for FY 2024 (1 Apr 2024 to 31 Mar 2025, in SGD million)

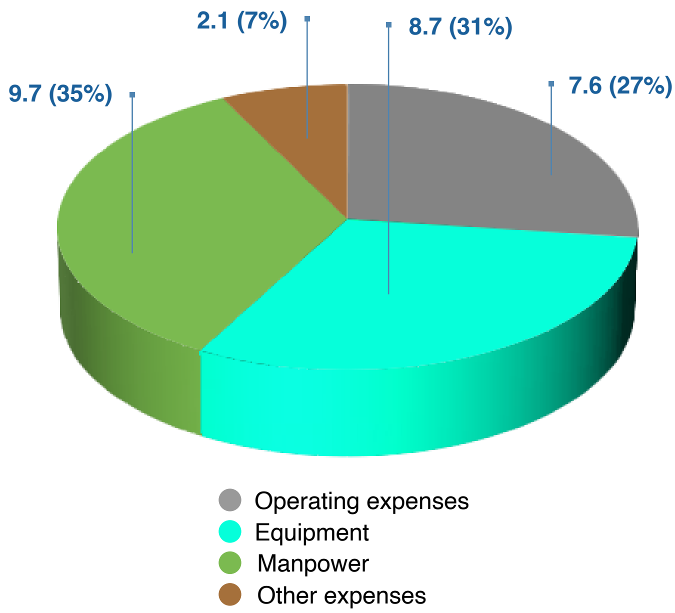


Fig. 2: Projected expenses for FY 2024 (1 Apr 2024 to 31 Mar 2025, in SGD million)

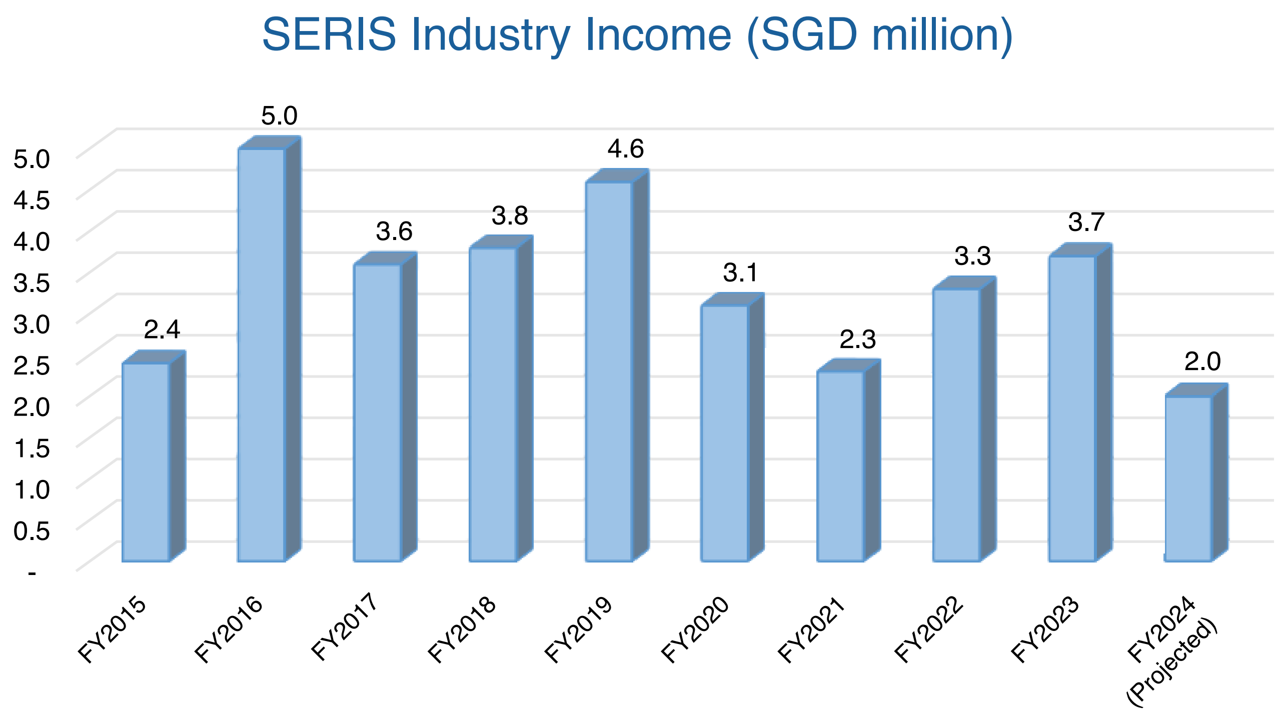
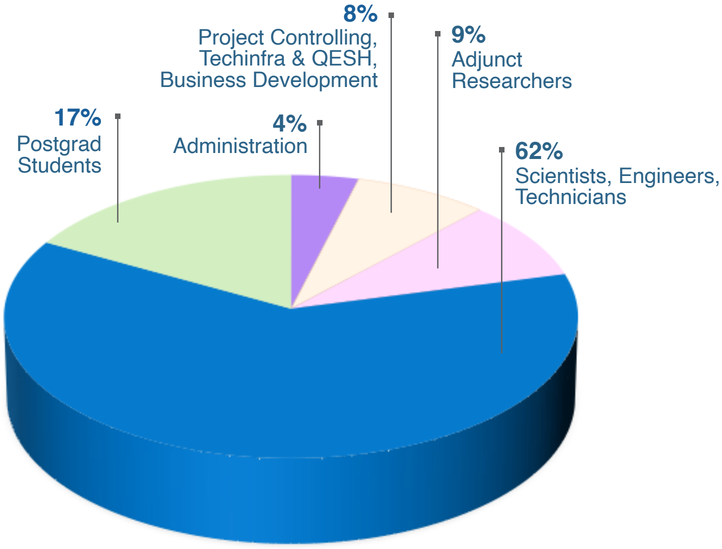


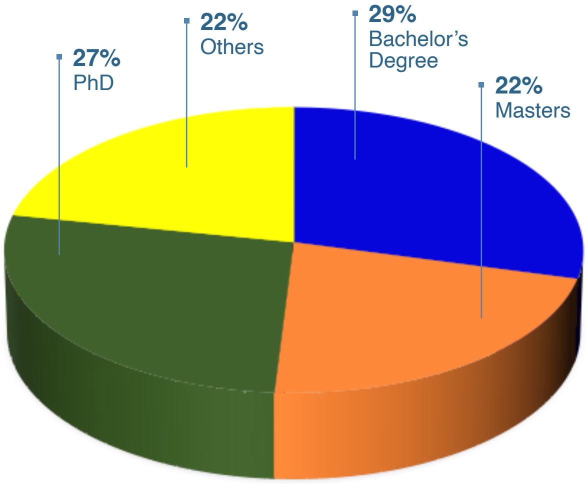
Fig. 3: Evolution of SERIS' annual industry income since FY 2015 (in SGD million)

Headcount

At the end of calendar year 2024 the SERIS headcount was 118, 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 88% 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 4% of the headcount.



Breakdown of SERIS headcount in December 2024



Highest education qualification of SERIS staff

Laboratory, Office and Rooftop Space

SERIS occupies approximately 5160 m^2 of space in the E3A building on the main NUS campus, including offices, laboratories and laboratory support facilities. SERIS also rents about 1415 m^2 of laboratory and office space at its off-campus location at CleanTech Park where the PV Module Development and Testing laboratories reside. In addition, SERIS utilises about 3330 m^2 of rooftop space at NUS and CleanTech Park for experimental outdoor solar installations.

SERIS' rooftop facilities at CleanTech Park

PV System Monitoring laboratory at SERIS, NUS

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
Member of President's Council of Advisors (PCAST), USA
Former Director of the National Renewable Energy Laboratory (NREL), USA
Former Chancellor of New Mexico State University (NMSU), USA

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

Mr Steve O'NEIL
President, REC Americas
Board Director, Endurans Solar
Executive Advisor, Nel Hydrogen and Solestial, USA

Mr Frank PHUAN
Vice-Chairman, Sustainable Energy Association of Singapore (SEAS)
Business CEO
EDP Renewables APAC

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

Prof Eicke WEBER
Prof emeritus, University of California, Berkeley, USA
Former Director, Fraunhofer ISE, Freiburg, Germany
Vice-Chair, European Solar Manufacturing Council (ESMC), Germany

SERIS Supervisory Board

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.

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 of The Institution of Engineers, Singapore

Dr KOH Shuwen
Director, Technology Transfer and Innovation, NUS Enterprise
National University of Singapore (NUS)
Deputy Group Chief Technology Officer and Director of Innovation
National University Health System (NUHS)

Mr LIM Wey-Len
Executive Vice President
Singapore Economic Development Board (EDB)

Mr LOW Xin Wei
Assistant Chief Executive
Energy Market Authority of Singapore

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

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

ORGANISATION STRUCTURE

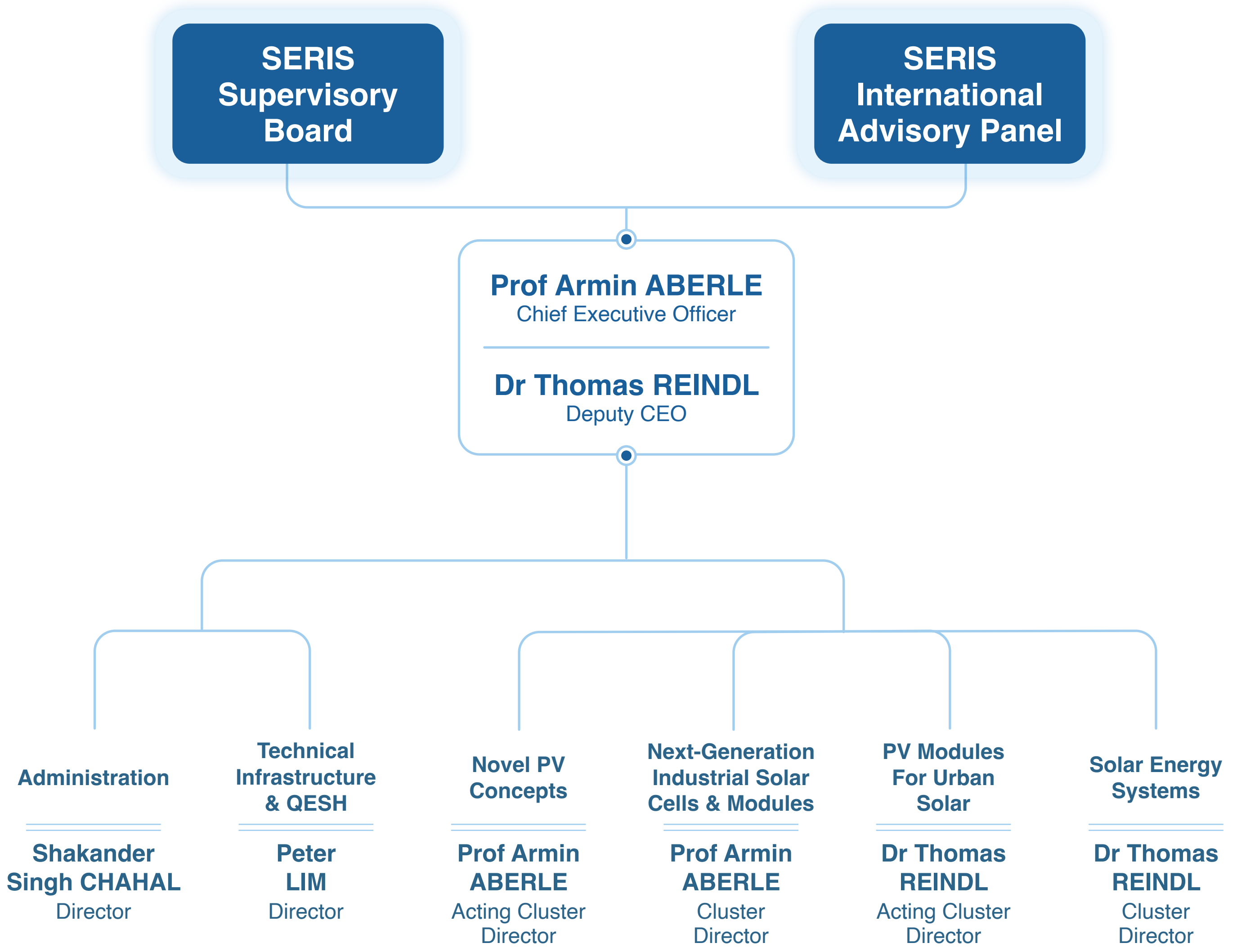
Organisational **Chart**

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 & QESH (Quality, Environment, Safety and Health)

Management Team

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

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

Dr Donny LAI
Senior Research Fellow
Perovskite-based Multijunction Solar Cells Group
NPVC Cluster
(until Nov 2024)

Dr Selvaraj VENKATARAJ
Laboratory Manager
Corporate Laboratory Group
NISCM Cluster
s.venkataraj@nus.edu.sg

Dr Yong Ryun KIM
Senior Research Fellow
Corporate Laboratory Group
NISCM Cluster
yrk08@nus.edu.sg

Dr Jinhyun KIM
Senior Research Fellow
Advanced Solar Cells Group
NISCM Cluster
j.kim@nus.edu.sg
(since Mar 2024)

Dr Krishna SINGH
Research Fellow
Corporate Laboratory Group
NISCM Cluster
krishna@nus.edu.sg

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

Dr WANG Puqun
Team Leader, Advanced Characterisation
PV Devices Characterisation Group
NPVC Cluster
puqun.wang@nus.edu.sg

Dr Nitin NAMPALLI
Deputy Cluster Director and Head of Corporate Laboratory Group
NISCM Cluster
(until Aug 2024)

Dr Biplab GHOSH
Project Manager
Corporate Laboratory Project
NISCM Cluster
biplab@nus.edu.sg

Dr JANG Yu Jin
Senior Research Fellow
Advanced Solar Cells Group
NISCM Cluster
jllv@nus.edu.sg

Dr Romika SHARMA
Research Fellow
Advanced Solar Cells Group
NISCM Cluster
romika@nus.edu.sg

LAM Yiin Fan
Laboratory Manager
NISCM Cluster
(until Feb 2024)

Aziz NAIRI
Head, PV Module Characterisation & Reliability Group
PVM Cluster
a.nairi@nus.edu.sg
(since Dec 2024)

Dr Carlos Enrico Cobar CLEMENT
Head, BIPV Group
PVM Cluster
carlos.clement@nus.edu.sg

Dr SAW Min Hsian
Team Leader, PV Module Reliability
PV Module Characterisation & Reliability Group
PVM Cluster
(until July 2024)

Eddy BLOKKEN
Business Development
SES Cluster
eddy.blokken@nus.edu.sg

Dr Jaffar Moideen YACOB ALI
Head, Solar System Technology Group
SES Cluster
jaffarmoideen@nus.edu.sg
(since Feb 2024)

Rachel TAN Yek Wha
Head, PV Quality Assurance Group, SES Cluster
racheltan@nus.edu.sg

Dr Firdaus Bin SUHAIMI
Laboratory Manager
Perovskite Solar Cells
Technical Infrastructure & QESH Unit
serfs@nus.edu.sg

Nicole YAO Baozhen
SERIS Business Partner Finance, NUS
nybz@nus.edu.sg

Dr LEOW Shin Woei
Head, PV Module Characterisation & Reliability Group
PVM Cluster
(until Nov 2024)

Dr LONG Jidong
Laboratory Manager
PVM Cluster
SERIS laboratory at CleanTech Park
jidonglong@nus.edu.sg

Dr André NOBRE
Deputy Cluster Director and Head of Smart O&M Group
SES Cluster
serv354@nus.edu.sg
(since Apr 2024)

Dr Serena LIN Fen
Head, Urban Solar Solutions Group
SES Cluster
lin.fen@nus.edu.sg

Dr Carlos RODRÍGUEZ
Head, Solar System Technology Group
SES Cluster
(until Jan 2024)

SOE Pyae
Team Leader, PV Monitoring
Digitisation of Energy Group
SES Cluster
soepyae@nus.edu.sg

TAN Mui Koon
Scientific Manager
Corporate Relations
muikoon.tan@nus.edu.sg

Janet GOH
SERIS Business Partner Human Resources, NUS
janetgoh@nus.edu.sg

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 2024, the following Adjunct researchers from NUS have been working with SERIS:

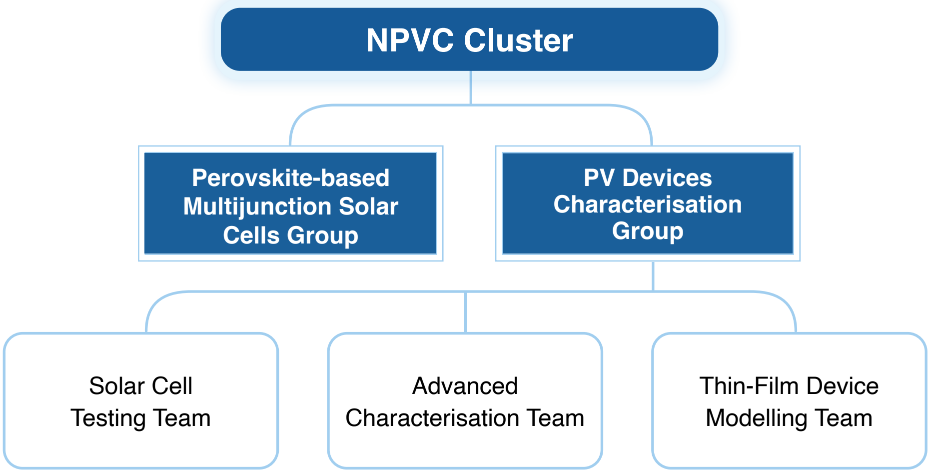
Name	NUS Department	Research Area / Role at SERIS
Prof Armin ABERLE	Electrical and Computer Engineering	Photovoltaic materials, devices and modules / CEO and Cluster Director
Assoc Prof Karl Erik BIRGERSSON	Mechanical Engineering	Modelling, optimisation and characterisation of solar cells; Modelling of PV modules / Team Leader, Thin-Film Device 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 / Group Head
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	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 and Development **Clusters and Groups**

1. Novel PV Concepts Cluster (NPVC)

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 2024, the Cluster had 35 members (including 15 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

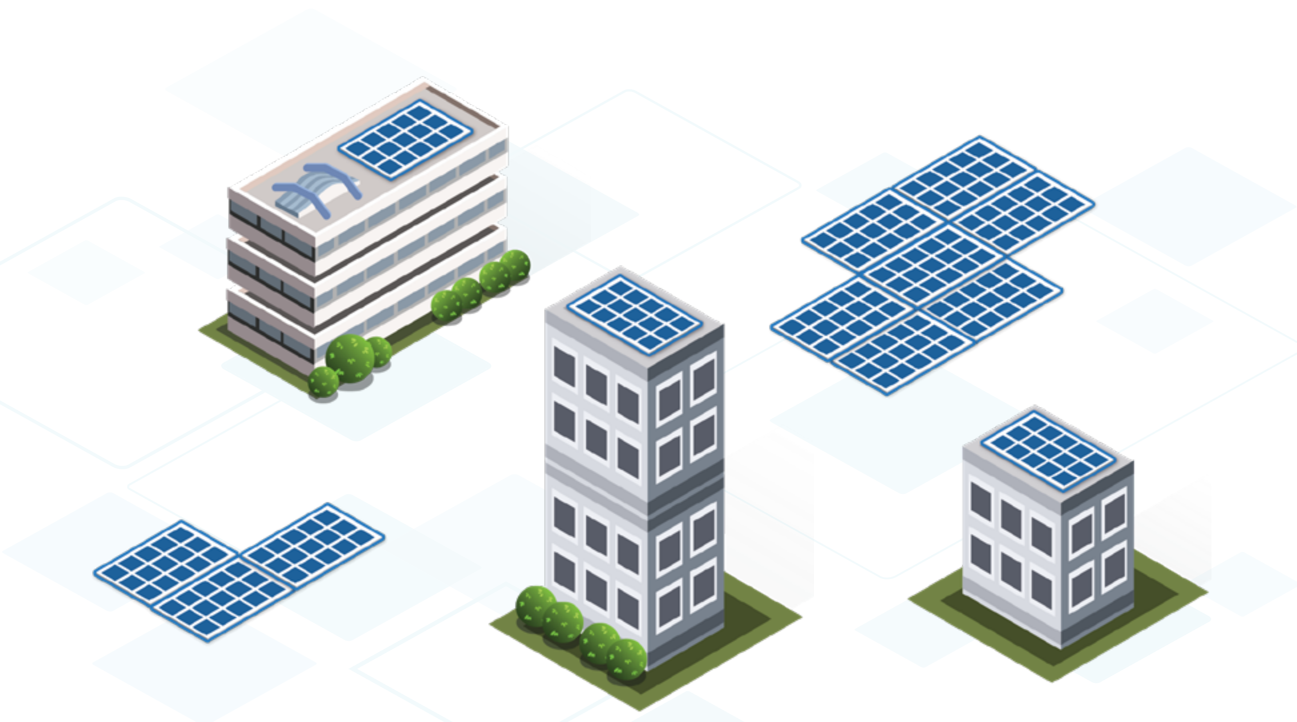


Organisation chart of the Novel PV Concepts Cluster (in Dec 2024)

Group Heads
Asst Prof HOU Yi Perovskite-based Multijunction Solar Cells
Dr CHOI Kwan Bum PV Devices Characterisation

Team Leaders
Assoc Prof Karl Erik BIRGERSSON Thin-Film Device Modelling
Dr WANG Puqun Advanced Characterisation
Dr CHOI Kwan Bum Solar Cell Testing

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)



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 GUO Renjun (until Aug 2024)
- Dr Hu Jingcong (since Sep 2024)
- Dr JIA Zhenrong
- Dr KAN Chenxia (since Oct 2024)
- Dr Donny LAI Jiancheng (until Nov 2024)
- Dr LI Nengxu
- Dr LIU Shunchang
- Dr LUO Chao (since Nov 2024)
- Dr NIU Xiuxiu
- Dr WANG Tao
- Dr YAO Yuxin (since Nov 2024)

PhD Students
- Ezra ALVIANTO
- CHEN Jinxi
- DONG Zijing
- DU Xinyi
- GUO Xiao
- JIANG Yuhui (since Sep 2024)
- LEE Ling Kai
- LIANG Haoming
- LUO Ran (since Sep 2024)
- MENG Xin
- SHI Zhuojie
- WANG Xi
- WANG Yuduan
- WEI Zhouyin
- ZHANG Xinyu (since Sep 2024)
- ZHOU Qilin

PV Devices Characterisation Group

The group researches and develops innovative characterisation and analysis 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. The Solar Cell Measurement Laboratory is ISO 17025:2017 accredited for the measurement of PV current-voltage characteristics and spectral responsivity. Selected R&D activities in 2024 include:

(i) Performing high-quality standard measurements, such as 1-Sun solar cell efficiencies, in accordance with the IEC 60904-1 international standard.
(ii) Conducting optoelectronic characterisations to uncover and understand PV material and device properties.
(iii) Developing novel mathematical models for tandem PV devices.
(iv) 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 CHOI Kwan Bum (Solar Cell Testing, Acting)
- Dr WANG Puqun (Advanced Characterisation)

Adjunct Researcher
Assoc Prof TAN Zhi Kuang

Research Scientists / Engineers
- Stella HADIWIDJAJA (since Apr 2024)
- Elisaveta UNGUR
- YE Jiayi

PhD Students
- Sai Prashanth JOSYULA
- Laxmi NAKKA (until Jan 2024)

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 that provide superior performance and cost-effectiveness than today's technologies. The experimental work in our solar cell laboratories focuses on (i) low-cost high-efficiency single-junction solar cells based on 244-cm² (M2-size) 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 cm², G12). In December 2024, the Cluster had 27 members (including 4 PhD students) spread over two R&D groups.

Cluster Director's Office
Prof Armin ABERLE Cluster Director
Ann Mythel ROBERTS Cluster Secretary
Deputy Cluster Director
Dr Nitin NAMPALLI (until Aug 2024)
Laboratory Manager
Dr Selvaraj VENKATARAJ (since Mar 2024)

Organisation chart of the Next-Generation Industrial Solar Cells and Modules Cluster (in Dec 2024)

Group Heads
Prof Armin ABERLE Advanced Solar Cells
Dr Nitin NAMPALLI Corporate Laboratory (until Aug 2024)
Dr Selvaraj VENKATARAJ Corporate Laboratory (since Sep 2024)

Adjunct Researchers, NUS
Prof Armin ABERLE Dept of Electrical and Computer Engineering (PV materials, devices and modules)
Assoc 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-area (> 200 cm^2) 30% efficient perovskite-silicon tandem solar cells and mini-modules (SERIS flagship project). A modern cleanroom lab (> 1200 m^2) enables single- and double-junction solar cell fabrication on n- and p-type industrial Cz silicon substrates. The group collaborates with several 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

Laboratory Manager
LAM Yiin Fan (until Feb 2024)

Research Scientists / Engineers
- Dr Yu Jin JANG
- Dr Jinhyun KIM (since Mar 2024)
- Dr Romika SHARMA
- John Derek Dumaguin ARCEBAL
- Gabby Alonzo DE LUNA
- YAP Qi Jia (until Aug 2024)

Adjunct Researcher
Assoc Prof Aaron DANNER

PhD Students
- Khalid Ibrahim ABU WARDAH (until Jul 2024)
- Varsha DAHIYA
- LAN Yuchi (since Feb 2024)
- Erik Maurits SPAANS
- YAP Qi Jia (since Sep 2024)

Corporate Laboratory Group

This group hosts, manages and operates the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics established at SERIS in 2023. The group focuses on the development and commercialisation of two-terminal (2T) perovskite-silicon tandem solar cell and module 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 tandem solar cells with high long-term device stability, (2) tackling process and equipment upscaling challenges to reduce the barriers to manufacturing for perovskite-silicon tandem solar cells, and (3) establishing rapid metrology and monitoring techniques suitable for production line environments to enable reliable process control methods for 2T tandem solar cell manufacturing. The heart of the Corporate Laboratory project is a dedicated 200-m^2 zone that will house state-of-the-art ultra-fast deposition machines for the fabrication of large-area perovskite solar cells on silicon substrates with sizes up to G12 (210 mm x 210 mm). The SERIS project staff also utilise SERIS' Silicon cleanroom lab where heterojunction bottom cells are made using large-area industrial Cz silicon substrates. The SERIS 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 since Sep 2024)
- Dr Nitin NAMPALLI (until Aug 2024)
- Dr Biplab GHOSH (Project Manager since Sep 2024)

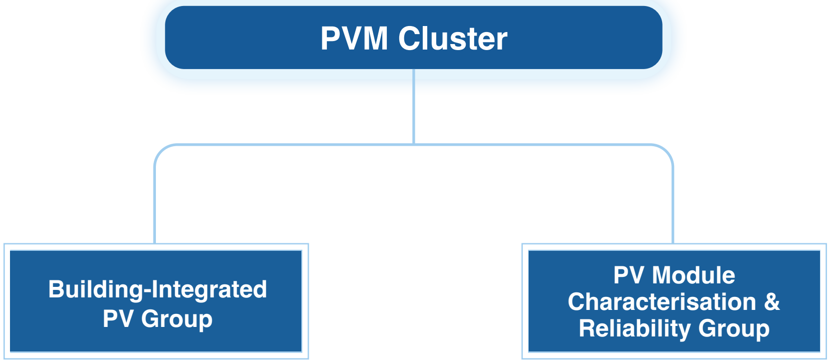
Principal Investigator
Prof Armin ABERLE

Research Scientists / Engineers
- Dr Biplab GHOSH (until Aug 2024)
- Dr Yong Ryun KIM
- Dr Krishna SINGH
- Dr Selvaraj VENKATARAJ (until Aug 2024)
- Jammaal Kitz BUATIS
- Edwin Decena CARMONA (since Feb 2024)
- Mohammed M. S. FARAJ
- Rosalie Cleofe GUERRA
- Jeffrey Garcia ISON
- Maria Luz Loria MANALO
- Mohd Asri Bin MOHD HAMDAN
- Delio Justiniani PEREZ
- Ashwath Narayan RAVICHANDRAN
- Louis Nicholas RETNAM
- Ranjani SRIDHARAN (until Aug 2024)
- Bobby Salinas UNGOS

3. PV Modules for Urban Solar Cluster (PVM)

The Cluster develops and characterises novel and advanced PV module technologies suited for urban and tropical applications. It consists of two research groups - the PV Module Characterisation and Reliability (PVMC&R) Group and the Building Integrated Photovoltaics (BIPV) Group. The Cluster is located in the CleanTech One (CTO) building at CleanTech Park, hosting the ISO/IEC 17025 accredited laboratory for PV module testing and the PV module technology R&D laboratory. 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 in the tropical climate, including Potential Induced Degradation (PID); 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 2024)

Group Heads
Dr Carlos Enrico Cobar CLEMENT BIPV
Dr LEOW Shin Woei PV Module Characterisation and Reliability (until Nov 2024)
Aziz NAIRI PV Module Characterisation and Reliability (since Dec 2024)

Team Leader
Dr SAW Min Hsian PV Module Reliability (until Jul 2024)

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 focuses on the development and deployment of PV modules for applications in the urban environment. These include curtain walls, facades, balustrades, sun-shades, noise barriers and other less conventional surfaces. The group's work pays particular attention to research in fire safety and the complex shading environment often faced by BIPV modules, as well as the development of new technologies for aesthetic PV modules on façades. Building Information Modelling (BIM) is also an area of interest, particularly how BIPV can be integrated into existing workflows in the building lifecycle.

Group Head
Dr Carlos Enrico Cobar CLEMENT

Research Scientists / Engineers
- Dr CHEN Tianyi
- Rupendra ARYAL (since Oct 2024)
- Gavin Prasetyo RAHARTO (until Feb 2024)

Visiting Researcher
Dr XIAO Zhenyu (until Aug 2024)

PhD Student
Vundrala Sumedha REDDY

Internship Students
- WANG Xinyi (until Feb 2024)
- LI Jingxuan (until Feb 2024)

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
- Dr LEOW Shin Woei (until Nov 2024)
- Aziz NAIRI (since Dec 2024)

Team Leader
Dr SAW Min Hsian, PV Module Reliability (until Jul 2024)

Research Scientists / Engineers
- Maryknol Estrada DELOS SANTOS (Quality & Safety)
- Henry LIM Kian Meng (Head of Metrology)
- Srinath NALLURI
- Jack Garcia VILLANUEVA (until Jan 2024)

R&D Project Executive
Zuraidah Binte JA'AFAR

Technicians
- CHOY Woon Loong
- CHUAH Tuang Heok
- LOH Joon Ann
- Abdul RAZAK BIN SAMAN

4. Solar Energy Systems Cluster (SES)

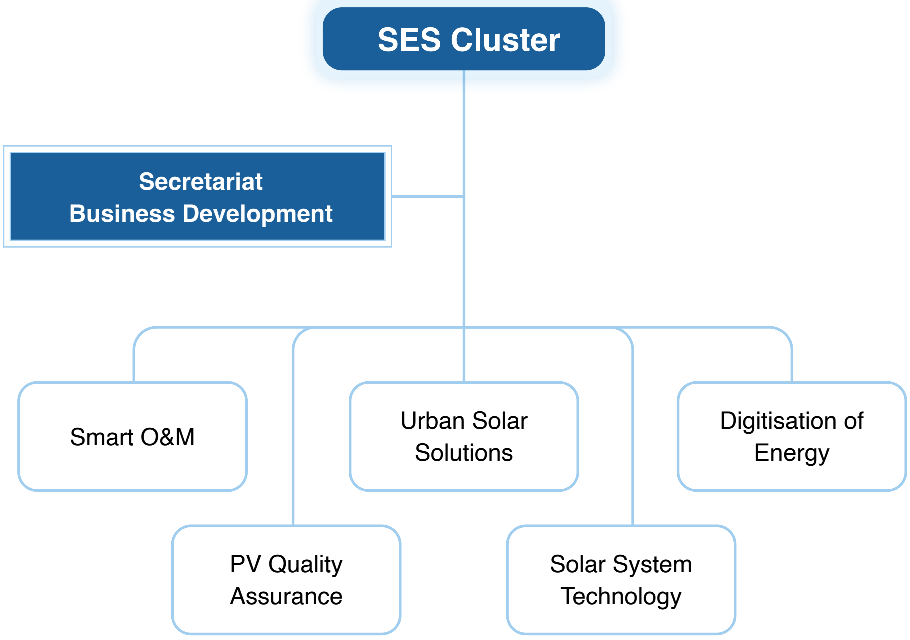
The Solar Energy Systems (SES) Cluster focuses on making solar power a cost-effective and trusted source of electricity. The SES activities have a wide variety and span from remote monitoring to novel PV system deployments such as Agrivoltaics (= combining agriculture + PV) and forecasting of irradiance 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

Marinel DUNGCA
Cluster Secretary



Organisation chart of the Solar Energy Systems Cluster (in Dec 2024)

Group Heads
Dr Serena LIN Fen Urban Solar Solutions
Dr André NOBRE Smart O&M (since Apr 2024)
Dr Thomas REINDL Digitisation of Energy (acting)
Dr Carlos RODRÍGUEZ Solar System Technology (until Jan 2024)
Rachel TAN Yek Wha PV Quality Assurance
Dr Jaffar Moideen YACOB ALI Solar System Technology (since Feb 2024)

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 special focus of the group is "Floating Solar", which is developing rapidly into the 3rd pillar of the global solar industry. The group has established international leadership in this field by gaining rich technical expertise in design, implementation, operation & maintenance (O&M) and energy yield assessments through the MW-scale Floating PV testbed at Singapore's Tengeh reservoir and numerous technical consultancy projects. The research is being expanded towards near-shore and off-shore floating solar solutions to better understand their potential and how to tackle the additional challenges in marine environments, be it for pure electricity generation or in combination with other uses such as fish farming or desalination.

Group Head

- Dr Carlos RODRÍGUEZ (until Jan 2024)
- Dr Jaffar Moideen YACOB ALI (since Feb 2024)

Research Scientists / Engineers

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

Technicians

- David KHUP
- Jamil Bin ZAINAL

PhD Student

ZHAO Shengnan

PV Quality Assurance Group

The perceived quality of a PV system encompasses a wide variety of factors, from components to systems to operation and maintenance (O&M) and economic feasibility. As a "Lender's Technical Advisor", the group provides economic analyses and a wide range of technical services, from independent third-party reviews of system design and execution to feasibility studies and comprehensive technical due diligence evaluations. Other important activities are "Owner's Engineer" services which include PV installation inspection and evaluation, system performance assessment or energy audit, and testing and commissioning (T&C) of PV systems in accordance with local and international best practices and standards. These services provide system owners, lenders, and government authorities with peace of mind.

Group Head

Rachel TAN Yek Wha

T&C Lead

Kendrick LOH Chun Ming

Research Scientists / Engineers

- Stanley PHUA Chee Siang (until Sep 2024)
- Lutfi Irawan Bin RAWAN
- Dexter TONG Yong Hong (since Jul 2024)

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 at the Power System Operation Division (PSOD) of Singapore's grid operator EMA (the Energy Market Authority of Singapore). 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 let 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
- Dr SUN Huixuan
- Dr Gokhan Mert YAGLI

Internship Student
CHIA Yu Hong (since May 2024)

Urban Solar Solutions Group

The group is dedicated to the research and development of innovative urban solar deployment concepts, with the aim to develop technologies and solutions that will contribute to the maximisation of solar PV deployment in Singapore and to overcome its specific challenges such as high urbanisation and space constraints. The research scopes include design, test-bedding and optimisation of novel urban PV concepts through the integration with existing infrastructures, for example overarching of carparks, roads, flood canals and "busy" rooftops. A special focus of the group is "Agrivoltaics", which aims to develop feasible solutions for the combination of solar PV with urban farming for achieving the balance between energy production, energy consumption and crop yield. The group operates both soil-based and soil-less Agrivoltaic testbeds in Singapore, from concept development to implementation, testing and optimisations. In collaboration with the Digitisation of Energy (DoE) group, the group is developing a self-learning AI algorithm to create an autonomous Agrivoltaics system. Additionally, the group is exploring ways to maximise solar PV deployment in the maritime sector, including electric harbour crafts and onshore charging infrastructures.

Group Head
Dr Serena LIN Fen

Research Scientist / Engineer
LIU Tianyuan, Damien

PhD Student
YIN Kaili (since Sep 2024)

Internship Student
LIEW Ka Yen Jeanette (until Aug 2024)

Smart O&M Group

The Smart O&M Group studies the performance of various photovoltaic (PV) systems with the goal of understanding their past, present and future behaviour. Such efforts are critical in safeguarding that PV assets perform as intended, both technically and commercially. As of Dec 2024, the group has been monitoring close to 100MW$_p$ across 300+ sites in 8 countries in Asia. These assets are part of an ever-growing database as more and more system owners (be it private individuals, companies or solar developers), EPCs and O&M providers seek guidance in comprehending their asset performance. PV systems managed by the group cover all types of deployment: from small residential rooftop systems of tens of kW$_p$, through commercial installations of a few hundred kW$_p$, all the way to megawatt-scale industrial systems and utility-scale ground-mounted or floating PV systems. Naturally, operational excellence is at the core of what the group aims to achieve: running & maintaining PV systems professionally in accordance with best industry practices, but also ensuring that assets achieve their returns on investment. Such focus is paramount for the safe & reliable PV systems operation in the long run. Additionally, the group also further deepens the worldwide scientific knowledge on PV system performance and reliability across different climates.

Group Head
Dr André NOBRE (since Apr 2024)

Research Scientists
- Dr HE Yaohua
- Dr Xiaoqi XU

Internship Students
- CAO Han (NUS Data Science and Analytics)
- Justin CHEE (since Sep 2024)
- Justin CHEONG Shao Hong (NUS Computer Science)
- Ginnie LEE Rou Ying (NUS Data Science and Analytics)
- NG Qi Ying (NTU Electrical Engineering)
- TAN Jun Wei (NUS Computer Science)
- TIONG Zee Cyn Cyndi (NUS Chemical Engineering) (since Dec 2024)
- Dylan WONG Kin Wai (NUS Mathematics & Computer Science)
- Sherry XU Yu (NUS Data Science and Analytics)

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 of Singapore (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
- Mitchell SENG Honghui (until Oct 2024)

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 2024, the Cluster's research focused on the development and improvement of small-area (up to 1 cm^2) single-junction perovskite cells and 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. The research is focused on exploring innovative perovskite compositions, passivation strategies, thin-film fabrication, 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 2024

Single-junction perovskite solar cells on glass:

In 2024, the Perovskite-based Multijunction Solar Cells Group achieved an in-house measured efficiency of 25.5% for a single-junction perovskite solar cell with an active area of 1.0 cm^2. This major progress resulted from innovative passivation strategies and interfacial engineering, giving both high fill factor and high open-circuit voltage.

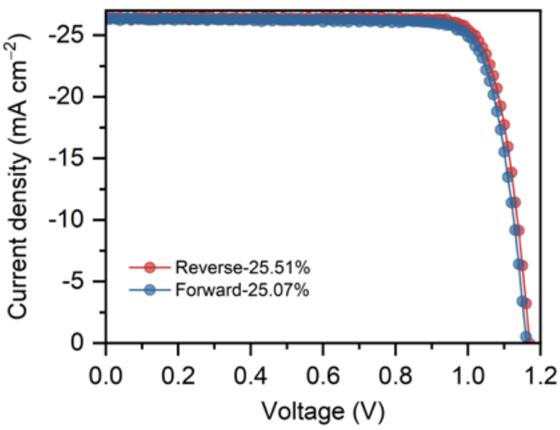


Fig. 1: Measured 1-Sun J-V curves of a 25.5% efficient SERIS-made 1-cm^2 single-junction perovskite solar cell on glass

Two-junction perovskite-silicon tandem solar cells:

The Multijunction Group also developed a 33.2% efficient small-area (1 cm^2) perovskite-silicon dual-junction tandem solar cell with record-high open-circuit voltage of 2.026 V, using a commercially available Cz-based silicon bottom sub-cell. This was achieved by depositing a high-quality perovskite film onto the textured silicon bottom cell (see Fig. 2). This efficiency result makes SERIS one of the top-3 labs in the world in terms of *small-area* (1 cm^2 aperture area) two-junction perovskite-silicon tandem cells. One of the core challenges of this research is how to further improve the optical pathlength of light in the tandem architecture to maximise the short-circuit current density. Ongoing work is focused on bridging the efficiency gap to the current world-record 1cm^2 perovskite-silicon tandem solar cell (34.6%, LONGi Green Energy Technology, China).

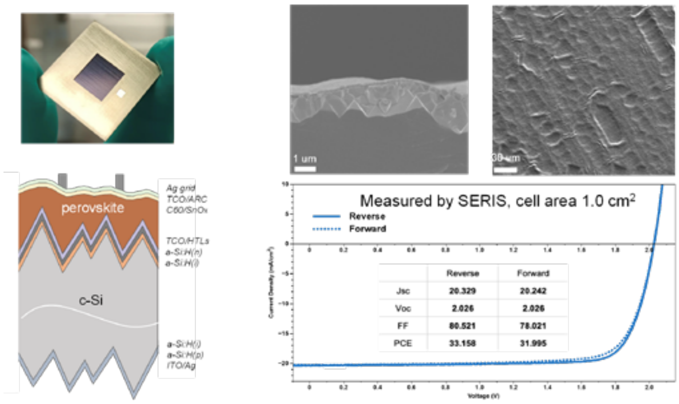


Fig. 2: (top left) Photograph of one of our high-efficiency perovskite-silicon tandem cells (1.0 cm^2 aperture area); (top right) Cross-sectional and top-view SEM images of a perovskite-Si two-junction tandem cell; (bottom left) Cross-sectional schematic of the perovskite-Si tandem solar cell; (bottom right) SERIS-measured JV curves of the 33.2% perovskite-Si tandem solar cell

Triple-junction perovskite-perovskite-Si tandem cells:

The Multijunction Group also made very good progress in 2024 with its high-efficiency triple-junction solar cells. This innovation combines a 1.55-eV perovskite middle cell with a 1.9-eV wide-bandgap perovskite top cell (both developed by SERIS) and a heterojunction silicon (Si) bottom cell supplied by an external collaborator. These cells employ double-side textured n-type Cz-Si wafers for the Si bottom cell. Meticulous process optimisation enabled the deposition of a high-quality 1.55-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. 3, one of these triple-junction solar cells made in 2024 has a 1-Sun efficiency of 29.1%, measured at SERIS using a shadow mask with an aperture area of 1.0 cm^2.

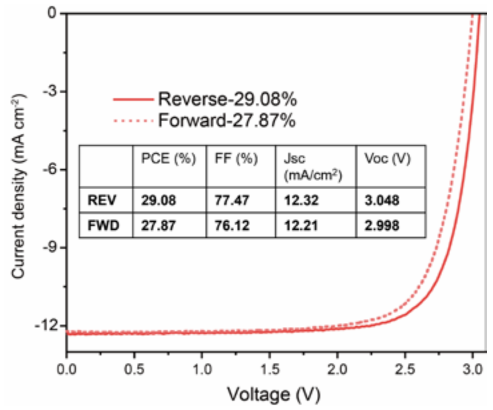


Fig. 3: Measured 1-Sun J-V curves (forward, reverse) of a 29.1% efficient perovskite-perovskite-silicon triple-junction solar cell (1.0 cm^2 aperture area) made in 2024 in SERIS on a textured Cz silicon bottom cell

Advanced characterisation of perovskite cells and tandem cells:

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 2024, our efforts focused on I-V measurements of tandem solar cells by implementing precise control of the spectrum of the LED solar simulator. This is particularly important for multi-junction solar cells, as each sub-cell must be in the correct current-limiting condition as it would be under the AM1.5G spectrum. By tuning the intensity of each individual LED of the solar simulator, the spectral mismatch of the two sub-cells can be minimised for the I-V measurement (see Fig. 4). Additionally, we commissioned a new external quantum efficiency measurement tool for tandem cells, which allows user-friendly measurement of each sub-cell, using variable light and voltage biasing conditions.

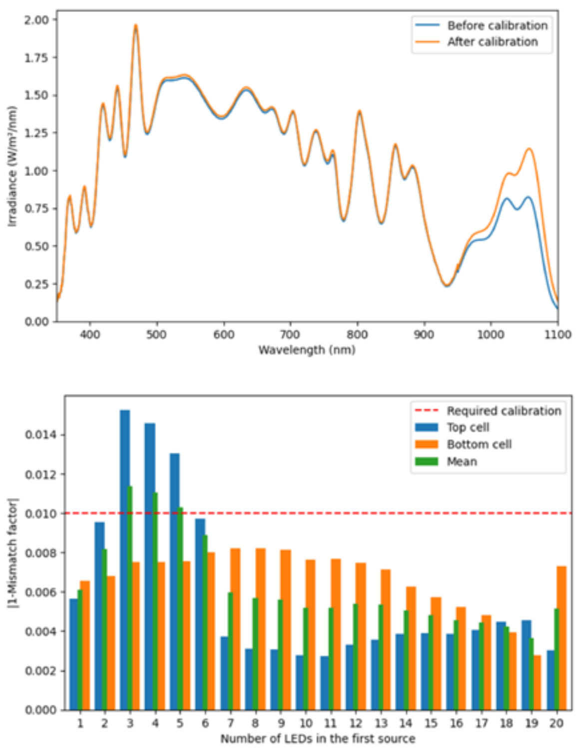


Fig. 4: (top) LED solar simulator spectrum before and after spectrum calibration for the specific tandem device under test. (bottom) Plot of mismatch factor over different choices of spectrum splitting for the optimisation. Splitting the spectrum at LED 19 gave the best result

Modelling of perovskite-based tandem solar cells:

We are developing neural networks to facilitate the fabrication and characterisation of tandem solar cells, specifically those with a perovskite top cell layered over various types of bottom cells. In 2024, a physics-based optoelectronic model generated a large dataset with a sample size of one hundred thousand, which trained neural network models for efficient prediction of device performance and recombination losses. Latin hypercube sampling, Bayesian regularisation, and Bayesian optimisation were applied for data preparation, model training, and optimisation of the neural networks, respectively. The most effective models achieved mean squared errors below 4 x 10^{-4} on a reserved testing dataset, enabling rapid device calibration in just 24 seconds — ten thousand times faster than traditional optoelectronic models. This reduced computational cost allows efficient device characterisation, parametric studies, sensitivity analysis, loss analysis and optimisation.

Selected publications:

- S. Liu, Y. Lu, C. Yu, J. Li, R. Luo, R. Guo, H. Liang, X. Jia, X. Guo, Y.D. Wang, Q. Zhou, X. Wang, S. Yang, M. Sui, P. Müller-Buschbaum and Y. Hou, Triple-junction solar cells with cyanate in ultrawide-bandgap perovskites, Nature 628, 306-312 (2024)
- X. Meng, Z. Jia, X. Niu, C. He and Y. Hou, Opportunities and challenges in perovskite-organic thin-film tandem solar cells, Nanoscale 16, 8307-8316 (2024)
- E. Alvianto, G. Wan, Z. Shi, H. Liang, X. Wang, X. Guo, C.H. Wang, C.H. Wu, J.W. Jiang, X. Niu, B.C.K. Tee and Y. Hou, Sustainable manufacturing of perovskite-CIGS tandem solar cells through lamination with metal-free transparent conductive adhesives, ACS Energy Letters 9, 2057-2064 (2024)

2. Plans of NPVC Cluster for 2025

- Achieve > 34% efficiency for a perovskite-silicon tandem solar cell with active area of at least 1 cm^2
- Achieve > 26% efficiency for a perovskite-silicon mini-module with active area of at least 150 cm^2
- 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 modules."

Research Focus / R&D portfolio of NISCM Cluster

In 2024, the cluster's research focus remained on next-generation industrial solar cells and modules that provide superior performance and cost-effectiveness ($/kWh) than today's market leading technologies. The experimental work in our laboratories focused on (i) low-cost high-efficiency single-junction solar cells based on 244-cm^2 (M2 size) monocrystalline Cz silicon substrates and (ii) low-cost large-area (up to M2) 30% efficient perovskite-silicon tandem solar cells and mini-modules (SERIS flagship project). In addition, the cluster 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 size).

1. Major activities / achievements in 2024

Advanced Solar Cells Group

Development of biPoly™ ("TOPCon") layers for single-junction 1-Sun solar cells:

In a collaborative R&D project with an external partner, the group developed ~23% efficient bifacial large-area solar cells on our biPoly™ platform using a polysilicon-based selective passivating contact on the front surface. The passivating contacts were realised with *in-situ* doped polysilicon films deposited using low-pressure chemical vapour deposition (LPCVD). This doping method is expected to simplify the industrial fabrication as compared to ex-situ doped polysilicon films. A schematic cross-sectional representation of the developed solar cell is shown in Fig. 1. Using thinner front poly-Si fingers and an improved alignment of the front metal fingers, this new single-junction solar cell has the potential to reach a 1-Sun efficiency of > 25%.

Development of biPoly™ ("TOPCon") layers for bottom cells of perovskite-silicon tandem cells:

The group also developed large-area bottom cells for 2-terminal tandem solar cell applications using our biPoly™ platform. The polysilicon-based passivating contacts were developed using both the LPCVD and the PECVD technology. The technologies are designed to be compatible with both high- and low-temperature metallisation methods. Our developed bottom cells achieve > 730 mV implied open-circuit voltage and > 85% implied fill factor under 1-Sun illumination, which can potentially lead to high-efficiency (30%) large-area perovskite-silicon tandem solar cells. A schematic of a perovskite-biPoly™ tandem solar cell architecture being investigated by us is shown in Fig. 2.

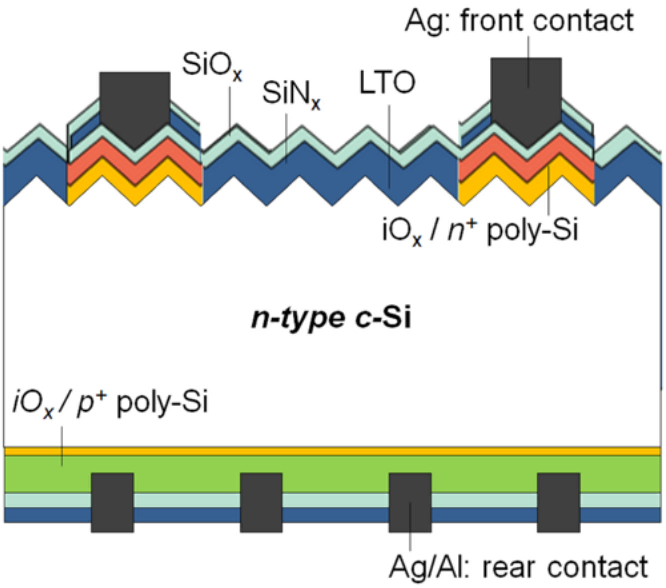


Fig. 1: Schematic representation of a front selective biPoly™ silicon solar cell

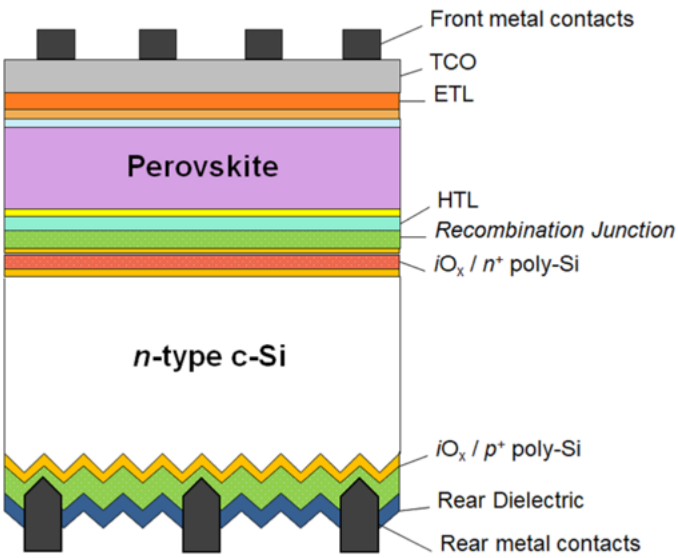


Fig. 2: Schematic representation of a perovskite-biPoly™ tandem solar cell being developed by SERIS

Development of perovskite-silicon tandem cell mini-modules:

Our R&D on perovskite-silicon tandem mini-modules centred around scaling up from lab-scale devices (area ~1 cm²) to M2-size mini-modules. The first key challenge we addressed was adapting our fabrication process to the low processing temperatures imposed by the perovskite top cells. This led to the redefinition of the Bill of Materials (BOM, see Fig. 3) to incorporate materials capable of low-temperature processing below 120°C without compromising the tandem cell performance. We made good progress in refining encapsulation and interconnection technologies, which are critical for preserving the integrity of the perovskite-silicon tandem cells and ensuring reliable module performance. We introduced new low-temperature encapsulants and lamination techniques that maintain the performance of the tandem cells. Additionally, we explored advanced electrically conductive adhesives (ECAs) that enable robust interconnections under these low-temperature conditions, minimising the cell-to-module (CTM) loss. A significant milestone in 2024 was the successful fabrication and testing of M2-size mini-modules, as shown in Fig. 4. These mini-modules demonstrated promising active-area efficiency and stability, validating our material choices and process optimisations.

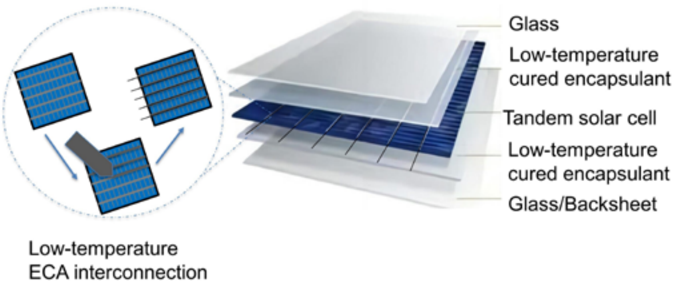


Fig. 3: Bill of Materials (BOM) for low-temperature fabrication of perovskite-silicon tandem modules

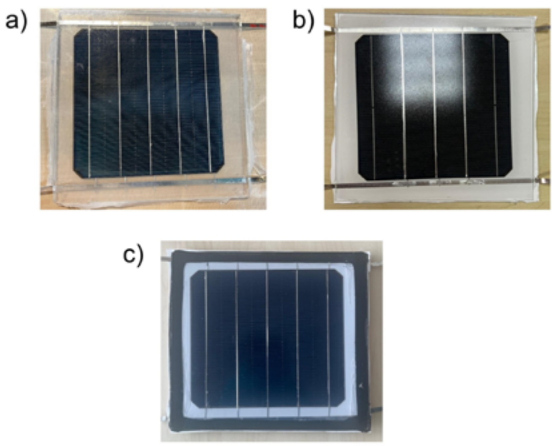


Fig. 4: Photographs of single-cell tandem mini-modules made by SERIS on 244-cm² perovskite-silicon tandem solar cells: (a) Glass-glass architecture without edge sealant, (b) Glass-backsheet architecture without edge sealant, and (c) Glass-backsheet architecture with edge sealant

We are presently working on further upscaling these mini-modules to larger sizes while continuously improving their 1-Sun efficiency and longevity. Climate chamber testing (for example damp heat) will play a crucial role in helping us refine our processes to meet the demands of real-world conditions and moving us closer to outdoor test bedding of our perovskite-silicon tandem technology.

Selected publication:

- E.M. Spaans, S. Venkataraj, K. Singh, A. Ravichandran, M.L. Manalo, R. Guerra, A.G. Aberle, N. Nampalli, Optical losses in silicon heterojunction solar cells: Analysis of record efficiency devices and practical limits based on ray tracing simulations (under review)

Corporate Laboratory Group

The group's major activities in 2024 were the further development of SERIS' large-area (full-wafer) perovskite-silicon two-terminal (2T) tandem solar cell, advancing high-performance silicon heterojunction sub-cells, integrating novel transparent metal oxides (TMOs) for both silicon heterojunction and 2T perovskite-silicon tandem cells, novel in-line metrology for 2T tandem solar cells, and establishing the lab infrastructure & equipment for an R&D pilot line for 2T tandem solar cells on G12-size (440 cm²) industrial Cz wafers. Once operational, this G12-compatible tandem pilot line is expected to be the largest in South-East Asia and one of the few globally among public research institutes.

Further development of large-area (up to 244 cm², M2-size) perovskite-silicon tandem solar cells:

In the last 3 years SERIS has established itself as an international leader in R&D for industrial perovskite-silicon 2T tandem solar cells with screen-printed contacts and upscaled processes. Notable achievements in 2024 include:

- Demonstration of ~22% efficiency (16 cm²) and ~20% efficiency (244 cm²) on screen-printed 2T perovskite-silicon tandem solar cells utilising only upscaled processes for perovskite sub-cells integrated with SERIS' in-house developed silicon heterojunction sub-cells
- Demonstration of V_{oc} of > 1.8 V and J_{sc} > 19 mA/cm² on large (full-wafer, 244 cm²) tandem solar cells
- Demonstration of ~10% add-on efficiency for advanced silicon heterojunction bottom cells
- Demonstration of < 7% layer thickness non-uniformity for all functional layers in SERIS' industrially compatible 2T tandem solar cell architecture (full-wafer, 244 cm²)
- Development of advanced metrology techniques for quality control tracking and routine (100% sampling) measurements directly on silicon sub-cells
- Development of defect detection and categorisation methods to enable in-line detection of perovskite-related process-induced defects in 2T tandem pilot lines
- Design and initiation of a next-generation R&D pilot line with high-rate deposition equipment for G12-size 2T perovskite-silicon tandem solar cells

SERIS 2T tandem technology platform:

In partnership with leading solar cell and equipment manufacturers, we have established the SERIS 2T tandem technology platform. This initiative focuses on identifying and overcoming the obstacles to market adoption of tandem solar technology, with the goal of creating a foundation for an industrial-scale manufacturing pilot line for perovskite-silicon tandem solar cells. Our objective is to advance the development of next-generation high-performance solar cells by industrialising perovskite-silicon tandem technology using silicon heterojunction cells. The platform is designed to provide a rapid and cost-effective approach for depositing high-performance durable perovskite top cells. The efficiency of our 2T tandem solar cells has improved rapidly in recent years, with a learning rate of about 2% absolute per year. Continued development of advanced integration solutions (& related processes) is projected to improve 2T tandem solar cell efficiencies at SERIS towards 27% in the short term (on 244 cm² M2 substrates) and towards 30% in the mid term (on up to 440 cm² G12 substrates, Corp Lab project).

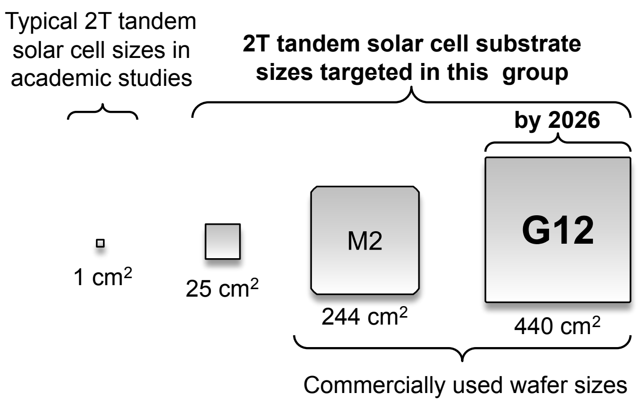


Fig. 5: Graphic showing typical sizes of 2T tandem solar cells in academic studies (left) and in our group (right)

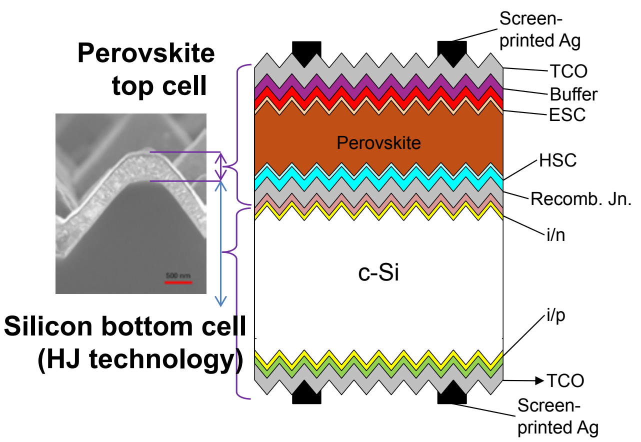


Fig. 6: Cross-sectional microscope image (left) and schematic architecture (right) of a SERIS-made 2T tandem solar cell, showcasing the thin perovskite top cell on a textured silicon wafer bottom cell

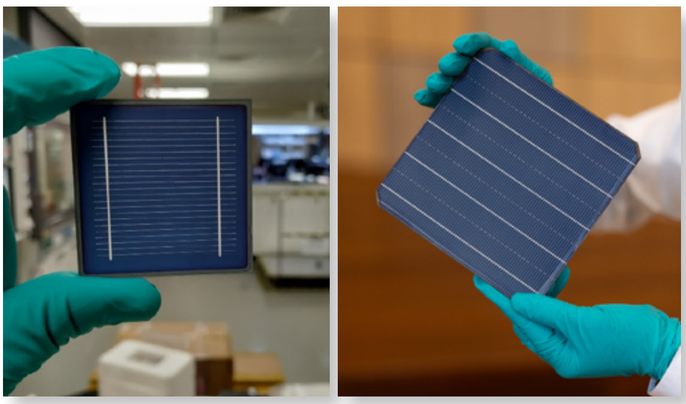


Fig. 7: In-house fabricated fully scalable 16-cm² and full-wafer (244 cm²) 2T perovskite-silicon tandem solar cells

2. Plans of NISCM Cluster for 2025

- Further enhance the fabrication and characterisation capabilities for perovskite-silicon tandem solar cells and mini-modules
- Develop new know-how and intellectual properties (IP) on processing steps for industrial 2T perovskite-silicon tandem solar cells
- Installation and start-up of advanced deposition tools for perovskite-silicon 2T tandem solar cell fabrication on G12-size substrates (area 440 cm²)
- Achieve 26% efficiency for a perovskite-silicon mini-module with active area of at least 150 cm²
- Conduct reliability studies for perovskite-silicon tandem solar cells and mini-modules

PVM **Acting Cluster Director's Foreword**

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

"The PVM Cluster strongly supports local and regional PV manufacturers with its accredited characterisation and testing services. It also drives the energy transition with innovative deployment options such as Building-integrated PV and the sustainability of PV through module recycling."

Research Focus / R&D portfolio of the PVM Cluster

In 2024, the Cluster's research focused on two main topics: (i) Reliability of PV modules, and (ii) Building Integrated Photovoltaics (BIPV). In addition, the Cluster's research on recycling of PV modules has achieved a major milestone by the successful establishment of a PV Module Recycling Laboratory, which makes SERIS one of the few solar research institutes in the world to be able to carry out holistic 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 2024

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. In 2024, the measurement of bifacial modules according to IEC TS 60904-1-2 Edition 1.0 was added to its scope to meet the increasing demand from industry to measure and characterise such modules. SERIS also provides "Golden module" measurements to PV manufacturers in Singapore, South-East Asia and the US, 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).

The group constantly upgrades its laboratory to support our industry partners. In 2024, our h.a.l.m. flash tester was upgraded and is now able to handle very large PV modules (up to 1.5 m x 2.5 m) while maintaining the highest uniformity (A+A+A+) across the in-plane irradiance. SERIS also commissioned a new salt mist chamber for large-sized PV modules and with full climate chamber functionality. This chamber enables specialised tests of PV modules in marine conditions, for example in near- and off-shore floating solar applications.

In the area of pre-normative testing, the group carried out round-robin tests with other leading laboratories around the world on the proposed new standard IEC 61853-2 for the incident angle modifier (IAM). A novel testing method developed by SERIS (see also Fig. 1) is mentioned in the draft version of the standard.

Further pre-normative tests were also carried out on Floating PV, with a focus on PV modules installed in near- and off-shore conditions. These experience a largely different set of environmental challenges than typical ground-mounted or roof-top installations. Figure 2 summarises the likely stress factors based on the classifications provided in IEC 60068-1, Environmental testing - Part 1: General and guidance. First mechanical tests that simulate the slamming forces of waves hitting the modules form the bottom were carried out. The forces are also known as "wave-in-deck impact" in maritime engineering.

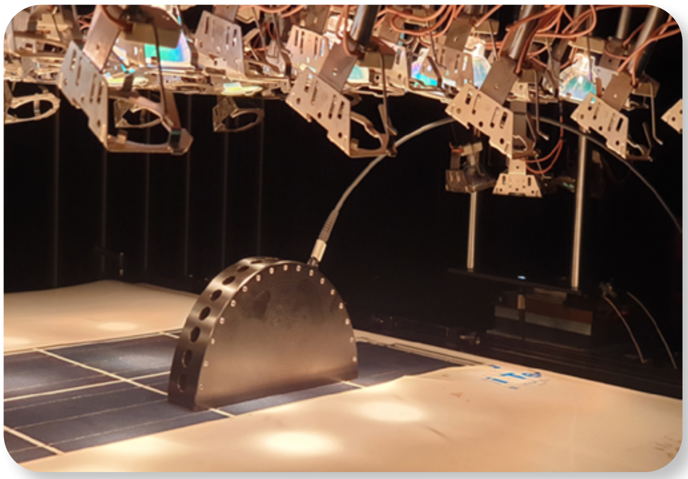


Fig. 1: Image of the incident angle modifier (IAM) measurement methodology developed by SERIS, which is also mentioned in the new draft standard IEC 61853-2.

BIPV Group

Singapore NDP BIPV flag

In celebration of Singapore's 59th anniversary, SERIS - in partnership with REC Solar Pte Ltd - jointly presented a locally fabricated "Singapore flag made of solar panels" as part of the National Day Parade (NDP) 2024 celebrations (see Fig. 3). While typical solar panels are black or dark blue (ideal for the absorption of sunlight), we have developed a patented technology for the colourful design of PV modules while minimising conversion efficiency losses and reducing the risk of hot spots. More info can be found in the report on the BIPV Flagship project of this Annual Report.

Environmental parameters	Principal effects	Typical failure resulting
High relative humidity	Moisture absorption and adsorption; swelling; loss of mechanical strength; chemical reactions; corrosion and electrolysis: increased conductivity of insulators	Physical breakdown, insulation failure, mechanical failure
Solar radiation	Chemical, physical and photochemical reactions; surface deterioration; embrittlement; discolouration, ozone formation; heating; differential heating and mechanical stresses	Insulation failure See also "High temperature"
Corrosive atmospheres	Chemical reactions; corrosion and electrolysis; surface deterioration; increased conductivity; increased contact resistance	Increased wear, mechanical failure, electrical failure
Wind	Force application; fatigue; deposition of materials; clogging; erosion; induced vibration	Structural collapse, mechanical failure. See also "dust and sand" and "corrosive atmospheres"
Rapid change of temperature	Temperature shock; differential heating	Mechanical failure; cracking; seal damage; leaks
Acceleration (steady state); vibration; bump or shock	Mechanical stress; fatigue; resonance	Mechanical failure; increased wear of moving parts; structural collapse

Fig. 2: Overview of environmental challenges, principal effects and likely failure modes for PV modules installed in near- and off-shore conditions, following the classifications provided in IEC 60068-1, Environmental testing - Part 1: General and guidance.

Fig. 3: The "Singapore flag made of solar panels" displayed at the National Day Parade (NDP) 2024 heartland exhibition in Bishan.

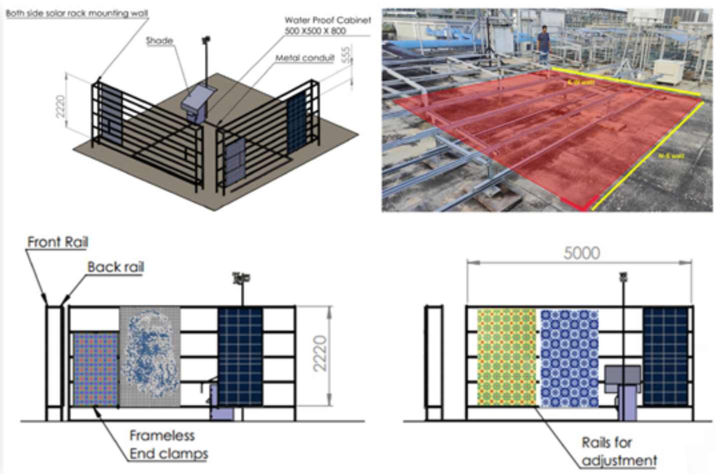


Fig. 4: BIPV outdoor testbed for façade systems. The testbed will be used to evaluate various technologies as well as mounting and interconnection strategies.

BIPV test-bedding

In 2024, we initiated the design and construction of a dedicated testbed on the rooftop of SERIS' CleanTech One facility. This setup is meant for outdoor monitoring of BIPV systems (see Fig. 4), incorporating versatile attachment points and a modular, swappable façade system. The testbed will serve as a platform for advancing BIPV technology, enabling comprehensive evaluation of various solutions under real-world conditions, with the advantage of rapid plug-and-play testing.

Building information modelling for BIPV

Building Information Management (BIM) systems allow architects, engineers and building owners to create and jointly manage 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. There is currently a lack of BIM models for BIPV products and no consensus on how to implement such models. This has resulted in BIPV being largely ignored as building material option at the design and development stage of new construction projects. If not considered at the very beginning, however, BIPV automatically becomes a "retrofit", which increases complexity and ultimately cost – with the consequence that in most cases BIPV will not be implemented at all. In 2024, the group has built a framework for the integration of BIPV into BIM systems based on BCA guidelines. Furthermore, we identified key indicators and Levels of Detail (LoD) for BIM models of BIPV components along the building lifecycle from conceptual design to operation and maintenance. More details can be found in the report on the BIPV Flagship project of this Annual Report.

PV Module Recycling via shockwave fragmentation

Solar PV is poised to become the world's leading renewable energy source, with the cumulative installed capacity projected to grow from 2 TW_p today to over 60 TW_p by 2050. In parallel, the volume of solar panels that need to be recycled at the end of their lifetime will also increase, with estimates for 2030 being in the range of 2-8 million tons of PV waste.

While conventional recycling methods rely heavily on pyrolysis at 500-600 °C for burning off the polymer parts of the module laminate (i.e., encapsulant and backsheet), SERIS has established a pilot recycling line that uses electro-hydraulic fragmentation to separate the various materials. In contrast to pyrolysis, the SERIS process does not require to separate the glass sheet from the laminate. After taking off the aluminium frame and the junction box(es), the entire laminate is grinded and then poured into the hydraulic fragmentation chamber (which is filled with water) where a high-voltage electric arc (at 50 kV) generates a shockwave that decomposes the grinded laminate pieces according to their acoustic properties and mechanical strengths. As a result, there are four discharges of residuals with different particle sizes, as shown in Fig. 5.

Major benefits of the SERIS method are the very high recovery rates and the significantly lower energy consumption. The recovery for glass-backsheet modules is approximately 98% with an average energy consumption of 225 kWh/ton, while for glass-glass modules the recovery ratio is around 96% with an average energy consumption of 133 kWh/ton. This compares to ~300 kWh/ton for the standard pyrolysis process. More information can be found in the R&D section of this Annual Report.

Fig. 5: Shockwave fragmentation machine (left). Separated PV module components such as backsheet, encapsulant, crushed glass and crushed cells after shockwave separation (right).

2. R&D plans of PVM Cluster for 2025

- Pre-normative reliability tests for perovskite modules and perovskite-silicon tandem modules.
- Continuation of pre-normative testing methods for PV modules in near- and off-shore floating solar applications.
- First pilot production batch of the coloured BIPV modules in collaboration with a local industry partner.
- Further explore PV integration into timber-based, modular façade structures (in collaboration with the University of Sydney).
- Support the Singapore Civil Defence Force (SCDF) in their working groups on fire safety of PV and BIPV.
- Development of a BIM BIPV library.
- Realisation of a testbed for "plug & play" BIPV at CleanTech Park.
- Optimise the SERIS recycling process for high throughput and high recovery rates.
- Explore the integration of PV into novel sound barriers with noise absorption properties, see the concept in Fig. 6 (in collaboration with NUS CDE).

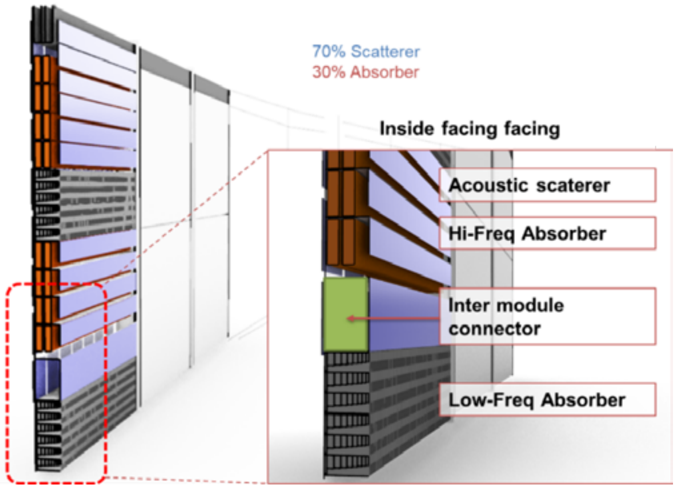


Fig. 6: Composite sound barrier concept with integrated PV and noise absorption properties.

SES **Cluster Director's Foreword**

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

"The research at SES aims at increasing the adoption of solar PV in Singapore and the region, for example through novel deployment options such as near-shore floating solar, agrivoltaics and solar canopies. Our innovations, technical standards and quality assurance are equally important for conventional systems (ground-mounted, roof-top) and existing installations, to ensure they operate safely and at their maximum possible yield."

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 2024

Solar System Technology Group

Floating Solar Systems

In 2024, the group dedicated significant efforts to research and development in floating photovoltaic (PV) systems, focusing not only on inland applications but also on near-shore and off-shore installations. SERIS is actively engaged in projects aimed at deploying floating PV systems both in Singapore and internationally. Having been involved in Floating PV since 2015, SERIS has broad technical expertise in design, implementation, operations & maintenance, and energy yield assessments, and provides a wide range of specialised technical advisory services.

One example is the study of the technical feasibility and the development of tender documents for a proposed off-shore floating PV (FPV) system in Tuvalu in the South Pacific (see Fig. 1). This location presents extremely challenging environmental conditions, including very high wind speeds of up to 275 km/h and maximum recorded wave heights of 3.6 m – factors that pose severe stresses to traditional FPV structures relying on pure floats. Despite these harsh conditions, SERIS - in collaboration with a Spanish consulting company - developed a comprehensive design concept and a complete set of tender documents to enable the deployment of this off-shore FPV system.

Another example is the novel Floating PV concept that won the Sustainability Open Innovation Challenge (SIOC) 2023. The innovative floating PV module and system deployment approach has the potential to revolutionise the way how floating PV systems are designed and implemented in the future.

The team also published a comprehensive journal paper on the "Global floating PV status and potential".

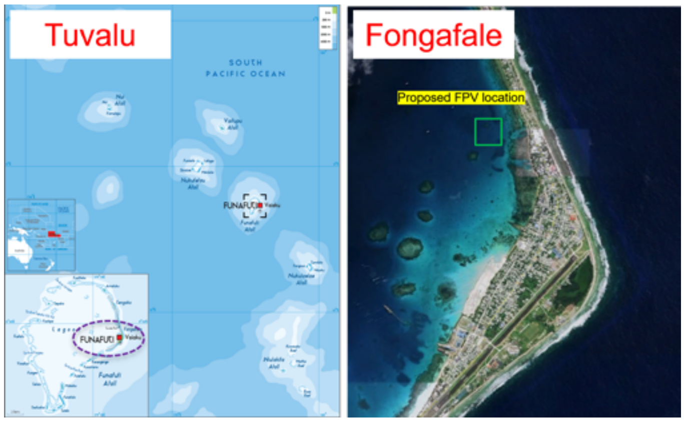


Fig. 1: Location of the proposed off-shore FPV plant in Tuvalu

Integrated PV+ ESS testbed

The group expanded its capabilities in the field of PV grid integration by adding energy storage system (ESS) expertise. SERIS completed a project to design, implement and operate a large test-bedding system in the region, which comprises several of the latest PV technologies (p-mono, n-type bifacial, HJT, single-axis tracking system), combined with different ESS systems (NMP, LFP, redox-flow, flywheel) as well as multiple weather and electrical performance sensors (see overview in Fig. 2). Total installed capacity is 5 MW_p PV and 1.5 MWh ESS.

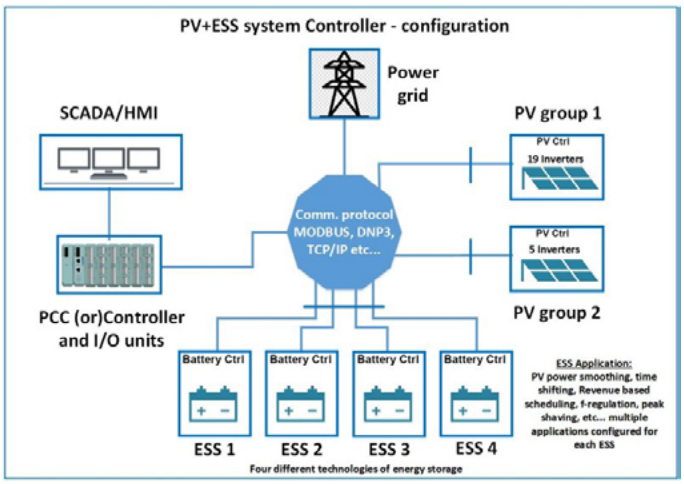


Fig. 2: Schematic drawing of the integrated PV and ESS testbed facility

The current research focus is on analysing the extensive data collected from the testbed. The in-depth studies allow to compare the advantages and disadvantages of the different technologies and system configurations with the aim to support the client in their future project engineering design.

Outdoor Module Testing (OMT)
The group continued to operate SERIS' Outdoor Module Testing (OMT) facility, which has been providing numerous R&D collaborations with industry partners since 2010. Clients appreciate the continuous high-quality and high time-resolved (as short as 10 second intervals) OMT data in the tropical climate of Singapore. The testbed covers a broad range of PV technologies such as p-multi, p-mono, n-PERT, heterojunction and IBC silicon cells, as well as several thin-film technologies. In 2024, the group successfully upgraded the OMT facility to be able to handle module power capacities of up to 1000 W_p, catering to the latest high-power modules and aligning with industrial standards.

TruePower™ Alliance
The group also continued its comparative research on PV module and system performance and energy yield across different climate zones, including the tropics (Singapore), desert (Australia) and two different temperate climates (Germany, China). The Singapore site is at the Marina Barrage and is operated in close collaboration with PUB, Singapore's national water agency. The long-term, high-time-resolution and high-accuracy data from the 4 sites has been attracting the attention of research institutes as well as industry partners aiming to deploy GW-scale PV installations in these climates.

PV Quality Assurance Group

The PVQA Group offers feasibility studies, lender's technical due diligence, and testing & commissioning (T&C) services for solar PV projects in Singapore and the region. In 2024, the group collaborated closely with the Housing and Development Board (HDB), acting as their technical expert representative during the construction phase of PV installations on HDB residential buildings, primarily under the SolarNova project, Phases 4, 6 and 8 (SN4, SN6, SN8). Additionally, the group is responsible for T&C services for other government agency installations, for example at Changi Airport.

The group has also secured Owner's Engineering or T&C contracts for significant installations in both the public and private sectors across Singapore. Furthermore, it is actively engaged in cross-group initiatives within the SES Cluster.

Urban Solar Solutions Group

Yuhua Agri-tech Solar Living Lab test-bedding
The USS Group has completed the first-year test-bedding at the Yuhua Agri-tech Solar (YAS) Living Lab (see Fig. 3). Different types of vegetables, such as lettuce, bok chye, nai bai, chye sim, kang kong and bayam (spinach), have been grown in the testbeds in two different growing setups, i.e., horizontal layered towers and vertical towers, under the solar panels. Rotatable solar panels are deployed to evaluate the amount of power gain via Sun tracking as well as to provide the flexibility in adjusting the panel angles in the experiments. More details of the test-bedding results can be found in the R&D section of this Annual Report. To guide the further improvement of the agrivoltaic system and future design of other agrivoltaic systems, we have carried out a 3D irradiance map simulation to investigate the light distribution at different levels within the two different growing setups. Based on the valuable data collected from operating these test-beds, the USS Group has also conducted a preliminary financial scenario analysis to determine how different types of farming (traditional soil-based, horizontal, vertical with multiple layers, vertical layers with LED support) compare in terms of crop yield and gross margin (revenue minus cost of operation).

Apart from the research activities, the YAS Living Lab serves as an excellent platform for outreach activities. The USS Group has conducted various tours and open houses in 2024 to showcase the agrivoltaics testbeds and our innovations to the public, including community residents, students, social media influencers, companies and government agencies. The testbeds were also featured in the 2024 World IP Day event co-organised by the Intellectual Property Office of Singapore (IPOS) and the Ministry of Sustainability and Environment (MSE).

Fig. 3: SERIS' two testbeds at the Yuhua Agri-tech Solar (YAS) Living Lab

Urban PV
Other research activities in the USS Group include design, test-bedding and optimisation of novel urban PV concepts through the integration of PV with existing infrastructures. The group has been exploring various innovative deployment solutions in order to push the boundary of solar PV deployment beyond the conventional limits, for example by considering solar canopies over large vacant areas such as flood canals or even over-arching buildings. Moreover, to contribute to the decarbonisation of the maritime sector through PV deployment, the group has also been actively involved in the assessment, evaluation and proposal of solar PV deployment on electric harbour crafts. More involvements on potential PV deployment at shore charging facilities are under discussion.

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).

In 2024, the PV Monitoring Team successfully implemented a project with the NUS University Campus Infrastructure (UCI) unit to deploy more than 60 remote monitoring stations to capture the output and performance of the 9.2 MW_p of installed solar PV capacity on the main NUS campus (Kent Ridge) and University Town. Leveraging its in-house developed "live" PV monitoring system and solar asset management platform, SERIS also provides the mandatory consolidation and real-time reporting to Singapore's grid operator (EMA, Energy Market Authority of Singapore). Expanding the scope of the system, the PV Monitoring Team is now also able to identify detailed error logs from various types and brands of inverters and to capture other sensor data, for example energy consumption meters. This enables the team to measure in real time whether solar power generation is consumed on site or gets exported to the grid (see Fig. 4). In many countries in Asia the latter (export to the grid) is either not allowed or not desirable (due to unfavourable economics). Therefore, this feature is highly sought after in the market. A first launch customer is Mapletree Logistics, for which SERIS is providing "live" monitoring services across Asia (Singapore, Malaysia and Japan).

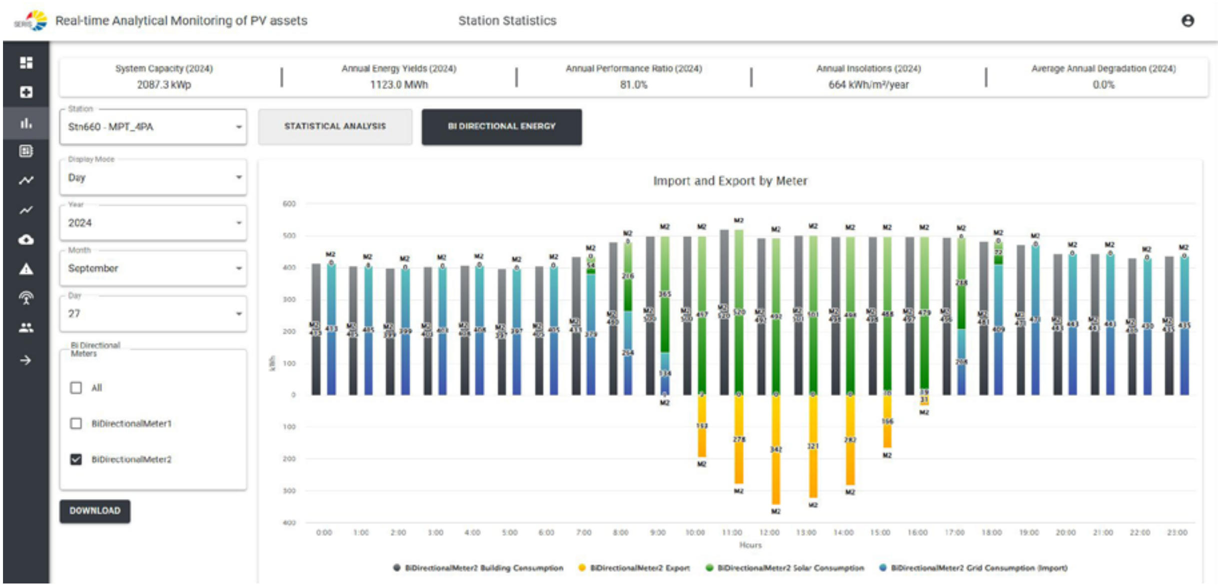


Fig. 4: Screenshot of the SERIS Energy Management platform, showing energy export during the day (yellow bars with negative values)

The Forecasting Team has transferred its fully operational solar forecasting system into the real-time Power System Operation Centre at EMA. The Solar Forecasting tool developed by SERIS went "live" in February 2024, and is now an integral part of the load and power projections over different time horizons in the national energy market of Singapore, managed by the market operator, Energy Market Company (EMC). The developed system has achieved the challenging targets of < 10% normalised root mean square error (nRMSE) for 1-hour-ahead forecasts and < 20% for 7-hour-ahead forecasts – which can be considered as benchmark levels for solar forecasting in tropical climates. The forecasting model was also showcased during the Singapore International Energy Week (SIEW) and the Asia Clean Energy Summit (ACES), see Fig. 5.

Beyond Singapore, the team has developed and tested a regional solar forecasting model which is largely using near-real-time satellite data. The regional model meets the same tight accuracy targets as the Singapore solution.

The group also has further expanded its IP portfolio. The "AI-Powered Software for Visual Impact Assessment (VIA) of Coloured Building Facades" has been successfully filed as provisional patent with the Intellectual Property Office of Singapore, IPOS (No. 10202403074W).

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.

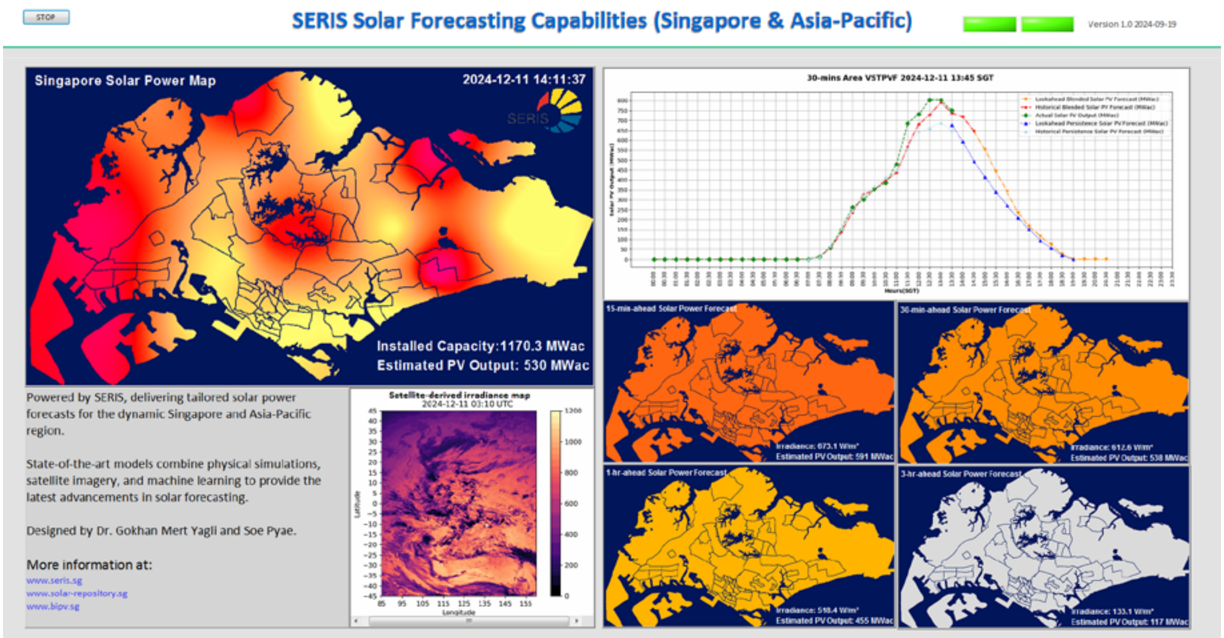


Fig. 5: Visualisation of the real-time ("live") solar forecast as shown during SIEW and ACES 2024

Smart O&M Group

The importance of monitoring of solar PV systems on a daily basis (and ideally in real time) cannot be overstated, given the number of PV assets that are underperforming in the world (a global assessment by a consulting company estimates annual losses of USD 4.6 billion worldwide). Poorly operating systems can also pose fire risks, which must be mitigated. The work of the Smart O&M Group showcases the importance of operating PV systems with modern asset management techniques to promote PV as a reliable, safe and trusted source of electricity. As an example, Fig. 6 shows the continuous daily tracking of the performance ratio across a site for the past 10 years.

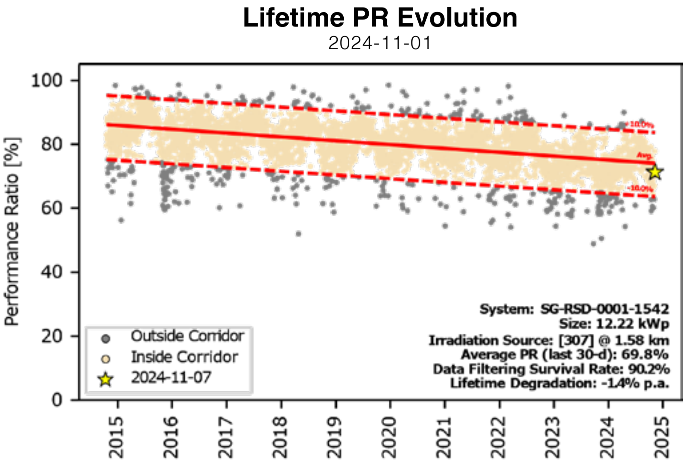


Fig. 6: Daily performance ratio progression over 10 years for a solar PV system in Singapore, showing a degradation rate of -1.4% per annum. (which is much higher than what system owners typically assume)

In 2024 the Smart O&M Group achieved to sign up more than 300 clients across Singapore, India and Southeast Asia, totalling close to 100 MW_p of "assets under management" (AUM) in only 9 months. These facilities span from residential PV systems (kW_p size) to educational, commercial and industrial sites (MWp size) to large solar farms (tens of MW_p range, for example in Thailand and Philippines). The high interest shown by potential clients indicates that more than 1 GW_p of AUM can possibly be achieved in 2025.

Going forward, the "Smart O&M" solutions will be commercialised through the PV DOCTOR™ spin-off (see also separate write-up in this Annual Report).

The PV DOCTOR™ is an Asset Performance Management (APM) company which was soft-launched during the keynote speech on "Smart O&M solution for asset management of solar photovoltaic systems" at the Asia Clean Energy Summit 2024 (ACES), part of the Singapore International Energy Week (SIEW) 2024.

2. Plans of SES Cluster for 2025

- Further expand the activities in the Floating Solar flagship project, in particular the test-bedding of the novel near-shore FPV technology, as well as multi-purpose floating systems (e.g., combination with desalination).
- Carry out research activities in the two agrivoltaic testbeds at YAS Living Lab to develop optimum configurations for balancing crop yield, energy generation and energy consumption, also with a focus on crops with higher revenue potential.
- Design and test novel deployment options, e.g., solar canopies for over-building existing infrastructures.
- Support the Maritime & Port Authority of Singapore (MPA) with solar PV deployment in marine spaces, on electric harbour crafts and on-shore solar-powered charging facilities.
- Further expand the scope of the PV monitoring platform towards real-time energy management.
- 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 2024**

SERIS Flagship Projects

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

1. Perovskite on silicon tandem solar cells
2. Building-integrated Photovoltaics (BIPV)
3. Floating Solar Systems

Selected R&D Projects

1. Enhancing the efficiency and longevity of invited perovskite solar cells with antimony-doped tin oxides
2. Triple-junction solar cells with cyanate in ultrawide bandgap perovskites
3. Design and development of front and back contact solar cells with selective poly-Si passivated contact on the front and local Al contact on the rear
4. Streamlining BIPV projects by integrating digital workflows with Building Information Modelling (BIM)
5. PV module recycling using shock wave fragmentation technology
6. Urban rooftop agrivoltaics (agriculture + PV) test-bedding in Singapore
7. Best practices for asset management in PV system applications
8. Advancing sustainability: The NUS campus-wide solar PV installation project
9. Estimating global horizontal irradiance using regional satellite imagery

SERIS **Flagship Project**

Perovskite on silicon tandem solar cells

Prof Armin ABERLE, Assoc Prof Erik BIRGERSSON, Asst Prof HOU Yi, Dr CHOI Kwan Bum, Dr JANG Yu Jin, Dr KIM Jinhyun, Dr Romika SHARMA

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 29% 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 conversion efficiencies while maintaining low manufacturing costs ($/W). For a 2-junction Si-based tandem solar cell the theoretical 1-Sun efficiency limit is 42.5%, whereby a practical cell efficiency limit of around 35% seems possible in future mass production (beyond 2030). Given their excellent efficiency prospects, Si-based tandem solar cells are of very high importance to Singapore's solar sector, for both the manufacturing and deployment sectors.

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 2024, our research efforts within the project 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 development of 1-cell mini-modules with active areas of 1 and 244 cm^2, as well as the enhancement of our characterisation, simulation and reliability study capabilities for tandem cells and mini-modules.

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

In 2024, the Perovskite-based Multijunction Solar Cells Group in SERIS' NPVC Cluster developed 33.2% efficient small-area (1 cm^2) perovskite-silicon dual-junction tandem solar cells with record-high open-circuit voltage of 2.026 V, using commercially available Cz-based silicon bottom subcells. This was achieved by depositing a high-quality perovskite film onto the textured silicon bottom cell (see Fig. 1). This efficiency result makes SERIS one of the top-3 labs in the world in terms of *small-area* (1 cm^2) two-junction perovskite-silicon tandem cells. One of the core challenges of this research is how to further improve the optical pathlength of light in the tandem architecture to maximise the short-circuit current density. Ongoing work is focused on bridging the efficiency gap to the current world-record 1cm^2 perovskite-silicon tandem solar cell (34.6%, LONGi Green Energy Technology, China).

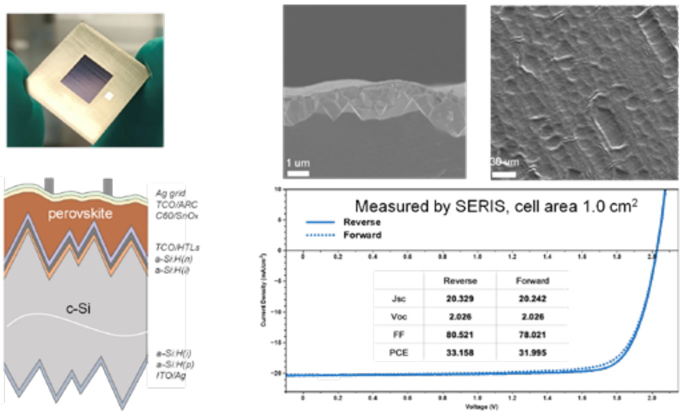


Fig. 1: (top left) Photograph of one of our high-efficiency perovskite-silicon tandem cells (1.0 cm^2 aperture area); (top right) Cross-sectional and top-view SEM images of a perovskite-Si two-junction tandem cell; (bottom left) Cross-sectional schematic of the perovskite-Si tandem solar cell; (bottom right) SERIS-measured J-V curves of the 33.2% perovskite-Si tandem solar cell.

Upscaling of perovskite-silicon tandem solar cells to large areas (244 cm^2) using textured bottom cells

In 2024, the NISCM Cluster made good progress with improving the conversion efficiencies of perovskite-silicon tandem solar cells with active areas of 16 cm^2 and 244 cm^2. Using SERIS-made heterojunction silicon bottom cells, we achieved 25% for 16-cm^2 tandem cells and 20% for M2-size (244 cm^2) tandem cells, as shown in Fig. 2. All layers of the perovskite cells were deposited at SERIS using industrially compatible deposition processes. A low-temperature screen-printed silver metallisation was utilised on both sides of the 2T tandem solar cells. These achievements make SERIS the only facility in Singapore, and one of the very 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 conversion efficiency, SERIS now ranks as one of the top-3 labs in the world for *large-area* 2-junction perovskite-silicon tandem solar cells.

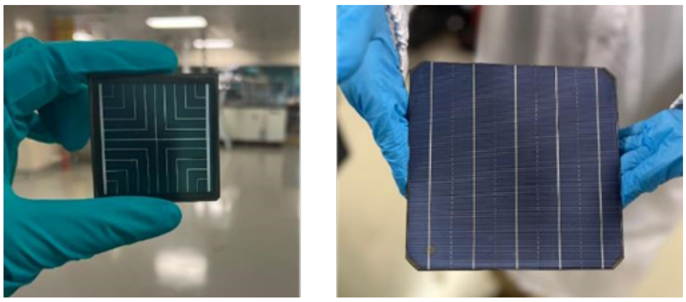


Fig. 2: Photographs of SERIS-made perovskite-silicon 2T tandem solar cells. (Left) 16-cm^2 (active area) device with 25% efficiency (measured in-house); (Right) M2-size (244 cm^2) device with 20% efficiency (measured in-house). Both the silicon bottom cells (heterojunction) and the perovskite top cells were fully fabricated at SERIS.

Development and up-scaling of perovskite-silicon tandem cell mini-modules

In 2024, the project's module team advanced the scaling of perovskite-silicon tandem cell mini-modules from lab-scale devices (1 cm²) to M2-sized (244 cm²) prototypes. This process required significant adaptation of our fabrication methods to meet the low thermal budget requirements imposed by the perovskite layers. The Bill of Materials (BOM, see Fig. 3) was optimised to ensure compatibility with low-temperature processes below 120°C, without sacrificing efficiency. A key achievement was the fabrication and testing of M2-sized mini-modules which delivered efficiencies of about 16%. This success resulted from significant improvements in low-temperature encapsulation and interconnection technologies, designed to meet the strict temperature requirements of perovskite layers. Key advancements were made in refining encapsulation and interconnection technologies to reduce thermal stress on the perovskite layers and protect the structural integrity of the tandem cells. The team developed low-temperature encapsulants and lamination techniques designed to withstand the thermal requirements (< 120ºC) of the perovskite layers. Electrically conductive adhesives (ECAs) were used for low-temperature interconnections. Further improvements were made to ECA pastes to minimise cell-to-module (CTM) losses.

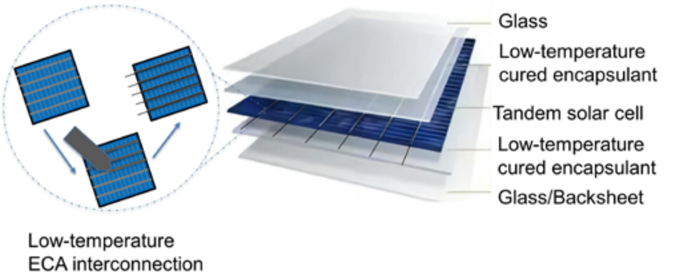


Fig. 3: Bill of Materials (BOM) for low-temperature fabrication of perovskite-silicon tandem cell modules

In 2024 the module team achieved two important technical milestones (see Fig. 4):

- Over 30% efficiency for a 1-cm² (aperture area) 1-cell tandem mini-module. This was achieved by reducing the cell-to-module (CTM) loss to less than 2%, and demonstrates the effectiveness of our low-temperature processing techniques and advanced interconnection methods.
- About 16% efficiency for a M2-sized 244-cm² (aperture area) 1-cell tandem mini-module. Using advanced BOM materials and encapsulation methods, we maintained the structural integrity and performance of these mini-modules, marking a key step towards commercialisation.

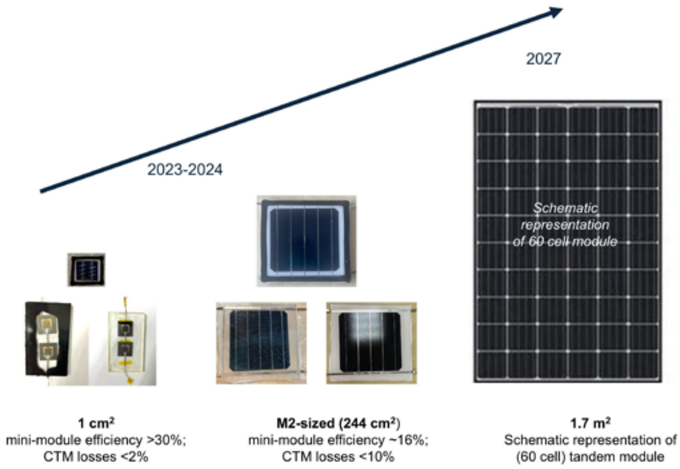


Fig. 4: Scaling from encapsulated 1-cm² tandem devices to 244-cm² tandem mini-modules and 60-cell (1.7 m²) perovskite-silicon PV modules

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 cell mini-modules to 60-cell (~1.7 m²) tandem modules by 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 also preparing for climate chamber testing, including damp heat tests, to refine our processes and improve the resilience and performance of these novel tandem modules in real-world conditions. This will be followed by actual outdoor testing of the prototype modules in Singapore's hot and humid tropical climate.

Overall, this tandem flagship project is progressing well and is making major contributions to bringing the perovskite-silicon tandem solar cell technology closer to commercial viability, with the potential to deliver very-high-efficiency (30%) PV modules optimised for space-constrained environments like Singapore.

Building-integrated Photovoltaics (BIPV)

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

Introduction

Solar deployment in Singapore has grown exponentially, from an installed capacity of 429 MW_p (Megawatt-peak) of photovoltaic (PV) panels in 2020 to 1.4 GW_p in 2024. At the current rate, the nation is projected to exceed its target of at least 2 GW_p (Gigawatt-peak) installed capacity by 2030. However, this translates to only about 3% of Singapore's annual electricity consumption, and there remains a need to expand PV deployment more aggressively. Singapore has an estimated PV installation capacity of 8.6 GW_p 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.

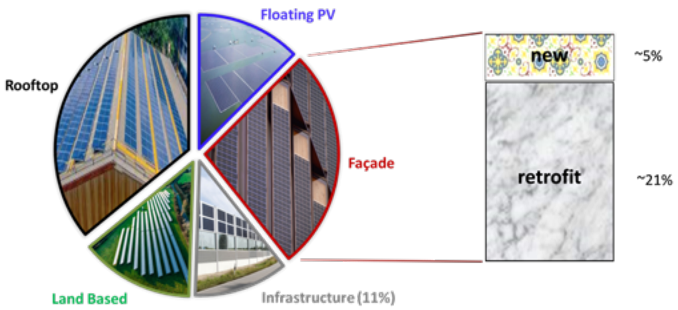


Fig. 1: Distribution of the techno-economic solar potential for PV deployment based on the Solar PV Roadmap of Singapore 2020.

While there still remain significant unexploited rooftop spaces, 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.

Aesthetic PV and test-bedding

To address the key issue of aesthetics, SERIS had previously introduced a novel colouring method for PV modules, called the "Peranakan PV" modules, which allows to create complex and heterogeneous images on panels with minimal optical loss and no current mismatch. More recently, the team further evolved another colouring method, the pointillism-inspired PV modules, that follow an algorithm that translates non-repeated images into a format suited for printing on BIPV modules, adding further design flexibility (see sample in Fig. 2). Through the guided light transmission properties of the inks, and proper design of the colour points, uniform light transmission throughout the entire PV module is maintained and consequently the modules are also hot-spot free.

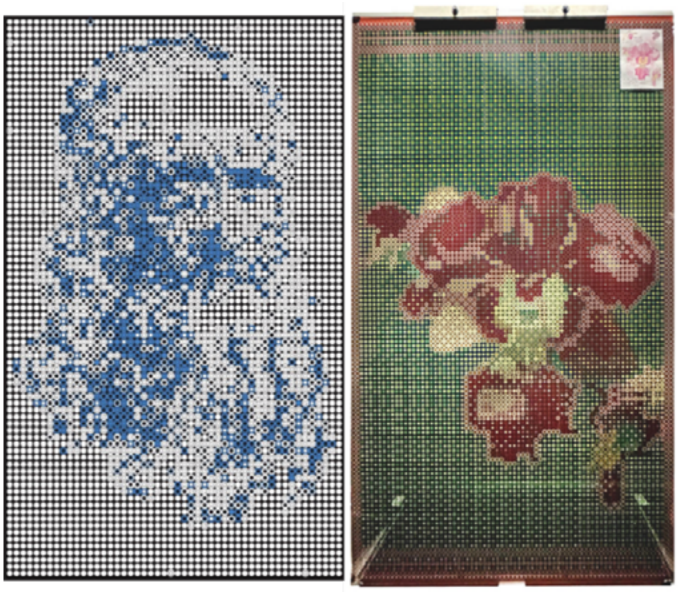


Fig. 2: Mismatch-free pointillism PV panels with various images such as the portrait of Leonardo da Vinci (left) and the Singapore national orchid (right).

In 2024, we initiated the design and construction of a dedicated testbed on the rooftop of SERIS' CleanTech One facility. This setup is meant for outdoor monitoring of BIPV systems (see Fig. 3), incorporating versatile attachment points and a modular, swappable façade system. The testbed will serve as a platform for advancing BIPV technology, enabling comprehensive evaluation of various solutions under real-world conditions, with the advantage of rapid plug-and-play testing.

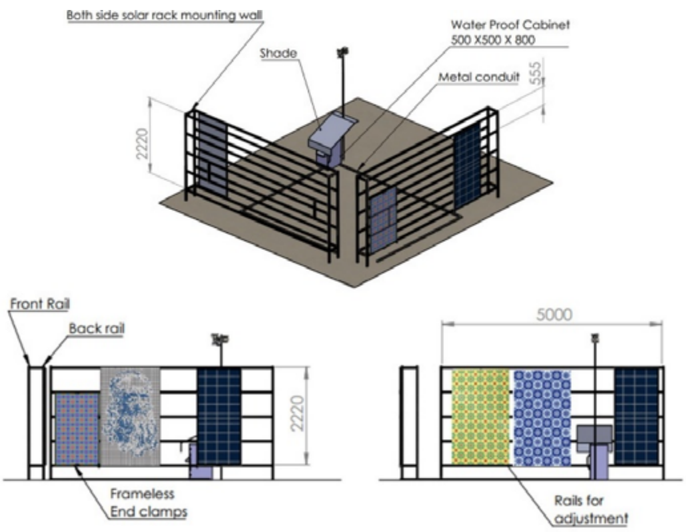


Fig. 3: Proposed BIPV outdoor testbed for façade systems. The testbed will be used to evaluate various technologies as well as mounting and interconnection strategies.

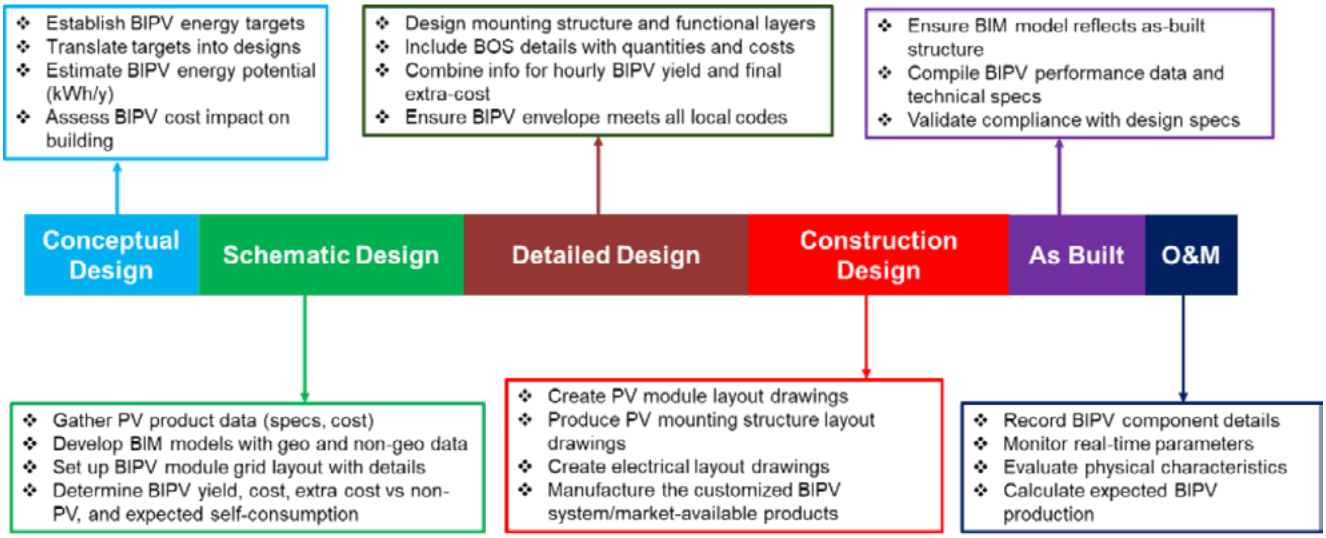


Fig. 4: BIPV-specific tasks integrated at each project stage along the BIM workflow

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 2024, we developed a BIM-based framework tailored to Singapore, integrating BIPV tasks into the existing BCA process across the six project stages (see Fig. 4). This framework includes precise Level of Development (LOD) specifications for BIPV components, covering geometric attributes like dimensions and textures, and non-geometric data such as electrical properties, certifications.

The approach ensures a seamless transition from conceptual design to operation, promoting better collaboration among stakeholders while improving efficiency and cost effectiveness. Our efforts will focus on building a digital BIPV component library, enabling accurate energy generation simulations and optimised façade performance within the BIM environment. This work supports Singapore's drive for low-carbon buildings under the SG Green Plan 2030.

BIPV Displays

Our efforts to advocate for BIPV as an attractive and viable solution for Singaporean facades include show-casing innovative displays at major events. During the 2024 National Day Parade (NDP) in August, we showed a special edition of a "Singapore flag made of solar panels", using digital ceramic inks and made from bifacial heterojunction solar cells, produced in collaboration with REC Solar Pte Ltd. This unique piece (see Fig. 5) was displayed at the NDP Bishan Heartland Exhibition and highlights the potential of BIPV as a prominent architectural feature.

In October, for the Singapore International Energy Week, we fabricated solar panel displays featuring the SIEW and ACES logos (see Fig. 6 for the SIEW logo), demonstrating the versatility of BIPV technology. Additionally, at the inaugural Ministry of Defence Sustainability Day, we presented our patented Peranakan PV and pointillism PV designs, further promoting the diverse applications and aesthetic possibilities in innovative urban architecture.

Fig. 5: Singapore Special Edition BIPV flag at the Bishan Heartlands Exhibition during the 2024 National Day Parade.

Fig. 6: SIEW logo made from BIPV panels, displayed at the main SIEW 2024 exhibition area.

Fig. 7: Showcasing of SERIS developed BIPV technologie at the Ministry of Defence Sustainability Day 2024.

SERIS **Flagship Project**

Floating Solar Systems

Dr Jaffar Moideen YACOB ALI, Dr Oktoviano GANDHI, Dr Thomas REINDL

Floating PV (FPV) offers great opportunities for renewable energy generation, particularly for countries with land constraints and available water bodies like Singapore, South Korea, Japan and the Netherlands. At the end of 2023, the cumulative installed global FPV capacity had reached around 7.6 GW_p (see Fig. 1).

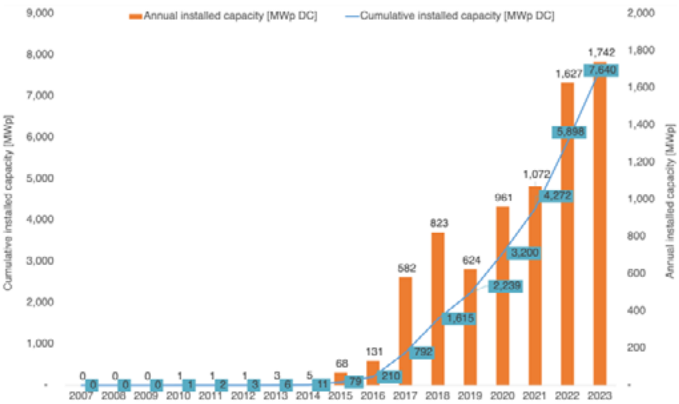


Fig. 1: Globally installed FPV capacity (Source: SERIS FPV database)

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 (see Fig. 2), 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.

Beyond that, the potential for marine FPV is even larger. A SERIS assessment showed that, when limiting the ocean regions to those with favourable environment and excluding protected areas, the resulting ocean area spans ~10.6 million km². By covering just 10% of this area with FPV, the resulting electricity generation would be 6 times larger than today's annual world electricity consumption.

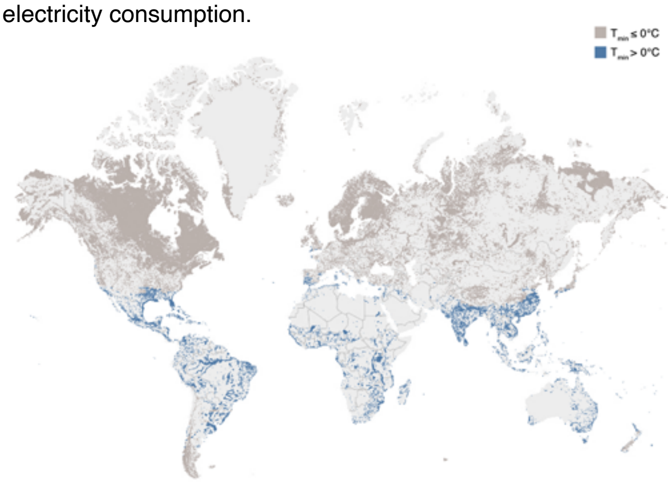


Fig. 2: Global potential of reservoir-based FPV systems

SERIS has been leading the Floating Solar research in Singapore and worldwide since 2016, and has created and maintained a FPV system database of more than 1300 installations to date.

Even though the installed FPV capacity is presently concentrated in only a handful of regions (see Fig. 3), FPV is a global phenomenon, with 63 countries hosting FPV installations at the end of 2023, and many more with projects under development.

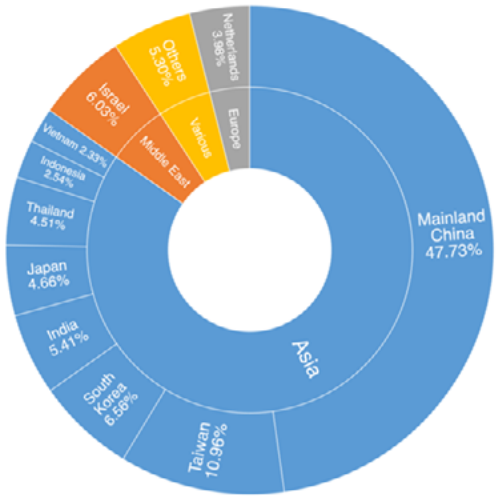


Fig. 3: Shares of cumulative installed FPV capacity by 2023 by region (Source: SERIS FPV database)

The increase in FPV installations, along with the advancements in technology, has brought down FPV cost from a median of 2.41 USD/Wp in 2015 to 1.05 USD/Wp in 2023 (see Fig. 4), which enabled even wider FPV adoption.

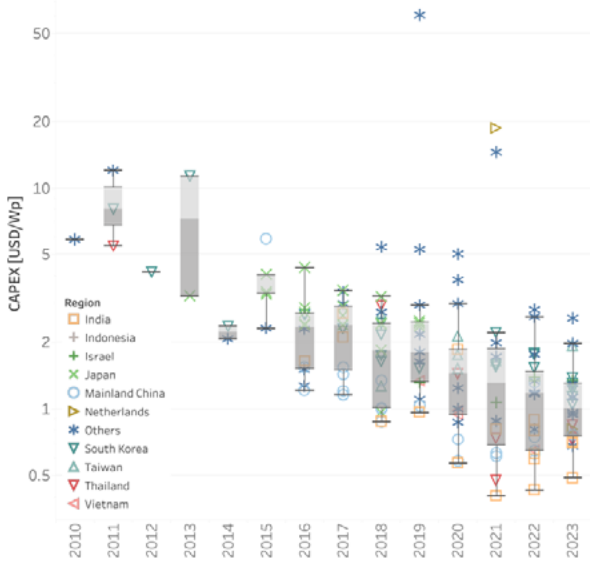


Fig. 4: Reported capital expenditure (CAPEX) for existing FPV installations. The values are not adjusted for inflation (Source: SERIS FPV database).

Such insights from SERIS' FPV database are highly valued by the industry, and regularly shared by SERIS in conferences and exhibitions. To share its knowledge, SERIS also published the "*Where Sun meets Water*" report series, together with the World Bank Group. As of September 2024, downloads of these reports from the World Bank sharing website (ESMAP) have surpassed 160000. This underlines 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. 5 and explained in more detail in the following sections.

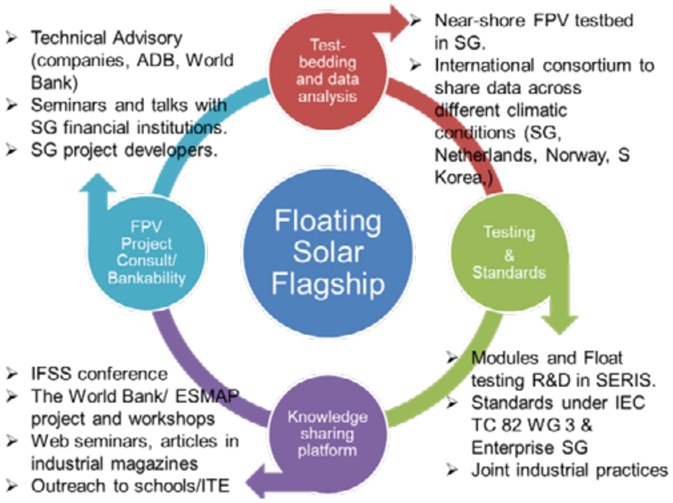


Fig. 5: Key thrusts of the floating solar flagship project

1. 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 would affect the mechanical stability of the floating structure. 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.

SERIS has continued to expand its technical expertise to marine floating solar, and especially near-shore floating PV systems.

SERIS, in partnership with Advario, has won Enterprise Singapore's Sustainability Open Innovation Challenge (SOIC) 2023. The winning project is based on pioneering self-buoyant and flexible floating PV modules, specifically engineered for near-shore conditions. These cutting-edge modules are designed to revolutionise the deployment, redeployment, operation and maintenance processes, setting new standards in efficiency and adaptability. SERIS will now spearhead a pilot deployment in one of Advario's "dead sea" spaces. This initiative not only underscores Singapore's commitment to sustainable energy but also positions SERIS at the forefront of floating solar innovation in marine environments.

SERIS continues to analyse the operation and long-term reliability of the existing FPV testbeds in the Tengeh reservoir, which in turn helps to better understand the long-term economic viability of FPV systems. Potential environmental causes for failures in FPV systems have been identified (see Fig. 6), and the relationships and inter-dependencies of these causes have also been studied. Moreover, a screening of potential failures associated with these root causes in both sub-system and component level has been conducted, with a specific focus on offshore FPV systems. This very detailed failure mode, effects and criticality analysis (FMECA) study has identified more than 100 possible failure modes as well as suitable mitigation measures.

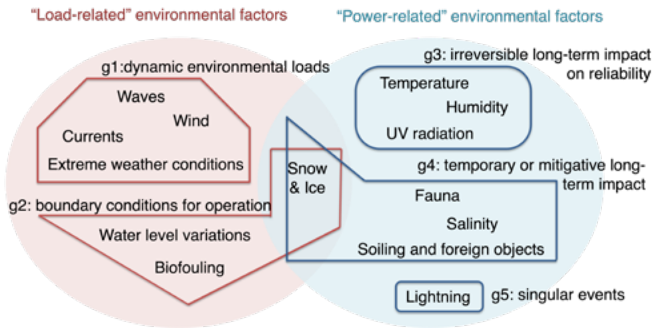


Fig. 6: Environment-related root causes for failures in FPV systems

SERIS has also developed simulation models for the numerical analysis of FPV systems, which can assist the development of the FPV system during the preliminary stage. A simplified version of the simulation process for a membrane-type floating platform is shown in Fig. 7.

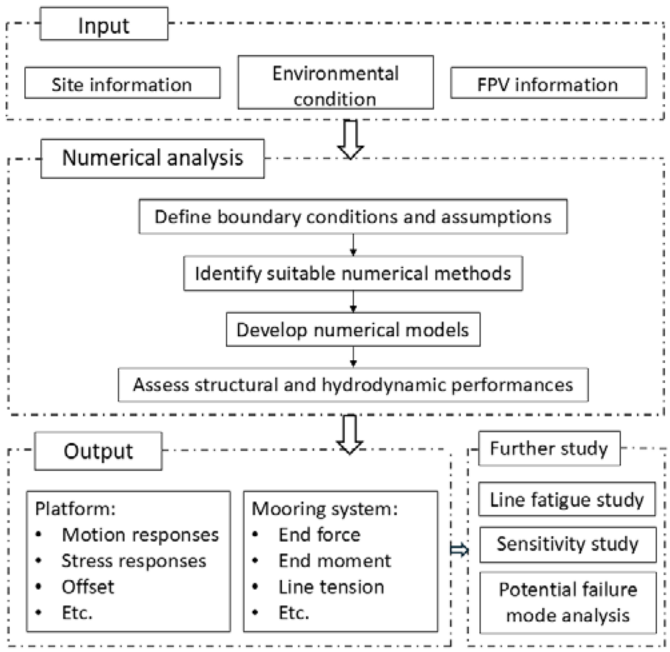


Fig. 7: Simplified workflow for the numerical analysis of membrane-type FPV systems

2. FPV testing & standards

SERIS has led the preparation and publication of a national standard for Floating Solar systems in collaboration with Singapore's standard-setting body, Enterprise Singapore (E-SG). The Technical Reference (TR) TR100:2022 on "*Floating photovoltaic power plants – Design guidelines and recommendations*" aims to further support the industry sector to achieve high-quality FPV installations.

Furthermore, SERIS is spearheading international efforts to establish standards for floating photovoltaics (FPV) through Singapore's active participation in IEC TC82 WG3. In the first quarter of 2024, SERIS took the initiative to convene the inaugural meeting and introduced the framework for the new IEC 62548-3 standard.

3. 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 2024, SERIS has been invited to major international PV conferences – in Austria, China, Indonesia, Japan, 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 a lecture on Floating PV at the "PV Academy" event of the EU PVSEC 2024 conference in Vienna and by actively participating in the half-day symposium on "Harvesting Sunshine: Exploring the Future with Floating Solar PV" organised by the Society of Floating Solutions (Singapore).

4. 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 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. For example, as of 2024, SERIS was involved in the feasibility studies and design of ~2.0 GW_p of FPV systems.

Plans for 2025

SERIS will continue to drive scientific excellence and innovation in Floating Solar and continue to share its know-how through technical advisory, international conferences and outreach, as well as scientific publications. Apart from the plans to set up a Floating Solar testbed in marine conditions, SERIS is also exploring the multi-purpose uses of space in near- and off-shore applications. The proposed uses aim to "solve more than one problem for Singapore", for example the additional generation of fresh produce (i.e., by combining FPV with fish farming and/or crop growing), fresh water (i.e., by combining FPV with desalination), or green hydrogen (i.e., by combining FPV with electrolysers).

Enhancing the efficiency and longevity of inverted perovskite solar cells with antimony-doped tin oxides

Dr Jia LI, Haoming LIANG, Asst Prof HOU Yi

1. Background

Perovskite solar cells (PSCs) have emerged as a promising technology in the field of photovoltaics, demonstrating remarkable progress in power conversion efficiency (PCE) over the past decade.[1] The carrier transporting layers play a vital role in boosting efficiency. For inverted planar *p-i-n* structured PSCs, organic self-assembled monolayer (SAM) molecule-based hole transporting materials (HTMs) have demonstrated good performance.[2] However, they are known to generate non-wetting surfaces and hinder the growth of defect-free perovskite layers. Consequently, it is common to integrate SAM with an inorganic HTM. Nickel oxide (NiO_x) is one of the most extensively studied inorganic HTMs due to its favourable optical properties and aligned energy levels. However, NiO_x is notorious for its reactivity towards perovskite, leading to material degradation.[3] This issue can only be slightly mitigated with a SAM layer coated on top due to its loosely packing nature, creating challenges for the long-term stability of perovskite devices.

2. Scope of project & objectives

The root cause of stability issues stems from the reaction between perovskite and NiO_x. Organic cations such as formamidinium (FA^+) can be deprotonated, while halide anions such as iodide (I^-) can be oxidised to form FA and I_2, followed by the dissipation of these species, leading to degradation. [4] To mitigate interfacial reactions and improve device stability, a more chemically stable material is needed to replace NiO_x. Among the metal oxides studied, tin oxide (SnO_2) is a promising candidate for an electron transporting material (ETM) in planar *n-i-p* structured perovskite devices. SnO_2 is known to easily change its electronic properties via doping strategies, such as indium tin oxide (ITO) and fluorine-doped tin oxide (FTO). However, SnO_2 is typically considered an n-type material with a relatively high concentration of electrons. To make it compatible with hole transport, antimony (Sb^{3+}) is introduced to bring extra holes into the system, transforming the antimony-doped tin oxide (ATO_x) into a p-type material. [5] ATO_x-based perovskite devices exhibit better performance and stability compared to NiO_x-based devices.

3. Significance & impact of project

In this study, we demonstrate a significant boost in device efficiency by replacing NiO_x with ATO_x, which can be attributed to suppressed interfacial reactions between the perovskite layer and the metal oxide HTL. We achieved a power conversion efficiency of 25.7% for 0.05 cm^2 devices and 24.6% for 1 cm^2 devices, with suppressed scale-up losses. ATO_x-based devices also exhibit superior stability, maintaining 93% of the initial PCE after 500 hours of operation under 1-Sun illumination, while NiO_x-based devices preserve only 77% of their initial PCE under the same conditions.

4. Methodology & Results

To characterise and compare the interface reactivity of NiO_x and ATO_x, we deposited a thin layer of formamidinium iodide (FAI) onto both metal oxide HTLs. The deprotonation reaction was then characterised using X-ray photoelectron spectroscopy (XPS) analysis on the corresponding elements. Figures 1A and 1B present the Ni 2p and O 1s spectra of NiO_x-based samples before and after FAI deposition. The Ni 2p spectra show a significant increase in the Ni^{2+} component intensity, while the intensities of higher oxidation state nickel components, such as Ni^{3+}, decrease. This suggests reaction at the HTL/perovskite interface such that nickel components with higher oxidation states are converted to Ni^{2+}. These interface reactions are often associated with the deprotonation of organic FA^+ cations and the formation of iodine, as suggested by Boyd et alia. [3] A similar trend is observed in the O 1s spectra, with a shift towards the lower energy region, indicating the conversion of higher binding energy oxygen components to lower energy components. Figures 1C and 1D present the XPS analysis for ATO_x-based samples. In this case, hardly any changes are observed in the tin, antimony, or oxygen spectra before and after FAI deposition, suggesting no interfacial reaction between the ATO_x and the perovskite layer. This can be attributed to the stable nature or high reaction energy barrier for the conversion between Sn^{4+}/Sn^{2+} and Sb^{5+}/Sb^{3+} redox pairs. Figures 1E and 1F present scanning electron microscope (SEM) images of perovskite layers deposited on NiO_x and ATO_x. For perovskite layers deposited on NiO_x, a significant amount of lead iodide (PbI_2) particles are found on the surface due to the reaction between perovskite and NiO_x. In contrast, only a few PbI_2 nanoparticles are observed on the surface of ATO_x-based samples.

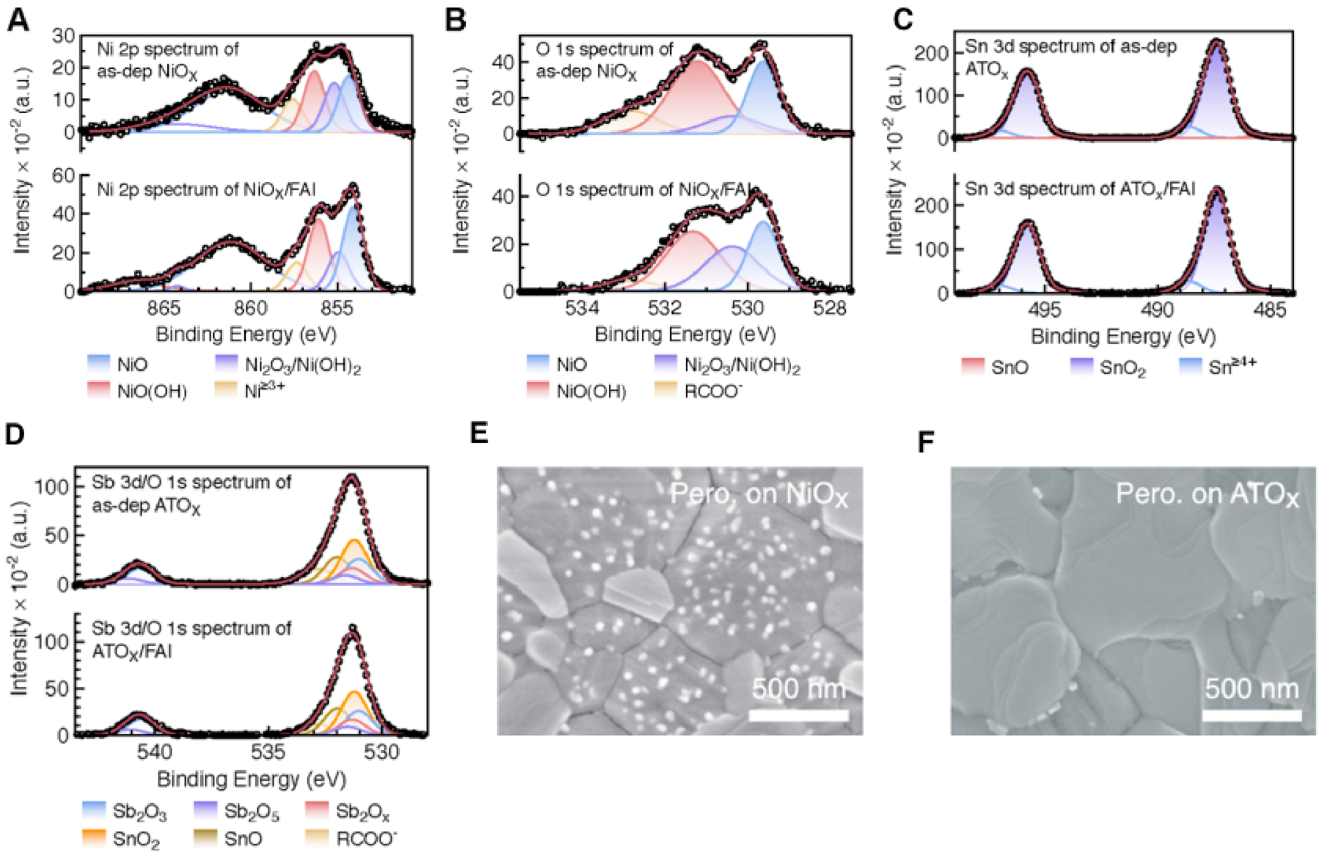


Fig. 1: XPS analysis of Ni 2p (A), O 1s (B) spectra of NiO_x-based sample and Sn 3d (C), Sb 3d & O 1s (D) spectra of ATO_x-based sample. SEM top view of perovskite on NiO_x and ATO_x.(This figure is reproduced from Li, J., Liang, H., Xiao, C. et al. Enhancing the efficiency and longevity of inverted perovskite solar cells with antimony-doped tin oxides. Nat Energy 9, 308–315 (2024), with permission from Springer Nature)

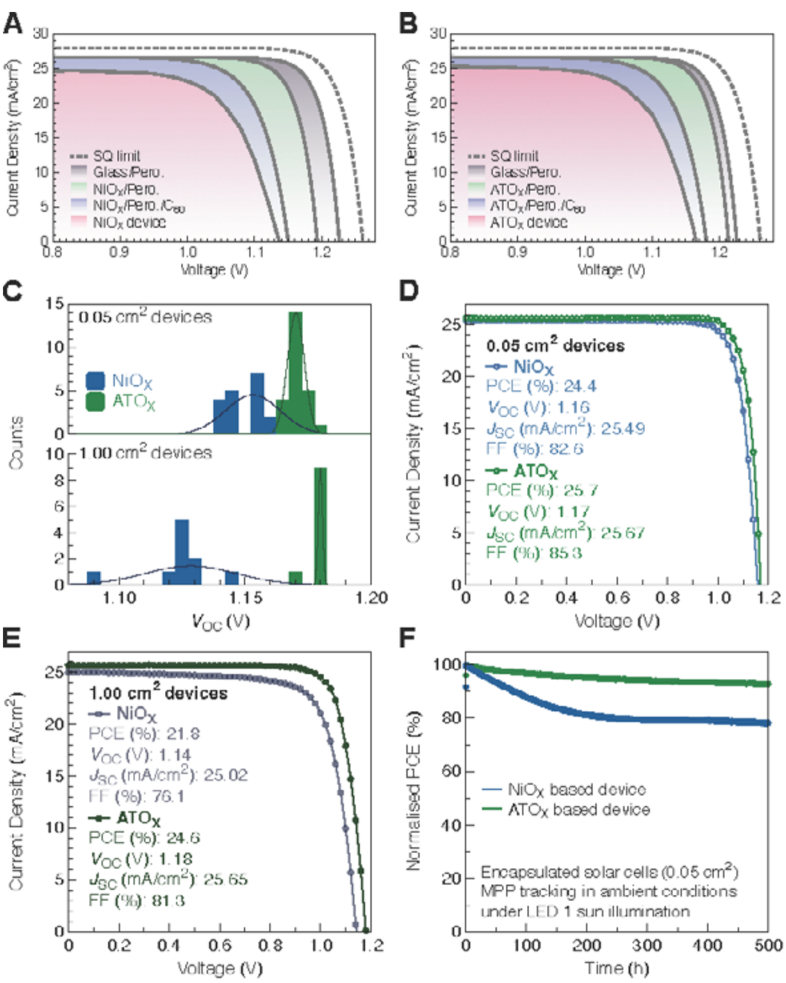


Fig. 2: Pseudo J-V characteristics of (A) NiO_x-based and (B) ATO_x-based sample reconstructed from Suns-QFLS measurements. (C) V_{OC} distribution of NiO_x-based and ATO_x-based devices. (D) 0.05 cm^2 and (E) 1 cm^2 champion devices based on NiO_x and ATO_x. (F) Operational stability measurements of 0.05 cm^2 NiO_x-based and ATO_x-based devices under 1-Sun illumination via maximum power point tracking. (This figure is reproduced from Li, J., Liang, H., Xiao, C. et al. Enhancing the efficiency and longevity of inverted perovskite solar cells with antimony-doped tin oxides. Nat Energy 9, 308–315 (2024), with permission from Springer Nature)

The benefits of ATO_x as a stable hole transporting material for perovskite-based devices were further investigated. Trap-assisted non-radiative recombination-induced open-circuit voltage (V_{OC}) loss was studied via measurements of quasi-Fermi level splitting (QFLS) values under different illumination intensities. These measured implied V_{OC} (iV_{OC}) were used to construct pseudo current density-voltage (J-V) plots, as shown in Figs. 2A and 2B. One main loss channel of iV_{OC} arises from the HTL/perovskite interface, with a significant loss of 33 mV observed between the bare perovskite sample and the NiO_x/perovskite sample, while only a 12 mV loss was found between the bare perovskite sample and the ATO_x/perovskite sample. This can be attributed to suppressed interfacial reactions, resulting in fewer defects at the HTL/perovskite interface. Moreover, the iV_{OC} loss from the ETL side is also slightly mitigated due to improved perovskite layer quality. The suppressed iV_{OC} loss is also reflected in the solar cell devices, regardless of the active area. For larger devices, an even larger gap is found in the mean V_{OC} between ATO_x-based and NiO_x-based devices. Figure 2C presents the statistical distribution of device V_{OC} obtained from J-V characteristics. For 0.05 cm^2 devices, the mean V_{OC} of NiO_x-based devices is 1.153 V, while ATO_x-based devices achieve 1.170 V, resulting in a V_{OC} gap of approximately 17 mV. For 1 cm^2 devices, the gap widens significantly, with NiO_x-based devices showing a mean V_{OC} of 1.124 V and ATO_x-based devices reaching 1.179 V, creating a substantial 55 mV difference. This observation underscores the advantage of ATO_x for scale-up applications. Figures 2D and 2E present J-V characteristics of 0.05 cm^2 and 1 cm^2 champion devices, respectively. For 0.05 cm^2 devices, the NiO_x-based device achieves an efficiency of 24.4%, while the ATO_x-based device reaches 25.7%, with the main difference observed in the fill factor (FF). As devices were scaled up to 1 cm^2, all performance parameters decreased for NiO_x-based devices, particularly the FF, which dropped to 76.1% for the champion device. In contrast, ATO_x-based devices maintain comparable short-circuit current (J_{SC}) and V_{OC} values to their 0.05 cm^2 counterparts, with only a slight decrease in FF, resulting in 81.3% for the champion device. Although both types of devices experienced a drop in FF during scale-up, ATO_x-based devices exhibited a smaller loss compared to NiO_x-based devices, further demonstrating the superiority of ATO_x for scale-up applications. Figure 2F presents the long-term operational stability for both types of devices, with ATO_x-based devices showing superior stability due to their more stable interface. The ATO_x-based device maintains 93% of its initial PCE after 500 hours of operation under 1-Sun illumination, while the NiO_x-based device preserves only 77% of the initial PCE under the same conditions.

5. Conclusions

This study demonstrates the significant advantages of utilising ATO_x as a hole transporting material in inverted planar perovskite solar cells compared to the conventional NiO_x. The replacement of NiO_x with ATO_x has led to substantial improvements in device performance and stability and has demonstrated advantages for scale-up applications. Moving forward, investigation on long-term stability studies under various environmental conditions to assess the real-world applicability of ATO_x-based devices could be considered.

References

[1] J. Park et al., "Controlled growth of perovskite layers with volatile alkylammonium chlorides," Nature, vol. 616, no. 7958, pp. 724–730, Apr. 2023, doi: 10.1038/s41586-023-05825-y.

[2] A. Al-Ashouri et al., "Monolithic perovskite/silicon tandem solar cell with >29% efficiency by enhanced hole extraction," Science (1979), vol. 370, no. 6522, pp. 1300–1309, Dec. 2020, doi: 10.1126/science.abd4016.

[3] C. C. Boyd et al., "Overcoming Redox Reactions at Perovskite-Nickel Oxide Interfaces to Boost Voltages in Perovskite Solar Cells," Joule, vol. 4, no. 8, pp. 1759–1775, Aug. 2020, doi: 10.1016/j.joule.2020.06.004.

[4] K. Schutt, P. K. Nayak, A. J. Ramadan, B. Wenger, Y. Lin, and H. J. Snaith, "Overcoming Zinc Oxide Interface Instability with a Methylammonium-Free Perovskite for High-Performance Solar Cells," Adv Funct Mater, vol. 29, no. 47, p. 1900466, Nov. 2019, doi: 10.1002/adfm.201900466.

[5] C. Liu et al., "Utilizing the unique charge extraction properties of antimony tin oxide nanoparticles for efficient and stable organic photovoltaics," Nano Energy, vol. 89, p. 106373, Nov. 2021, doi: 10.1016/j.nanoen.2021.106373.

Triple-junction solar cells with cyanate in ultrawide-bandgap perovskites

Dr Shunchang LIU, Ran LUO, Dr Renjun GUO, Haoming LIANG, Xiao GUO, Asst Prof HOU Yi

1. Background

Perovskite-based tandem solar cells offer an effective approach for surpassing the Shockley-Queisser (S-Q) efficiency limits in existing photovoltaic technologies [1]. The advancement of ~1.67 eV and ~1.77 eV wide-bandgap perovskites has catalysed rapid progress in the field of perovskite-based dual-junction solar cells, with a current power conversion efficiency (PCE) record of 33.7% for perovskite/Si tandem [2]. Drawing inspiration from III-V multijunction solar cells, the incorporation of an ultrawide-bandgap (UWBG) perovskite with a bandgap above 1.90 eV into a triple-junction solar cell (TJSC) offers a pathway for further boosting the efficiency, potentially achieving efficiencies as high as 51% [3]. Initial studies have indicated the feasibility of constructing perovskite-based TJSCs, with efficiencies reaching 24.3% in all-perovskite configurations and 22.23% in perovskite/perovskite/Si configurations [4,5].

2. Scope of project & objectives

In this work, we successfully incorporated a novel pseudohalide, cyanate (OCN^-), into UWBG perovskites. Notably, cyanate exhibits an effective ionic radius (1.97 Å) comparable to that of bromide (1.95 Å). This substitution led to lattice constant reduction, bandgap increment, and enhanced crystal orientation. Furthermore, this incorporation induced moderate lattice distortion, contributing to increased film uniformity and elevated formation energy for defects. Consequently, a remarkable V_{OC} of 1.422 V was attained in OCN-substituted inverted UWBG perovskite solar cells, coupled with a V_{OC} × FF product exceeding 80% of the S-Q limit and stable performance under maximum power point (MPP) tracking. The cyanate-substituted perovskite was further implemented in a perovskite/perovskite/Si TJSC, achieving a certified efficiency of 27.10%, with a peak efficiency of 27.62%, across an active area of 1 cm^2.

3. Significance & impact of project

Our work confirms the atomic-scale incorporation of OCN anions into the perovskite lattice, and shows that the OCN ions significantly reduce the nonradiative recombination in the ultrawide bandgap perovskite film. Therefore, single-junction perovskite solar cells incorporated with cyanate can achieve a higher V_{OC} of 1.422 V compared to 1.357 V for conventional perovskite solar cells. As a result of the above innovations and advancements, our work achieves a world-record efficiency of 27.62% (certified 27.1%) in perovskite-based triple-junction solar cells. This accomplishment significantly surpasses the PCEs previously reported for all other perovskite-based triple-junction tandems as well as single-junction perovskite and silicon solar cells.

4. Methodology & Results

OCN serves as a linear pseudohalide that is anticipated to exhibit strong interaction with Pb. It possesses an effective ionic radius close to that of Br, making it a promising candidate for bromide substitution in UWBG perovskites. The optimum ratio of 5% OCN was incorporated into the $FA_{0.75}Cs_{0.25}Pb(I_{0.5}Br_{0.5})_3$ perovskites with a suitable bandgap of 1.93 eV. To gain deeper insights into the impact of OCN on modifying the crystal lattice structure of perovskites, we performed low-dose atomic-resolution TEM to systematically investigate the role of OCN in the perovskite lattice. TEM images, acquired along the [001] zone axis and presented in Fig. 1a and b, enabled us to obtain the corresponding fast Fourier transform (FFT) patterns for the perovskite films, both with and without OCN. The angle between the (001) and (010) crystal planes of the original perovskite is approximately 90.5°, signifying a cubic phase with no evident structural distortion (Fig. 1a). However, on incorporating 5% OCN, a noticeable alteration in the angle in the diffraction patterns is observed, with an increase to 96.6° (Fig. 1b). This deviation is consistent with the calculated angle between the (210) and ($\bar{2}10$) planes in the new OCN-incorporated phase. The shift in the angle can be primarily attributed to the induced structural distortion and changes in the vibrational degrees of freedom in the PbX_6 octahedra [6].

Then we turn our attention to the device performance of UWBG single-junction cells. Our investigation commenced with photoluminescence (PL) measurements, and the corresponding quasi-Fermi level splitting values (QFLSs) were calculated. Figure 1c shows a summary of the device V_{OC}, QFLS, radiative voltage (V_{OC}, rad), and S-Q limit (V_{OC}, SQ). Although both the control and target stacks exhibit similar levels of nonradiative loss at each interface, they significantly differ in their bulk nonradiative losses. Specifically, the bulk nonradiative loss of the target sample is reduced by 71 mV, underscoring its ability to mitigate nonradiative recombination defects in the bulk of perovskites. Density functional theory (DFT) calculations confirm that OCN incorporation increases the defect formation energy and the energy barrier of ion migration (Fig. 1d).

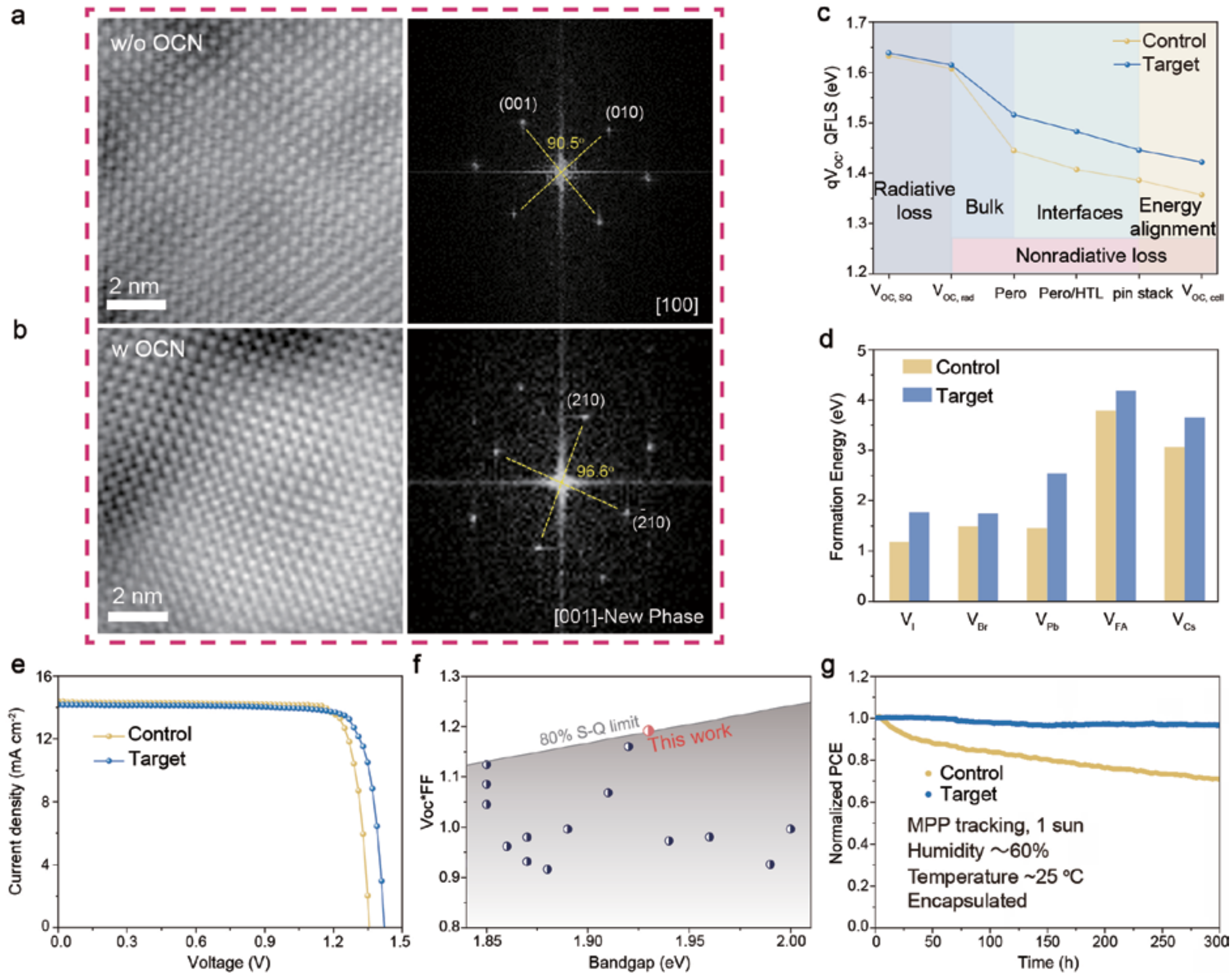


Fig. 1: a-b) High-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) images of the perovskite films without and with 5% OCN, the corresponding FFT images are shown on the right side. c) Schematic of the voltage evolution with different stacks. d) Calculated formation energy of different vacancy defects. e) J–V curves of champion control and target single-junction devices. f) Comparison of V_{OC}×FF products between this work and other reported UWBG perovskite solar cells with a p–i–n structure. g) Long-term operational stability under 1-sun illumination.

Next, we examined the best-performing single-junction solar cell with a p-i-n structure. As shown in Fig. 1e, the incorporation of OCN sharply increases V_{OC} from 1.357 V to 1.422 V, agreeing well with the above analysis. We compared V_{OC} × FF products in our work and previously reported UWBG perovskite solar cells with p-i-n structures. Our target device delivers a V_{OC} × FF product of 80.3% of its S-Q limit, surpassing all the reported results (Fig. 1f), making it promising as a top cell in TJSCs. Finally, when continuously operated under the MPP for 300 hours with encapsulation in air (humidity >60%), the PCE of the target device remains above 96%, whereas the control device preserves an ~70% PCE (Fig. 1g).

Encouraged by the promising device performance imparted by OCN, we fabricated perovskite/perovskite/Si TJSCs. Prior to assembling a TJSC, a high quality perovskite (middle cell)-Si dual-junction half-cell was obtained. Figure 2a shows a cross-sectional scanning electron microscopy (SEM) image of this dual-junction device, which has a PCE of 25.03%, with a V_{OC} of 1.841 V, a J_{SC} of 16.71 mA cm^{-2}, and an FF of 81.3%. We integrated the UWBG perovskite with this dual-junction half-cell to create a monolithic perovskite/perovskite/Si TJSC. The final configuration of this TJSC is textured Si/ITO/Me-4PACz/1.55-eV perovskite/C_{60}/SnO_2/ITO/NiO_x/Me-4PACz/UWBG perovskite/C_{60}/SnO_2/ITO/LiF, as shown in Fig. 2b. The cross-sectional SEM image shows that the UWBG perovskite uniformly covers the middle cell without obvious damage to the underneath layer. Figure 2c gives the J-V curves of the TJSCs with different top cells. Notably, the incorporation of OCN boosts the efficiency from 25.32% (V_{OC} = 3.021 V, J_{SC} = 11.48 mA cm^{-2}, FF = 73.01%) to 27.62% (V_{OC} = 3.132 V, J_{SC} = 11.58 mA cm^{-2}, FF = 76.15%) with an active area of ~1 cm^2. After continuous operation under MPP tracking for 600 s, the efficiency of the champion device stabilised at 27.27% (Fig. 2d). The integrated J_{SC} values from EQE measurements for the top, middle, and bottom cells of the champion target device are 12.22, 11.29, and 15.63 mA cm^{-2}, respectively (Fig. 2e), aligned with the J-V curve. We also sent the champion device to an accredited independent PV calibration laboratory (Shanghai Institute of Microsystem and Information Technology, SIMIT) for certification, and a certified PCE of 27.10% was obtained under a reverse scan with no hysteresis (Fig. 2f), agreeing well with the value measured in-house. Our result represents the highest-performing perovskite-based TJSC to date.

We evaluated the long-term stability of TJSCs using International Summit on Organic Photovoltaic Stability protocols, ISOS-D-3 and ISOS-L-3 (Fig. 2g). After 700 hours of exposure to a temperature of 65 °C and 85% relative humidity (RH), the encapsulated control and target devices retained 91% and 96% of their initial PCEs, respectively. Furthermore, under AM 1.5G 1-sun illumination at 65 °C and 50% RH, the target device maintained 80% of original PCE after 300 hours (T_{80} = 300 h), whereas the control device quickly dropped to 80% of initial PCE after 70 hours.

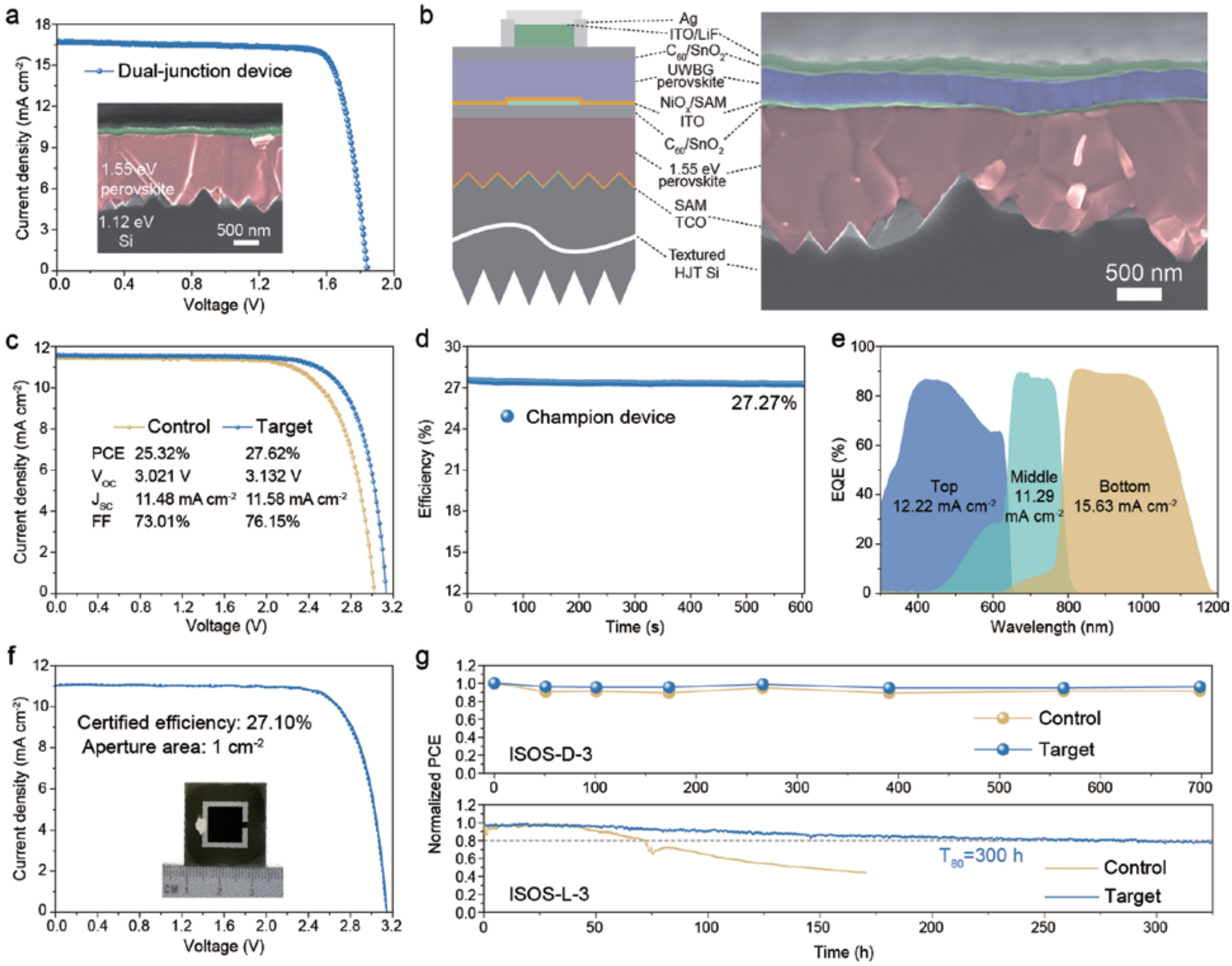


Fig. 2: a) J–V curve from the reverse scan of champion dual-junction device. Inset, cross-sectional SEM image of the typical dual-junction device. b) Schematic structure and cross-sectional SEM image of the TJSC. c) J–V curves of control and target TJSCs. d) MPP tracking measurement of the champion TJSC. e) EQE spectra for each subcell of the champion TJSC. f) Certified J–V curves by SIMIT. Solid line, reverse scan; dashed line, forward scan. Inset, picture of the champion device. g) Long-term stability test of control and target TJSCs following ISOS-D-3 and ISOS-L-3 protocols.

5. Conclusions

We discovered that the pseudohalide OCN^-, which bears a similar effective ionic radius to Br^-, can be integrated into the crystal lattice of UWBG perovskites. Comprehensive studies showed that this substitution enhances the uniformity of the perovskite film, and elevates the formation energy of vacancy defects, consequently greatly elevating V_{OC} and resulting in the highest $V_{OC} \times FF$ product for UWBG perovskite solar cells. Our findings on the role of the pseudohalide OCN ion contribute a fresh perspective to understanding how halide anions influence perovskite properties. Moreover, we fabricated monolithic perovskite/perovskite/Si TJSCs using commercial heterojunction Si solar cells and achieved a record efficiency of 27.62%, certified at 27.10%, highlighting the potential of perovskite-based TJSCs.

References

[1] T. Leijtens et alia, Opportunities and challenges for tandem solar cells using metal halide perovskite semiconductors. Nature Energy 3, 828-838 (2018).

[2] Best research-cell efficiencies. NREL https://www.nrel.gov/pv/cell-efficiency.html (September 2, 2023).

[3] A. W. Y. Ho-Baillie et alia, Recent progress and future prospects of perovskite tandem solar cells. Applied Physical Review 8, 041307 (2021).

[4] Z. Wang et alia, Suppressed phase segregation for triple-junction perovskite solar cells. Nature 618, 74-79 (2023).

[5] Y. J. Choi et alia, Atomic layer deposition-free monolithic perovskite/perovskite/silicon triple-junction solar cells. ACS Energy Letters 8, 3141-3146 (2023).

[6] W. Weiet et alia, An unusual phase transition driven by vibrational entropy changes in a hybrid organic-inorganic perovskite. Angewandte Chemie International Edition 57, 8932-8936 (2018).

This article is an extract of a more comprehensive work published in Nature in 2024: "Triple-junction solar cells with cyanate in ultrawide bandgap perovskites" (Nature 628, 306–312 (2024). https://doi.org/10.1038/s41586-024-07226-1), by Shunchang Liu, Yi Hou, et al.. Reproduced with permission from the publisher Springer Nature.

Design and development of front and back contact solar cells with selective poly-Si passivated contact on the front and local Al contact on the rear

Dr Pradeep PADHAMNATH, Wook-Jin CHOI, Gabby DE LUNA, John Derek ARCEBAL, Ajeet ROHATGI

1. Background

The commercial production of passivated contact silicon solar cells is expected to capture 60% of the global market share within 10 years [1]. The polysilicon (poly-Si) based passivated contact utilises an ultrathin (1-2 nm) interfacial oxide layer (iO_x) capped by a heavily doped poly-Si layer. Efficiencies exceeding 26% have been achieved for both small-area lab-scale devices [2, 3] and for large-area commercial-scale solar cells [4]. Parasitic absorption in the poly-Si layers has predominantly limited the application of the technology to the rear side of the solar cells [5-8]. However, solar cells incorporating poly-Si based passivated contacts on both front and rear of a solar cell could have the potential to achieve efficiencies exceeding 26% [9, 10]. Limiting the front poly-Si layers to only under the metal contacts provides excellent contact passivation, boosting the open-circuit voltage (V_{oc}) while minimising the losses in the short-circuit current density (J_{sc}) of the solar cells. The increased interest in solar cells with passivated contacts on both front and rear side resulted in several studies on different metallisation approaches for such devices. These include a low-temperature Ag metallisation process [11, 12], two-sided Ni/Ag plating to form metal contacts [13], or high-temperature metallisation with front Ag and rear Ag/Al contacts [14]. Here, we present a 22.5% efficient M2-size n-type rear-junction biPoly™ solar cell with front and back passivated contacts, and with front Ag on top of a selective poly-Si film and a rear local Al contact using a non-fire-through paste.

2. Scope of project & objectives

In our previous work we presented the biPoly™ solar cell, where the poly-Si on the front was patterned using an industrial inkjet process and the metal contacts to the poly-Si layers on both sides were screen-printed using high-temperature fire-through pastes, reaching efficiencies 22% [14]. To further improve the performance and lower the cost of such solar cells, we investigate the feasibility of using non-fire-through Al paste making local contacts through areas ablated with a laser. The impact of Al paste with different conditions such as (a) different pitch of local contact openings (LCO); (b) different Si content in the Al paste, and (c) impact of firing temperature on the rear side contacts are investigated. Through thorough investigation and loss analysis, we try to analyse the reasons behind the change in the solar cell performance and try to suggest possible pathways for further enhancement of the device performance.

3. Significance & impact of project

This work highlights the flexibility and wide range of application of the poly-Si passivated contact technology with a unique metallisation technique using rear local Al contacts using a non-fire-through paste. Development of this metallisation technique on front and back passivated contact solar cells could extend its PV market dominance with improved efficiency and cost reduction with the use of a non-scarce metal such as Al paste. This work also shows that solar cells featuring passivated contacts on both front and rear can be fabricated using industrial processes and equipment. Further, such solar cells have the potential of achieving high V_{oc}, making them an ideal candidate for bottom cells in tandem solar cell applications.

4. Methodology & Results

Processing details:

All solar cells fabricated in this work feature selective poly-Si contacts on the front side. The front side of the solar cells incorporates poly-Si fingers over which the metal fingers were screen-printed. All biPoly™ solar cells fabricated in this work are rear-junction bifacial cells on n-type substrates, with p^+ poly-Si on the rear and n^+ poly-Si on the front. Full fabrication details prior to the metallisation process can be found in our previous work [14]. Two different metallisation schemes were used for the rear surface. In one scheme, contact fingers were screen-printed using commercial fire-through (FT) Ag-Al metal paste on the p^+ poly-Si layer. In the other scheme, a non-fire through (nFT) Al paste was used. For using nFT paste, a nanosecond green laser was used to open dot-like patterns on the rear side. Three different dot-to-dot pitches were experimented with: 100, 250 and 400 μm. Finally, the metal fingers were screen printed over the dot pattern using non-fire through (nFT) Al paste. The solar cells with nFT Al rear contacts were fired at three different peak temperatures (700, 720 & 740 ºC). The silicon content in the nFT Al paste was also varied (low, medium, and high). All nFT Al pastes used for metallisation in this work were provided by our research collaborator (Toyo Aluminium KK, Japan). The cross-section schematics of the solar cells and the experimental design for the experiment is shown in Fig. 1.

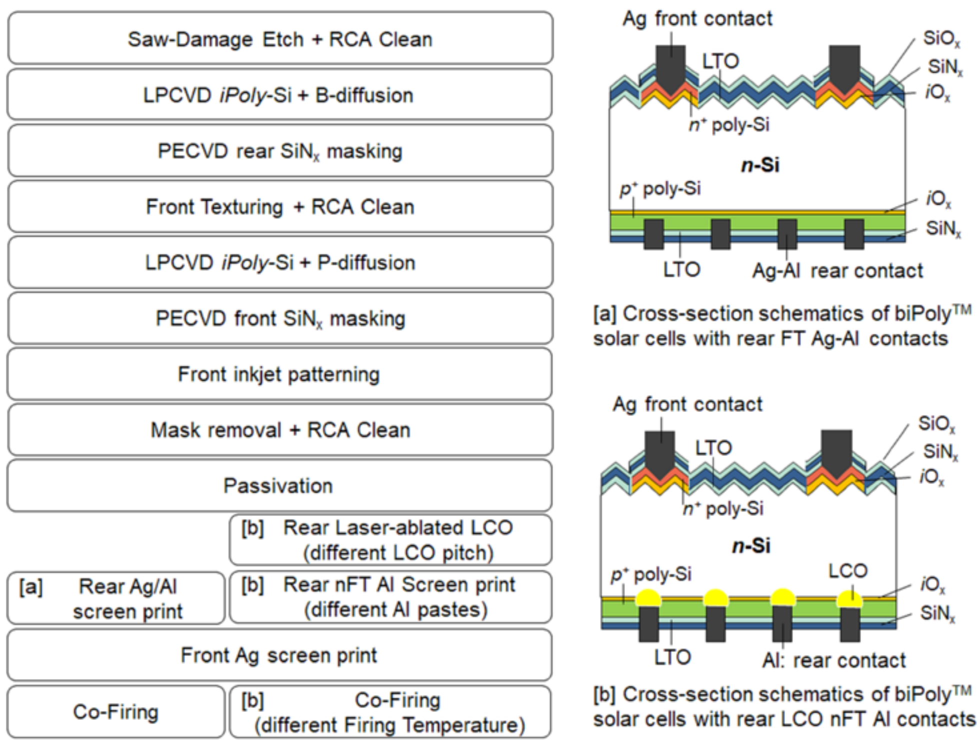


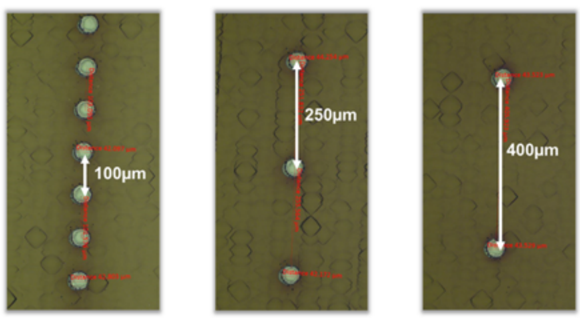
Fig. 1: (Left) Experimental process flow for the fabrication of the biPoly™ solar cells. (Right) Cross-sectional schematics of biPoly™ solar cells featuring a) FT Ag-Al contacts and b) LCO nFT Al contacts to the rear side p+ poly-Si.

Results and discussion:

Different experiments were designed and carried out to understand the impact of the design parameters on the performance of the solar cells and to improve it further. Three crucial design parameters used for developing the metallisation process were investigated: i) the local contact opening (LCO) pitch for the local contacts on the rear side, ii) nFT Al paste with different silicon content, and iii) the firing temperature of the metallised solar cells.

i) Local contact opening (LCO) pitch

Three LCO pitch distances (100, 250 and 400 μm) were selected to understand its impact on the solar cell performance. The LCO pitch controls the actual metallised area where Al-Si contact is formed. The laser ablated pattern was circular (diameter 40 μm) and had a finger pitch of ≈ 1 mm. All solar cells were fired at a peak firing temperature of 740°C. The area fractions opened by the laser for the different dot pitches were estimated as 1.3%, 0.5% and 0.3% for 100 μm, 250 μm and 400 μm, respectively. Optical microscope images of the laser ablated dots are shown in Fig. 2.



Dot pitch = 100µm [*metal contact fraction= **1.3%***] | Dot pitch = 250µm [*metal contact fraction= **0.5%***] | Dot pitch = 400µm [*metal contact fraction= **0.3%***]

Fig. 2: Microscopic images of the laser ablated regions on the rear side showing the different LCO pitch distances. The percentage of area contacted by the metal is also indicated for each LCO pitch. The diameter of the ablated circular region is ≈ 40 μm.

Figure 3 shows the 1-Sun J-V parameters of the solar cells. The cells with 400-μm LCO pitch had the highest mean efficiency. The highest efficiency achieved for the 400-μm LCO pitch was 22.3%. The variation in the V_{oc} and the FF for the different solar cells is clearly visible for the solar cells with different LCO pitches. The V_{oc} increased steadily with increasing LCO pitch, which is a result of both lower area where the poly-Si was damaged by the laser and the lower contact fraction of the metal. The fill factor of the solar cells improved slightly when the LCO pitch was increased from 100 μm to 250 μm, but then deteriorated with further increase in the LCO pitch. However, for all LCO pitches, the FF of biPoly™ solar cells with nFT Al metallisation on the rear was higher than that achieved with the FT Ag-Al paste.

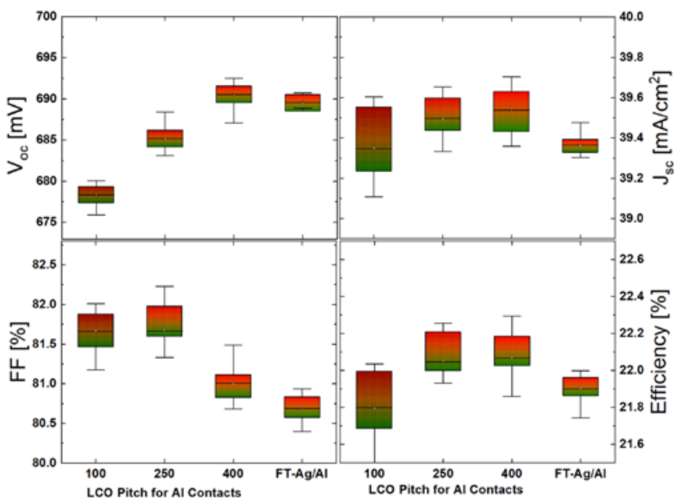


Fig. 3: J-V parameters for the biPoly™ solar cells fabricated using different LCO pitches on the rear side. The reference solar cell is metallised with fire-through Ag-Al paste on the rear side. The front side metallisation is same for all solar cells.

ii) Effect of adding Si to the nFT Al paste

Three metal pastes with different Si content were developed by our research collaborator Toyo Al. For this experiment, the LCO pitch distance was kept constant at 400 μm, while the solar cells were fired at a peak firing temperature of 720°C. The 1-Sun J-V parameters of the solar cells are shown in Fig. 4. It is obvious from the figure that the FF dominates the solar cells efficiencies. The V_{oc} of the cells did not vary by more than 3 mV for the different Al pastes. The J_{sc} is also observed to be independent of the Si content in the Al paste. However, FF was found to depend strongly on the Si content in the Al paste. The FF was lowest for the cells metallised with Al paste without any silicon. The FF increased with increasing silicon content in the Al paste, reaching values of above 82.5%. The champion solar cell was metallised with the Al paste with the highest Si content and has 22.3% efficiency ($V_{oc} \approx 687$ mV, $J_{sc} \approx 39.5$ mA/cm^2, FF ≈ 82.4 %).

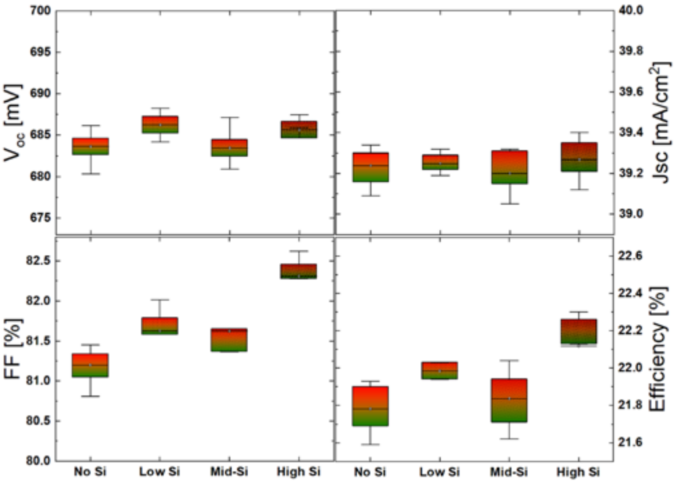


Fig. 4: J-V parameters for the biPoly™ solar cells fabricated using Al pastes with different Si content for the rear side contacts. The LCO dot pitch for the rear side was kept constant at 400 μm. The reference solar cell is metallised with Al paste with no Si content. The front side metallisation is same for all solar cells and uses the same Ag paste.

iii) Effect of peak firing temperature

We further analysed the effect of firing temperature on the performance of the solar cells with nFT Al contacts on the rear. The LCO pitch for this experiment was set to 400 μm since the primary purpose of this experiment was to see the impact on the V_{oc}. For the rear metallisation, Al paste with high Si content was used. The peak firing temperature was varied from 700 to 740 °C. The solar cell 1-Sun J-V parameters are shown in Fig. 5.

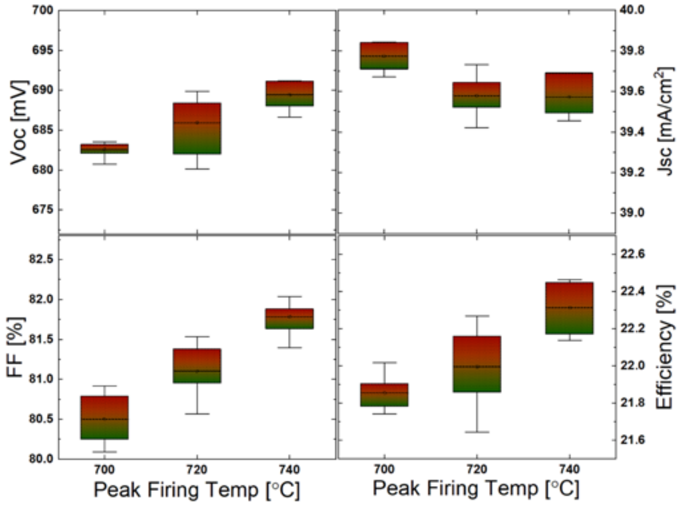


Fig. 5: J-V parameters for the biPoly™ solar cells fabricated using Al pastes fired at different peak firing temperatures. The LCO dot pitch for the rear side was kept constant at 400 μm. The front side metallisation is same for all solar cells and uses the same Ag paste.

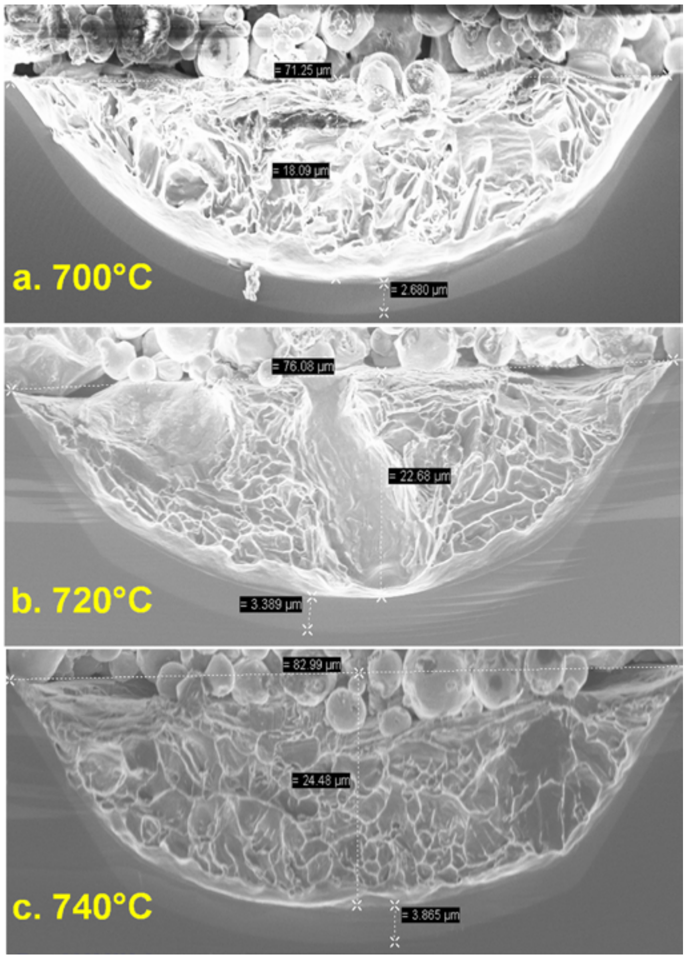


Fig. 6: SEM images showing the cross section of the LCO metallised with Al-Si paste and fired at peak temperatures of a) 700°C b) 720°C and c) 740°C. All images were taken at the same magnification (1500x).

The V_{oc} and FF of the solar cells were found to increase with increasing firing temperature. To further characterise the behaviour of the Al-Si contacts, metallised samples were cleaved mechanically with the help of laser defined notches to bisect the LCO into approximately two equal halves. SEM images of the cross section of the LCO after metallisation and firing at different peak firing temperatures are shown in Fig. 6a, b and c for 700, 720 and 740 °C, respectively.

It was observed that the diameter of the LCO opening increased significantly after metallisation. Just after laser ablation, the diameter of the LCO was ≈ 40 μm, while after metallisation the diameter of the LCO was observed to be in the 71 - 84 μm range. Further, it was observed that the diameter of the LCO increased with increasing firing temperature. The increase in the depth of the BSF has been linked in earlier studies (PERC cells) with improved passivation properties [15]. This might be a possible reason for the improved V_{oc} at higher peak firing temperature. It was also observed that the front surface passivation under the poly-Si regions deteriorated at higher firing temperature, while the passivation quality for the field region remained relatively stable with the firing temperature.

5. Conclusions

In this work we presented front and back contacted solar cells with iO_x and poly-Si based passivation on both sides. The poly-Si on the front side was patterned into poly-Si fingers onto which the screen-printed contacts were deposited. For the rear side contacts using non-fire-through Al paste, the contacting areas were opened locally using a laser. The rear contacts were formed using Al fingers aligned to cover the LCO. The performance of the Al contacts on the rear side was investigated by varying the LCO pitch, the Si content in the Al paste, and the co-firing temperature. With increasing LCO pitch the V_{oc} was found to improve while the FF deteriorated. The solar cells metallised with the highest Si content in the paste resulted in the best efficiencies owing to the improvement in FF. It was observed that the V_{oc} improved with increase in the firing temperature. This can be attributed to the improved passivation at the rear BSF formed with Al-Si paste upon high-temperature firing, which overcompensates any deterioration in the passivation properties under the poly-Si fingers on the front textured surface. The FF also improved at higher temperature owing to the reduction in the series resistance and the non-ideal recombination at higher temperatures.

As a result of these developments, a peak efficiency of 22.5% was achieved with a 400-μm LCO pitch and using a rear Al paste with a high Si content. The experimental results presented in this work highlight the flexibility and the wide range of application of the poly-Si passivating contacts. Minimising the laser impact can push the efficiencies higher. This could be achieved by using a ps or fs laser. Further thinning down of the poly-Si fingers on the front and improvement in the passivation quality of the field region would push the cell efficiency towards 23%.

References

[1] ITRPV, International Technology Roadmap for Photovoltaics 2022. 2022: VDMA, Germany.

[2] Richter, A., et al., Design rules for high-efficiency both-sides-contacted silicon solar cells with balanced charge carrier transport and recombination losses. Nature Energy, 2021. ***6****(4): p. 429-438.*

[3] Haase, F., et al., Laser contact openings for local poly-Si-metal contacts enabling 26.1%-efficient POLO-IBC solar cells. Solar Energy Materials and Solar Cells, 2018. ***186****: p. 184-193.*

[4] Bellini, L., JinkoSolar achieves 26.1% efficiency for n-type TOPCon solar cell. PV magazine, ed. online, 2022.

[5] Reiter, S., et al., Parasitic absorption in polycrystalline Si-layers for carrier-selective front junctions. Energy Procedia, 2016. ***92****: p. 199-204.*

[6] Padhamnath, P., et al., Optoelectrical properties of high-performance low-pressure chemical vapor deposited phosphorus-doped polysilicon layers for passivating contact solar cells. Thin Solid Films, 2020. ***699****: p. 137886.*

[7] Padhamnath, P., et al., Development of thin polysilicon layers for application in monoPoly™ cells with screen-printed and fired metallization. Solar Energy Materials and Solar Cells, 2020. ***207****: p. 110358.*

[8] Messmer, C., et al., Efficiency roadmap for evolutionary upgrades of PERC solar cells by TOPCon: impact of parasitic absorption. IEEE Journal of Photovoltaics, 2019. ***10****(2): p. 335-342.*

[9] Ingenito, A., et al., Silicon solar cell architecture with front selective and rear full area ion-implanted passivating contacts. Solar RRL, 2017. ***1****(7): p. 1700040.*

[10] Jain, A., et al., Design, optimization, and in-depth understanding of front and rear junction double-side passivated contacts solar cells. IEEE Journal of Photovoltaics, 2021. ***11****(5): p. 1141-1148.*

[11] Larionova, Y., et al., Ultra-thin poly-Si layers: passivation quality, utilization of charge carriers generated in the poly-Si and application on screen-printed double-side contacted polycrystalline Si on oxide cells. Solar RRL, 2020. ***4****(10): p. 2000177.*

[12] Desrues, T., et al. Poly-Si/SiO x Passivating Contacts on Both Sides: A Versatile Technology For High Efficiency Solar Cells. in 2021 IEEE 48th Photovoltaic Specialists Conference (PVSC). 2021. IEEE.

[13] Singh, S., et al., Large area co-plated bifacial n-PERT cells with polysilicon passivating contacts on both sides. Progress in Photovoltaics: Research and Applications, 2022. ***30****(8): p. 899-909.*

[14] Padhamnath, P., et al., Design, development and analysis of large-area industrial silicon solar cells featuring a full area polysilicon based passivating contact on the rear and selective passivating contacts on the front. Solar Energy Materials and Solar Cells, 2023. ***256****: p. 112351.*

[15] Gatz, S., et al., Analysis and optimization of the bulk and rear recombination of screen-printed PERC solar cells. Energy Procedia, 2012. ***27****: p. 95-102.*

Streamlining BIPV projects by integrating digital workflows with building information modelling (BIM)

Dr CHEN Tianyi

1. Background

Building Integrated Photovoltaics (BIPV) represents a promising convergence of photovoltaic (PV) technology and the Architecture, Engineering, and Construction (AEC) sector. However, the BIPV industry faces significant challenges in translating PV data and design details into 3D models efficiently. The process is often fragmented, leading to inefficient information flow and potential errors. This fragmentation, particularly when coordinating between the building and the electrotechnical domains, poses a threat to the sector's competitiveness. A significant portion of BIPV system costs is influenced by both product-related factors and inefficiencies at various project stages. Currently, the BIPV sector lacks a fully integrated digital workflow that ensures streamlined structures, optimised operations, and cost reductions throughout the entire project lifespan.

To address these challenges, there is a pressing need to establish a digitalised Building Information Modelling (BIM) BIPV process framework that streamlines information workflows. This framework should be tailored to the context of Singapore, considering local BIM guidelines and industry practices. By implementing such a framework, labour-intensive and fragmented tasks can be transformed into a unified, interoperable workflow covering the entire project lifecycle, leading to significant cost savings for BIPV projects.

2. Scope of project & objectives

The project aims to develop a comprehensive digitalised BIM for the BIPV process framework within the Singaporean context.

The primary objectives of this research are to establish a framework that streamlines the project process and to define appropriate Levels of Detail (LOD) for BIPV components within the BIM environment. This framework aims to address the current fragmentation in the industry while aligning with Singapore's building regulations and BIM guidelines. By developing LOD specifications, the research ensures that the right information, including both geometric and non-geometric attributes, is available at each project stage. This approach facilitates better information management and collaboration among stakeholders throughout the BIPV project lifecycle, from conceptual design to operation and maintenance.

3. Significance & impact of project

By facilitating the integration of BIPV into building designs, the framework encourages wider adoption of solar energy in urban environments, contributing to Singapore's target of increasing solar energy deployment. The work contributes to the broader goals outlined in Singapore's Green Plan 2030 specifically on super-low energy and high-efficiency buildings. Furthermore, the framework optimises information flow and collaboration among stakeholders based on the existing Singapore BIM guidelines, thereby clearly delineating responsibilities and involvement among stakeholders.

4. Methodology & Results

The framework was developed by integrating BIPV-specific tasks and considerations into the existing BCA BIM project process. This approach ensures alignment with Singapore's established BIM guidelines while addressing the unique requirements of BIPV projects.

The framework encompasses six key stages, each with specific BIPV tasks integrated into the BCA BIM process (see Fig. 1). In the Conceptual Design stage, architects and BIPV consultants collaborate to conduct building massing studies and identify potential BIPV integration areas. They perform initial solar radiation analyses and estimate energy generation potential, considering factors such as building orientation, shading, and local climate data.

Moving to the Schematic Design stage, the focus shifts to refining BIPV integration with the building's architecture. Architects and BIPV consultants work on generalised BIPV component layouts, determining approximate dimensions, orientations, and quantities. They conduct more detailed energy simulations and preliminary economic analyses, considering factors such as module efficiency, tilt angles, and initial cost estimates. This stage also involves early consultations with structural engineers to assess the feasibility of BIPV integration with the building envelope.

The Detailed Design stage is pivotal, bringing together architects and MEP engineers. Here, they finalise the BIPV specifications, creating detailed models with accurate dimensions, materials, and electrical characteristics. MEP engineers integrate the BIPV system with the building's electrical infrastructure, designing inverter layouts, wiring schemes, and connection points. Detailed energy production estimates are conducted, incorporating factors like module degradation and system losses. This stage also involves a comprehensive cost analysis and adherence to relevant building codes and standards.

During the Construction stage, contractors and BIPV installers become the primary actors, ensuring proper installation according to the detailed designs. They coordinate closely with other trades to integrate BIPV seamlessly with building envelope construction, addressing challenges like waterproofing and structural integrity. Quality control measures are implemented to verify proper electrical connections and system functionality.

The As-Built stage focuses on documenting the installed BIPV system, capturing any deviations from the original design. This documentation is crucial for future reference and maintenance.

Finally, the Operation & Maintenance stage involves setting up monitoring systems to track BIPV performance, establishing maintenance protocols, and providing training for facility managers to ensure optimal long-term operation of the BIPV system.

Throughout these stages, the framework emphasises data flow and stakeholder collaboration. It specifies the roles and responsibilities of key stakeholders at each stage and outlines the information required as input and output. This structured approach ensures that each phase builds upon data from previous stages, promoting efficiency and reducing errors.

The framework incorporates Level of Development (LOD) specifications for BIPV components, a concept that defines the degree of detail and reliability of information in BIM models at various project stages. For BIPV, these specifications encompass both geometrical data (such as module size, colour, cell number, and texture) and non-geometrical data (including electrical characteristics, U-value, optical properties, certifications like fire ratings and green product labels, and warranty information). The framework aligns different LODs with specific project phases: LOD 100 and 200 are utilised in conceptual and schematic design stages, providing architects and developers with essential data for quick feasibility studies. These early LODs include basic geometric information and general electrical parameters like average power output. As the project advances to detailed design (LOD 300), the model incorporates more comprehensive data, including the exact electrical specifications, supplier information, and detailed cost estimates, crucial for MEP integration. LOD 400 and 500, used in the construction and as-built stages respectively, contain the most detailed information necessary for bidding, installation, and facility management. Ideally, LOD 500 should mirror the as-built condition, serving as a comprehensive digital twin for long-term operation and maintenance.

5. Conclusions

In this work, we developed a BIM BIPV framework for Singapore, integrating BIPV tasks into established BCA BIM stages and defining appropriate LODs for BIPV components. This standardised approach aims to streamline workflows, reduce costs, and improve project quality. Future work will focus on creating a digital BIPV component library based on this framework. This library will enable more accurate simulations within BIM environments, allowing for precise models of energy generation, façade performance and project costs.

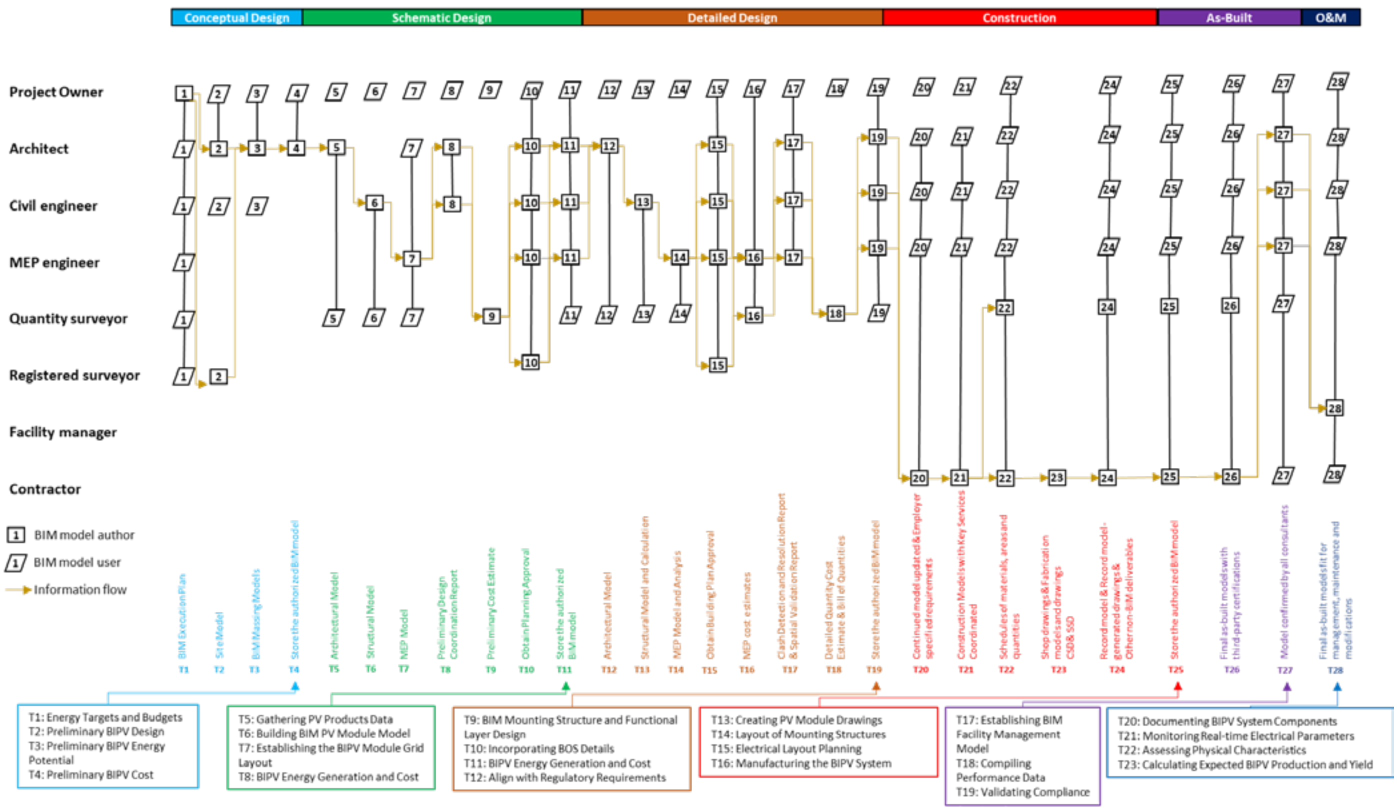


Fig. 1: The framework of the BIM for BIPV in Singapore

PV module recycling using shock wave fragmentation technology

Srinath NALLURI, Dr LEOW Shin Woei, Dr Thomas REINDL

1. Background

Global photovoltaic (PV) installations have grown exponentially, with cumulative capacity rising from 1.2 GW in 2000 to an impressive 1600 GW by 2023, and projections indicating it will reach 4.5 TW by 2030 [1, 2]. Singapore has mirrored this global trend, achieving an installed PV capacity of 1.3 GW as of 2024. By 2050, this could possibly be as high as 8.6 GW, driven by innovative deployment strategies like floating solar systems, building-integrated photovoltaics (BIPV), solar EVs, and PV-integrated noise barriers [3].

This rapid growth, however, raises concerns over managing waste from decommissioned PV systems. With an average lifespan of 25–30 years and potential premature failures, global PV module waste is expected to reach 8 million tonnes (Mt) by 2030 and 78 Mt by 2050 [4]. Integrating PV recycling into the PV value chain is thus vital for reducing waste, promoting environmental sustainability, and unlocking new economic opportunities within the solar energy sector.

The major challenge in recycling PV modules lies in disassembling their complex multi-layered structure. Crystalline silicon (c-Si) panels, which account for 97% of the market [5], are composed of materials such as glass, interconnected silicon cells, aluminium, silver, copper, polymers, and encapsulants, all tightly bonded into a single structure through lamination. Delamination is the critical step for material recovery, and it typically involves mechanical, chemical, or thermal processes. Among these, the thermal method (pyrolysis) is the most widely used industrial technique. It involves heating the module in a furnace at 500–600°C to eliminate the encapsulant through vapourisation. However, this approach is highly energy intensive, generates significant carbon emissions, and releases harmful gases like hydrogen fluoride (HF) into the atmosphere [6].

Hence, the development of alternative and more sustainable module separation techniques is of great importance for effective PV recycling.

2. Scope of project & objectives

The research scope of this project includes:

(1) to propose and analyse electrohydraulic (shock wave) fragmentation as an alternative to pyrolysis for separating PV modules into their constituent materials.
(2) to formulate recipes and optimise them for the recycling of glass-backsheet and glass-glass modules to achieve high throughput and cost-effectiveness.

The following sections introduce the concept of shock wave fragmentation, provide an overview of the PV Module Recycling Plant at SERIS, and describe the process customisation techniques to achieve different output distributions.

3. Significance & impact of project

Discussions with waste disposal experts in Singapore during the feasibility study revealed that the current PV disposal practice involves removing the frame and discarding the module body due to its perceived lack of value. Also, discarded PV modules often end up as e-waste in landfills, highlighting the need for sustainable solutions.

The SERIS method addresses this challenge by demonstrating a cost-effective, low-carbon, chemical-free recycling process using shock wave fragmentation. The process includes a complete disassembly, capable of separating modules into glass cullets, ribbons, polymer (encapsulant and backsheet) foils, and cell materials, while optimising recycling methods for various module types. By enabling PV material separation and customisable output facilities locally, this project reduces costs, enhances commercial viability, and aligns with Singapore's broader sustainability goals, particularly its Zero Waste vision.

4. Methodology & Results

Figure 1 shows the PV Recycling line at SERIS using the shock wave fragmentation plant.

The decommissioned PV module, after the removal of the junction box(es) and the frame, undergoes a crushing process to prepare the infeed material. The crusher reduces the module into smaller pieces, ranging in size from 1.5 cm to 2 cm in length. These crushed fragments are then transferred to the shock wave fragmentation plant for further processing.

The shock wave fragmentation plant comprises four main components: the infeed conveyor, shock wave chamber, sieve tower, and filter unit (Fig. 2).

The infeed conveyor transports the crushed PV fragments to the shock wave chamber, where the shock wave separation process occurs. Inside the chamber, an intense arc is generated between two electrodes submerged in deionised (DI) water to produce shock waves. These shock waves propagate through the liquid and strike the immersed PV fragments with high pressure, weakening the bond and breaking the complex laminate into the individual components. This separation is based on differences in acoustic properties and mechanical strength of the materials in the laminate. Towards the end of the process, a fragmented mixture with glass cullets, encapsulant foils, backsheet foils, ribbons, and cell powder is produced.

The DI water containing this fragmented mixture is emptied from the chamber and pumped into the sieving tower, where the mixture is segregated into four different sizes (> 5 mm, 1-5 mm, 0.25-1 mm and < 0.25 mm). The DI water passes through the filter unit, where particles smaller than 0.25 mm are filtered from the water. The cleaned water is pumped back into the fragmentation chamber for the subsequent process.

The output material for each of the four size-based categories are: > 5 mm (encapsulant and backsheet foils), 1–5 mm (glass cullets and ribbons) 0.25–1 mm (mostly powdered glass and some cell fragments), < 0.25 mm (cell powder). The semiconductor material obtained can be further recycled to extract silicon, aluminium and high-purity silver through downstream chemical etching processes, the glass can be used for float glass manufacturing and abrasive sandblasting, copper contacts can be reused post purification and melting works, while the polymer foils can be remade into sheets through electrospinning.

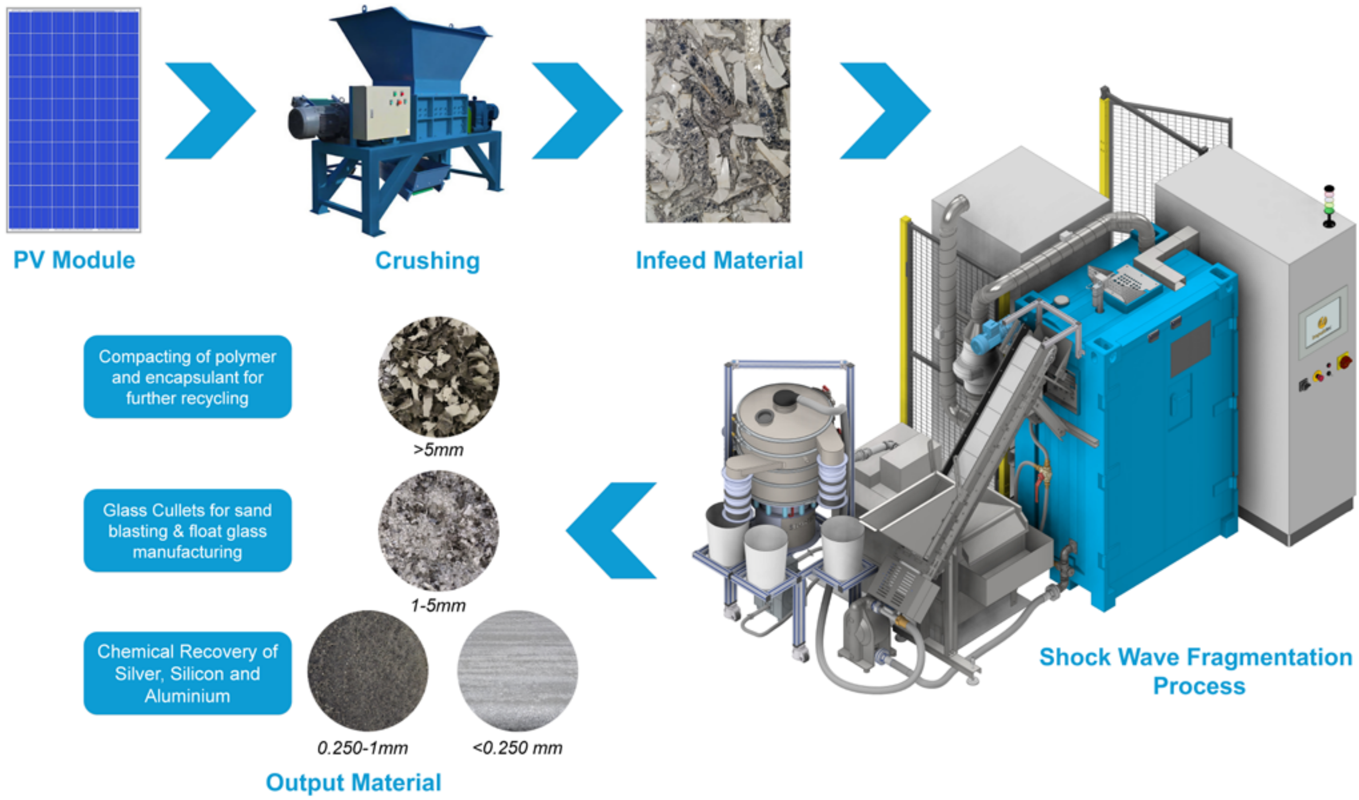


Fig. 1: PV module recycling process at SERIS

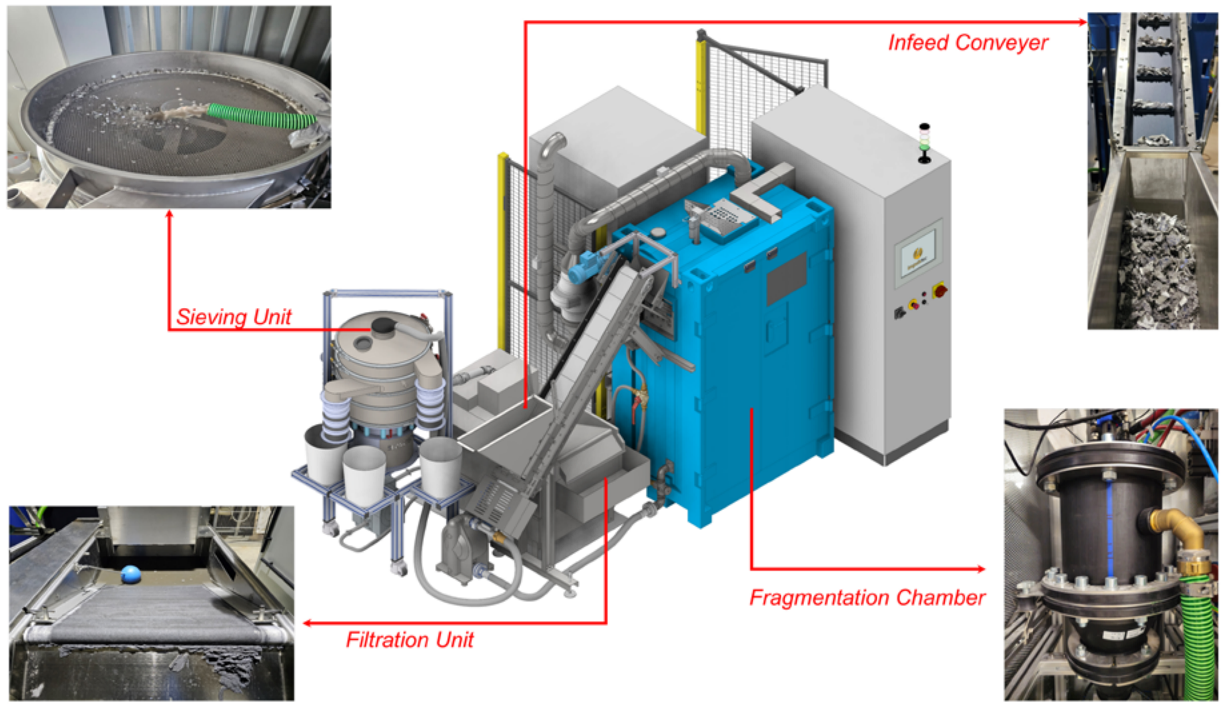


Fig. 2: Features of the shock wave fragmentation plant

Another key feature of this process is that the output can be customised. Recipes can be formulated to achieve different distributions of the output material.

For example, with the High Recovery Process Recipe, the infeed belt speed is lowered to release smaller quantities of material into the fragmentation chamber. This enables a more targeted and efficient application of high shock wave impacts to the PV fragments. More cell material is removed from the polymer foils, resulting in cleaner foils and significantly higher recovery of valuable cell materials like silver and silicon. However, this approach operates at a lower throughput, making it slower, and more glass is recovered as powder rather than cullets due to increased pulverisation.

On the other hand, the High Throughput Process Recipe prioritises speed and efficiency by processing larger quantities of material per cycle. This method is ideal for quickly handling large volumes of PV panels and recovering substantial amounts of glass as cullets. However, the reduced shock wave impact per fragment means less cell material is separated from the foils, resulting in lower recovery rates for high-value materials like silver and silicon.

Thus, the shock wave fragmentation offers flexibility to cater to different off-taker requirements, balancing between high recovery of valuable materials and high-speed throughput for large-scale recycling.

For glass-backsheet PV modules, the high recovery process in our R&D tool achieves a recovery rate of 10 kg/hour, equivalent to approximately six modules per day, while the high throughput process recovers 20 kg/hour, processing around 11 modules per day. For glass-glass modules, the high recovery process recovers 24 kg/hour, translating to 10 modules per day, whereas the high throughput process recovers 30 kg/hour, enabling the recycling of about 13 modules per day. Higher rates can be achieved through a larger shock wave chamber. The recovery for glass-backsheet modules is approximately 98% with an average energy consumption of 225 kWh/ton, while for glass-glass modules, the recovery ratio is around 96% with an average energy consumption of 133 kWh/ton. This compares to ~300 kWh/ton for the standard pyrolysis process.

The difference in processing comes from the fact that for glass-backsheet modules, the primer-coated inner side of the backsheet enables diffusion of encapsulant molecules under pressure, forming a robust bond that requires longer processing time for separation. In contrast, for glass-glass modules, the adhesion between the encapsulant and the glass relies on wettability, resulting in a weaker bond that can be disintegrated more quickly, giving shorter processing times [7].

5. Conclusions

A proof of concept for the shock wave fragmentation method for recycling glass-backsheet and glass-glass PV modules has been successfully demonstrated. The process consumes little energy, has a low carbon footprint, and uses no harmful chemicals for PV module separation.

Future efforts will focus on refining separation processes to meet recyclers' requirements, enabling targeted recovery of high-purity materials, including silicon for fabrication of ingots, tempered glass cullets for float glass production, and silver for PV cell manufacturing.

This project was carried out in collaboration with Singapore Polytechnic. It was supported by the National Research Foundation Singapore, and the National Environment Agency, Singapore, under its Closing the Waste Loop Funding Initiative (Award No. USS-IF-2019-5)

References

[1] "IRENA_IEAPVPS_End-of-Life Solar_PV_Panels_2016".

[2] Snapshot of Global PV Markets 2024. [Online]. Available: www.iea-pvps.org

[3] "What is the potential of solar energy in Singapore?" Accessed: Nov. 26, 2024. [Online]. Available: https://www.ema.gov.sg/resources/faqs/energy-supply/solar/what-is-the-potential-of-solar-energy-in-singapore

[4] P. H. Chen, W. S. Chen, C. H. Lee, and J. Y. Wu, "Comprehensive Review of Crystalline Silicon Solar Panel Recycling: From Historical Context to Advanced Techniques," Jan. 01, 2024, Multidisciplinary Digital Publishing Institute (MDPI). doi: 10.3390/su16010060.

[5] F. Ise and P. Projects GmbH, "Photovoltaics Report-Fraunhofer Institute for Solar Energy Systems, ISE with the support of PSE Projects GmbH," 2024. [Online]. Available: www.ise.fraunhofer.de

[6] I. PVPS Task et al., End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies End-of-Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies Operating Agent. 2018.

[7] B. Adothu, S. Zele, A. K. Singh, S. Kumar, and S. Mallick, "Effect of Curing Temperature on Properties of Ethylene Vinyl Acetate (Eva) Used For Crystalline Silicon Solar Module Encapsulation," 2020. [Online]. Available: https://www.researchgate.net/publication/339142348

Urban rooftop agrivoltaics (agriculture + PV) test-bedding in Singapore

Dr Serena LIN Fen, LIU Tianyuan, Dr Thomas REINDL

1. Background

As the world's second most densely populated country, Singapore has high demands in both food and energy supplies. The SG Green Plan 2030 has set the goal to deploy at least 2 GW_p of solar photovoltaic (PV) systems by 2030. It now also includes the ambitious "30 by 30" initiative, which pledges to sustainably produce 30% of the nutritional needs locally by 2030. As both agriculture and solar PV deployment require large areas of space, it is wise to consider using the same area for both crop growth and renewable energy generation, given the space scarcity in Singapore. This even more so, as most plants need to be shaded from the hot mid-day sun anyway (typically using a netting). In addition, one of the major challenges faced by local farmers are the ever-increasing costs of energy. Hence it also makes economic sense to promote the integration of solar PV on farmlands, providing farmers with access to cheaper electricity and a source of additional income. The combination of agriculture and PV, also known as "Agrivoltaics", is a growing trend around the world. Since both agriculture and solar PV depend on geographical locations of the deployment, it is of great value to study the impacts of solar PV on agriculture in Singapore's local context.

2. Scope of project & objectives

In 2023 SERIS has set up two agrivoltaic testbeds, each measuring 7 m x 5 m, on an HDB rooftop carpark located at Block 354, Jurong East Avenue 1. This is part of the Yuhua Agritech Solar (YAS) Living Lab that serves as an innovation hub striving to foster innovation and experimentation in solar PV and soil-less agritech in an urban farming concept. We have since completed the first year of test-bedding, and selected results will be reported in this article. The scientific objective is to study the balance between crop yield, clean energy generation and energy consumption. For both testbeds, rotatable PV modules are used to track the sun during the day for maximised power generation and to provide flexibility in adjusting the panel angles. A large number of sensors are deployed, with the aim of developing a self-learning AI algorithm for a future automated control.

Fig. 1: Aerial view of the Yuhua Agritech Solar (YAS) Living Lab located on an HDB rooftop carpark. The two testbeds set up by SERIS are circled by the green dashed line.

3. Significance & impact of project

The testbeds allow us to test, and further develop, the different set-ups, and continuously improve them to eventually find the optimum configuration of a stand-alone AI-driven greenhouse that can be commercialised and deployed on other rooftops in Singapore and the region.

4. Methodology & Results

While both testbeds are configured with rotatable solar panels, two different growing setups which enable high crop yields per unit area are being compared. In the first testbed, vertical growing towers are employed. As shown in Fig. 2, these towers, in combination with a fish tank, constitute an aquaponics system where the nutrients required for the growing towers are mineralised from fish waste. The plants in this testbed receive natural sunlight that is partially blocked by solar panels. In the second testbed, shown in Fig. 3, horizontally layered growth beds for hydroponics are used. LED stripes are installed to provide complementary light. Hence, there is an option to control the growth rate of the plants via adjusting the LED light intensity.

Fig. 2: SERIS' testbed 1 in the Yuhua Agritech Solar (YAS) Living Lab with an aquaponics system consisting of vertical growing towers.

Fig. 3: SERIS' testbed 2 in the Yuhua Agritech Solar (YAS) Living Lab with a hydroponics system consisting of horizontally layered growing beds.

In one of the growing cycles, a batch of lettuces from the same batch of germinated seedlings were transplanted into both testbeds on the same day, and the grown lettuces were harvested 5 weeks after transplantation for biomass measurements. As shown in Fig. 4, eight different groups of samples were compared with 15 samples measured in each group. Lettuces grown in different growing setups with different intensity of complementary LED light and at different levels in the tower (for horizontal towers), or with different facings and row numbers (for vertical towers) are compared.

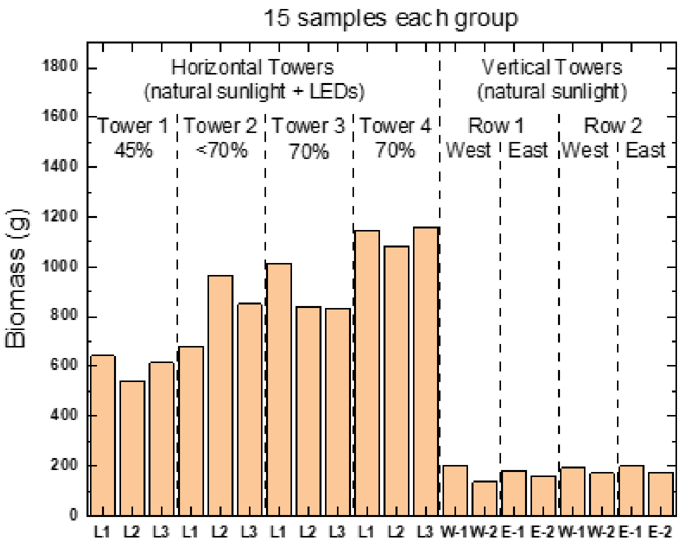


Fig. 4: Biomass comparisons of lettuces harvested from different growing setups. The "45%" and "70%" for the horizontal towers indicate the percentage of LED intensity vs the highest available intensity in the setup.

As can clearly be seen in Fig. 4, there is a significant increase in the lettuce biomass when complementary LED lights are applied. The difference in the amount of natural sunlight received also affects the plant growth rate, such as the differences between Tower 3 and Tower 4 for the horizontal towers. While it is beneficial to have complementary LED lights to enable shorter harvesting cycles due to the boosted growth rates, it is noted that the energy consumption of the LED lights should largely come from the electricity generated by the solar panels, to avoid any additional energy costs.

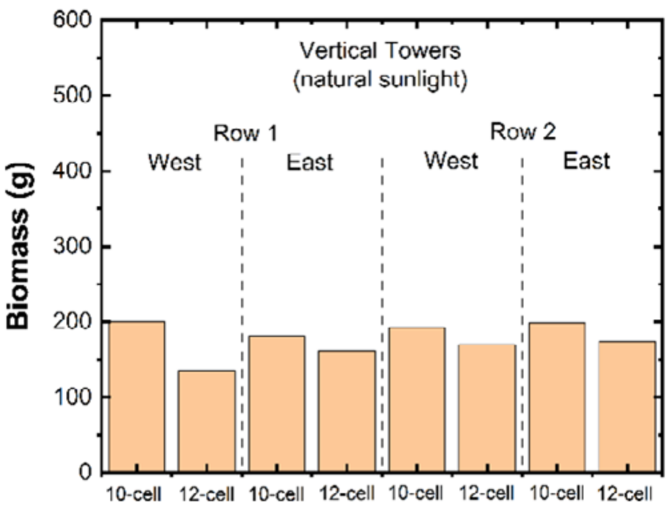


Fig. 5: Biomass comparisons of lettuces harvested from vertical towers. "10-cell" and "12-cell" indicate the type of solar panels directly above the lettuces, which either contain 10 cells in a panel stripe or 12 cells in a panel stripe.

As shown in Fig. 5, it is also interesting to note that the biomass of the lettuces grown in the vertical towers, relying fully on natural sunlight, also varies depending on the type of solar panels above them. The solar panel with 10 cells in a stripe corresponds to ~50% of shading while the 12-cell stripe corresponds to ~60% of shading. Their difference in shading results in 12% to 15% of biomass difference for the lettuces, indicating that the amount of shading would directly impact the crop yield, and it needs to be carefully designed based on economic calculations.

It is found that common leafy green vegetables in Singapore need to receive an amount of light corresponding to a photosynthetically active radiation (PAR) value of 400 – 600 mol/m^2 per month. To investigate the light distribution on the crops at different levels within a greenhouse depending on respective solar panel designs as well as growing setup designs, we developed a 3D irradiance simulation model. Figure 6 shows examples of irradiance simulations based on these two testbeds. These simulations will guide the future improvements of the testbeds, as well as the design of future agrivoltaic systems.

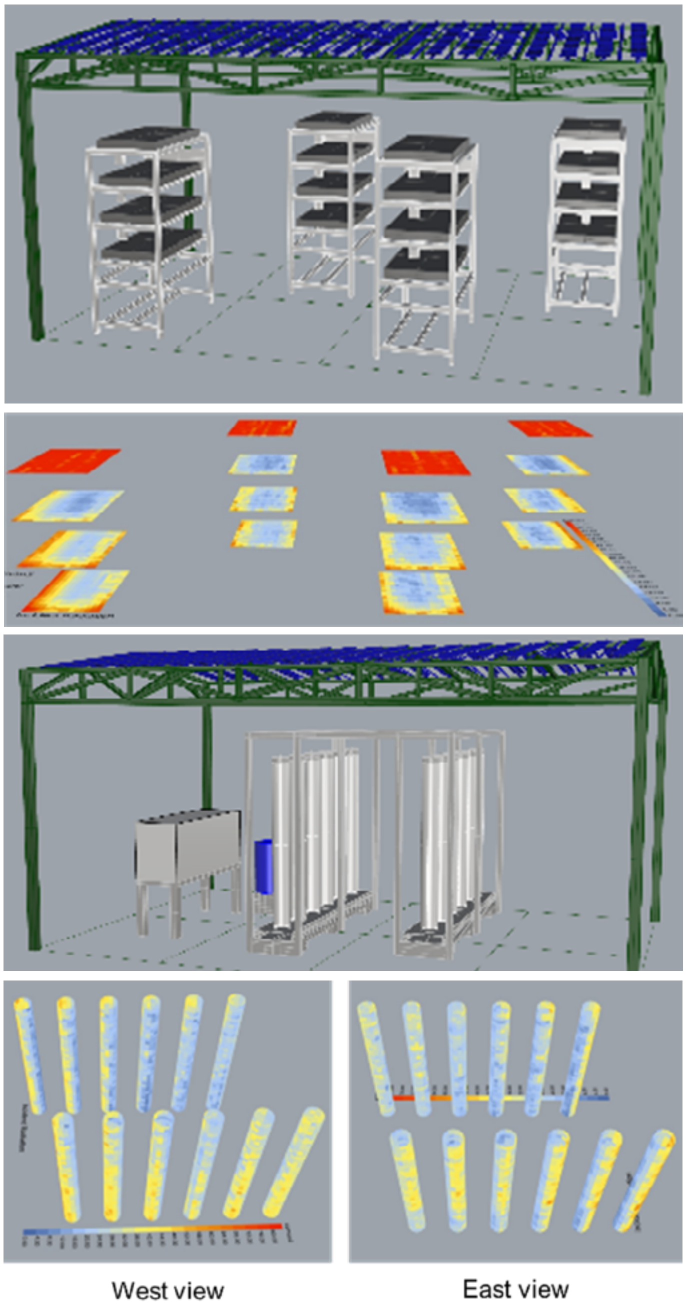


Fig. 6: Agrivoltaic testbed and corresponding 3D irradiance map simulation based on SERIS' testbeds in Yuhua Agritech Solar (YAS) Living Lab.

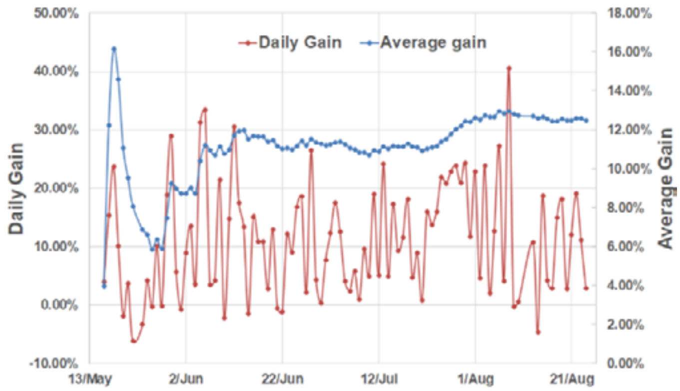


Fig. 7: Daily gain and average gain of energy generation by rotatable solar panels with sun-tracking function in comparison with fixed solar panels.

Furthermore, energy generation from solar panels with the sun-tracking function is compared with that of fixed solar panels for a duration of 3 months. As shown in Fig. 7, sun-tracking leads to an overall average gain of 10% to 12% in energy generation. The energy gain is most prominent during sunny days, with more than 20% extra energy. There is little difference during rainy days, and around 4% - 12% gain during cloudy days which are more common in Singapore. Hence, considering the additional energy consumption to supply the motors for tracking, there is no clear benefit to deploy sun-tracking in this setup.

In the past 12 months, different types of leafy green vegetables, such as lettuce, bok chye, nai bai, chye sim, kang kong and bayam (spinach), have been test-bedded using both types of growing setups. As different types were grown at different times during the year, the amount of light received during each cycle varied. Nevertheless, it is still evident that that kang kong and bayam (spinach) are among those that require less sunlight to grow. They can be harvested in 2.5 to 3 weeks from seedling transplantation, indicating that they are good candidates for growing healthily under shaded conditions (solar panels). Bok chye and nai bai require most sunlight and/or nutrients among the test-bedded vegetable types, which took an average of 5 weeks or longer to grow from seedling transplantation to harvest.

Based on our test-bedding data, a financial scenario analysis was conducted to determine how different types of farming would benefit from agrivoltaics. The associated monthly operational costs, crop yields, sales revenue and profits for different local farm scenarios are compared. Further detailed analysis is still ongoing. From the preliminary analysis, it is important that, regardless of the farming types, the PV panel shading should not adversely impact the crop yield as this would reduce the crop yield and hence the sales revenue. Highest yields and highest profits can be achieved in a 2-layered horizontal growth setup whereby the PV panel shading doesn't affect the crop yield of the top layer and the PV generated electricity supplies the supplementary LEDs for the second layer. Any further increase in the number of supplementary LEDs beyond the solar generated capacity would lead to higher energy cost, and eventually to reduced profits despite the higher crop yields. Hence it is important to evaluate the deployment site details and the types of plants and types of growing setups of a farm when designing suitable agrivoltaic solutions.

5. Conclusions

SERIS' agrivoltaic testbeds in the Yuhua Agritech Solar (YAS) Living Lab provide an excellent platform to innovate and testbed suitable combinations of crop growth and solar PV generation. We have completed the first year of test-bedding and obtained a large amount of valuable data. It is found that supplementary LED lighting significantly boosts the growth rate and biomass of the vegetables. However, from an economic perspective, the wise option is to only use the electricity generated by the solar panels to power an equivalent amount of LEDs, to keep the energy costs low. The impacts of solar panel shading on the biomass of the vegetables have also been studied to understand the suitable amount of PV coverage on common leafy green vegetables. To guide the further improvement of the agrivoltaic system and the future design of other agrivoltaic systems, we have established a 3D irradiance map simulation capability to investigate the light distribution at different levels within a greenhouse with regards to different solar panel and growing setup designs. No clear benefit of performing sun-tracking has been found so far, considering the amount of energy gain vs the additional energy consumption by the motors. Among the types of vegetables testbedded so far, kang kong and bayam (spinach) were found to be good candidates for agrivoltaics, given their high shade tolerance. Furthermore, the valuable data collected through the test-bedding enabled us to conduct a preliminary financial scenario analysis to determine how different types of farming would benefit from agrivoltaics. Through the 3-year research project, we aim to develop feasible and sustainable rooftop agrivoltaic configurations that can be commercialised on other rooftops in Singapore and the region.

Selected **R&D Project**

Best practices for asset management in PV system applications

Dr André NOBRE, Dr Xiaoqi XU, Dr Thomas REINDL

1. Background

Global installed capacity for photovoltaic (PV) systems has now surpassed 2 TW_p [1]. It took more than 60 years to achieve the first terawatt, but only 2 years to double that to 2 TW_p. With annual growth rates consistently exceeding 20%, the exponential expansion of the global PV fleet is set to continue. Solar power is now the lowest-cost electricity (LCOE) in many parts of the world, including Singapore and Southeast Asia.

Since 2010, the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) has been at the forefront of understanding and improving the performance of PV systems in tropical climates, with several well-received publications in this field [2-4]. Understanding the potential yield of these assets, however, is just one aspect. Maintaining the systems in a "healthy" operational state introduces an entirely new set of challenges.

Managing PV systems in real-world conditions (see Fig. 1 for one of the sites under SERIS monitoring) poses challenges which are often underestimated, even by professionals in the field. One example is the understanding that systems must be monitored daily (and ideally in real time). This enables the immediate detection of system faults which otherwise could cause continuous underperformance for days, weeks or even months.

Fig. 1: Photovoltaic systems installed on the rooftops of the CREATE buildings at the National University of Singapore's U-Town campus.

2. Scope of project & objectives

As part of the "Smart O&M" (Operation & Maintenance) project, SERIS and its recent spin-off, the PV DOCTOR™, are monitoring close to 100 MW_p of PV assets across more than 300 sites in 8 countries (Singapore, Southeast Asia and India). The primary objectives of this project are:

A) To deepen the understanding of operational challenges in PV systems, especially those installed in the harsher tropical climate conditions.

B) To establish benchmarks for different system categories (such as industrial rooftops) and for various regions. These benchmarks allow to optimise PV performance based on local environmental conditions, beyond the individual system configurations, which in turn can drive systemic improvements across assets.

C) To advocate for the critical role of early fault detection, which ensures higher returns on investment and enhances the overall safety and reliability of system operations.

3. Significance & impact of project

PV systems along the equator, where the annual solar irradiation averages ~1500 kWh/m², are expected to reach a performance ratio (PR) of at least ~80%. In reality, however, actual PV installations are operating at significantly lower levels, as shown in Fig. 2 for a large set of PV assets across ~500 sites in 7 countries in South and Southeast Asia. Even the more conservative "budgeted PR levels" (green band) are often not achieved.

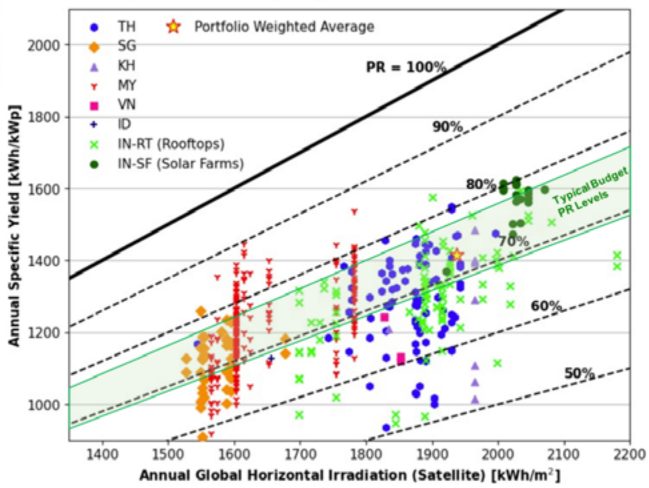


Fig. 2: Performance ratios (PR) of a fleet of PV assets across ~500 sites in 7 countries in South and Southeast Asia [5].

On a global level, an assessment of the cost of under-performance by a consulting company estimates annual losses of USD 4.6 billion worldwide [6].

4. Methodology & Results

The "Smart O&M" project has three key steps to evaluate the "health" status of a PV assets.

Irradiance source:

Having accurate irradiance data as the base for PR calculations is absolutely critical. For the case of Singapore where ~40 MW_p of PV installations across around 200 sites are being monitored (see Fig. 3 for the portfolio map), the team can tap into the 25 well-maintained and reliable irradiance stations which SERIS has built up since 2012.

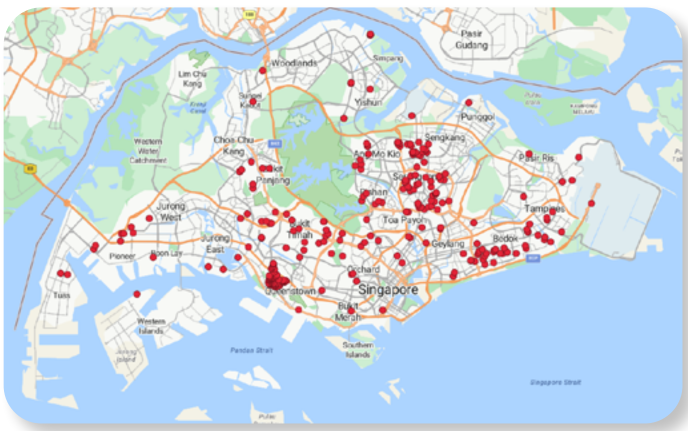


Fig. 3: Overview of approximately 40 MW_p of solar PV installations being monitored in Singapore, covering around 200 sites.

In locations where no reliable ground sensor data are available, the use of high-quality satellite data is an effective alternative, as demonstrated in [7]. Typically, various resources are collected and then aggregated into a coherent irradiance source file by advanced algorithms. Figure 4 shows the differences in PR calculations when using various irradiance sources. If available, the data will also be referenced with ground measurement.

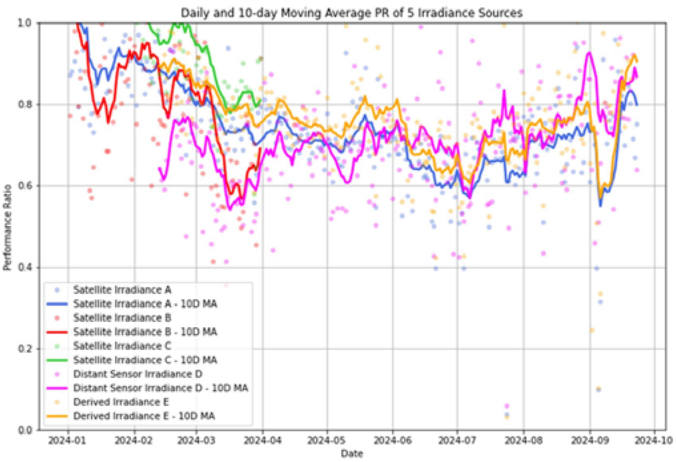


Fig. 4: Illustration of multiple satellite data sources for calculating the performance ratio of a commercial rooftop PV system in the Philippines, also incorporating distant ground sensors.

Daily observations:

As mentioned in the primary objectives, daily assessments of energy yield and performance are vital for keeping the performance at optimum levels. One advanced method is to apply “internal benchmarking” of the various inverters within a PV installation, which can be carried out even in the absence of local irradiance values. High-time resolution data and colouring codes allow to analyse performance patterns such as component faults and to detect early signs of gradual downward shifts. Figure 5 shows one such colour profile.

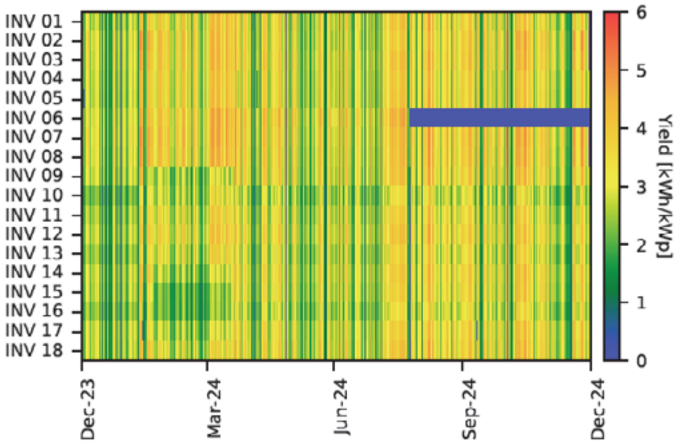


Fig. 5: Daily performance “heat map” of 18 solar inverters at an industrial site in Singapore. This visualisation demonstrates how system section outputs can facilitate early detection of issues or minor deviations, independent of irradiance sensor data. Notably, inverter #6 showed no operation for several months, indicating a lack of timely intervention by the client or O&M contractor (this event occurred prior to SERIS taking over the PV monitoring).

Long-term trends:

Understanding the long-term behaviour of PV installations is crucial for effective asset management and decision-making. Figure 6 illustrates the performance ratio over a one-year period for a PV system in Singapore. It shows the undetected under-performance of the system (data shown in red circle), which occurred prior to the SERIS team monitoring the system. Since the system has been under daily assessment using pre-programmed algorithms, any further underperformance is immediately detected and rectified, see the event in the green circle and associated improvement of the 30-day moving average (red line).

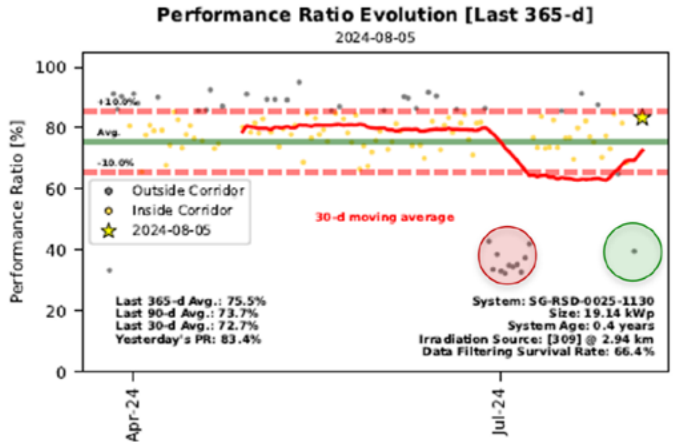


Fig. 6: One-year performance ratio and 30-day moving average (red line) of a PV system in Singapore. Deviations beyond the optimal operational corridor are detected by team-developed algorithms, enabling rapid response to early warnings.

5. Conclusions

The global installed solar PV capacity now exceeds 2 TW_p, with solar energy becoming the most cost-effective source of electricity in many parts of the world. The Solar Energy Research Institute of Singapore (SERIS) is spearheading research into PV performance in tropical climates, with close to 100 MW_p of PV assets across more than 300 sites in 8 countries (Singapore, Southeast Asia and India) under monitoring. This initiative aims to understand operational challenges, set performance benchmarks, and promote early fault detection to enhance system reliability and investment returns. The assessment leverages both on-site meteorological data and satellite information for the performance analysis. Advanced algorithms have been developed for carrying out internal system benchmarking in real time and for early detection of system faults, as well as long-term degradation trends. This will help PV asset owners to increase their energy yield, which in turn leads to higher revenues and ultimately also higher profits.

References

[1] PV Magazine. Global installed PV capacity tops 2 TW. 13 November 2024. Access Link: https://www.pv-magazine.com/2024/11/13/global-installed-pv-capacity-tops-2-tw/

[2] A. Nobre, Z. Ye, H. Cheetamun, T. Reindl, J. Luther, and C. Reise, "High performing PV systems for tropical regions — Optimization of system performance," presented at the 27th European Photovoltaic Solar Energy Conference & Exhibition, Frankfurt, Germany, 2012, pp. 3763–3769

[3] Z. Ye et al., On PV module temperatures in tropical regions, Sol. Energy 88 (0) (2013) 80-87

[4] A. Nobre, R. Malhotra, C.H. Tang, C. Reise, K. Kiefer, R. Rüther, T. Reindl. Degradation Analysis of Photovoltaic Systems in a Tropical Environment. 28th European Photovoltaic Solar Energy Conference and Exhibition, Paris, France, 2013

[5] Nobre, A.M. et al. The early death of PV systems in Asian sites set in industrial areas. 40th European Photovoltaic Solar Energy Conference and Exhibition, Lisbon, Portugal 2023

[6] Solar asset underperformance estimated to cause $4.6 billion in preventable losses, https://www.pv-magazine.com/2024/03/14/solar-asset-underperformance-estimated-to-cause-4-6-billion-in-preventable-losses-in-us/

[7] A.M. Nobre, S. Karthik, C. Liu, R. Jaswal, R. Baker, R. Malhotra, A. Khor. Irradiance Measurement Considerations for System Performance Assessment when managing fleets of photovoltaic assets across Asia. 44th IEEE Photovoltaic Specialists Conference, Washington DC, USA, 2017

Selected **R&D Project**

Advancing sustainability: The NUS campus-wide solar PV installation project

SOE Pyae, Dr Thomas REINDL, Erik AUNG Naing Thu, KYAW Zin Win, Sholihin Bin SANI

1. Background

The National University of Singapore (NUS) has embarked on a transformative journey towards sustainability by commissioning its Campus-Wide Solar PV Installation Project. In a strategic collaboration initiated in 2018, the NUS University Campus Infrastructure (UCI) unit asked the Solar Energy Research Institute of Singapore (SERIS) to conduct a comprehensive feasibility study for deploying photovoltaic (PV) panels across the university's campuses. This ambitious project now spans over 60 buildings at the Kent Ridge Campus and University Town (UTown).

Aligned with the university's sustainability roadmap, the project signifies NUS' profound commitment to decarbonisation, marking a crucial step towards achieving a 30% reduction in Scope 1 and 2 emissions by 2030. The installation project includes 20425 solar panels, delivering a renewable power capacity of 9.2 megawatt-peak (MW_p). This innovative project is expected to curtail NUS' annual carbon emissions by roughly 4151 tons of CO_2, contributing to around 4% of the university's total annual electricity needs. This renewable energy supply is akin to powering about 2200 four-room HDB flats for an entire year.

Fig. 1: 135.3 kW_p PV system at NUS Ventus. (Image credit: ENGIE South East Asia)

The ongoing efforts to explore additional rooftop solarisation highlight NUS' dedication to enhancing its clean energy generation capabilities. This project not only underscores NUS' leadership in mitigating climate change through forward-thinking initiatives, but also sets a compelling example for other educational institutions to emulate. As an integral component of NUS' broader Campus Sustainability Roadmap 2030, this initiative demonstrates how academic institutions can spearhead significant environmental transformation, fostering a sustainable future for all.

2. Scope of project & objectives

Sustainability isn't just about installation - it's also about longevity. The objective of SERIS' Monitoring team in this project is to employ its in-house developed cloud-based real-time PV monitoring system to track all PV systems across the NUS campuses. SERIS has implemented an advanced monitoring system that continuously assesses the health of the PV systems. With real-time analytics, this system detects early signs of system faults or degradation, preventing performance losses and maximising lifespan.

SERIS' solution also provides live power and irradiance data submission in compliance with Singapore's power system operator requirements, ensuring seamless asset management and operational efficiency across the campuses. This project showcases NUS' commitment to renewable energy and sustainable practices, setting a powerful example in the region. The energy management platform deployed by SERIS let's asset owners know their PV power generation and the detection of faults in real time, which greatly assists in troubleshooting, energy flow optimisations for self-consumption, and reporting to the authorities (e.g. to the grid operator).

The monitoring solution also provides the generation data to the NUS billing team, which has significantly reduced not only the manual process but also the waiting time to collect the required data for building consumption compared to the original setup.

3. Significance & impact of the project

In addition to standard monitoring of PV systems, the SERIS solution offers critical fault detection capabilities, and is able to detect and analyse detailed error logs from various types and brands of inverters. This functionality significantly benefits the maintenance team by providing essential insights that help prevent potential device failures and minimise system downtime, ultimately maximising energy generation.

Furthermore, SERIS' monitoring solution enables the identification of underperforming areas within the systems, as well as the verification of any discrepancies between the actual PV configuration and the initially intended design. This comprehensive analysis enhances operational efficiency and contributes to the overall effectiveness of the renewable energy installation.

Fig. 2: SERIS' real-time PV asset management platform.

4. Methodology & Results

The cloud-based PV monitoring system developed by SERIS incorporates several key components, designed for scalability and ease of configuration. The entire deployment of the project was completed within nine months, with a significant portion of this timeline dedicated to preparing the necessary documentation to ensure site safety and readiness.

The PV monitoring solution features 1-minute time resolution data for critical weather parameters, energy generation metrics, inverter performance, and other system indicators. It compiles comprehensive error logs that include fault notifications and device performance metrics. By leveraging advanced algorithms, the system analyses these error logs to effectively identify critical faults and performance anomalies.

Fig. 3: 128 kW$_p$ system at the NUS Education Resource Centre. (Image credit: ENGIE South East Asia)

Additionally, the system facilitates the implementation of fault analysis based on the types of fault, thereby minimising equipment downtime and extending the lifespan of the components.

The monitoring solution also includes functionality for evaluating individual system performances. Regular assessments of the performance ratio (PR) of each PV system enable the identification of underperforming areas within the large fleet of PV installations across the NUS campuses. This process involves a comparison and verification of the actual PV system configuration against the original design, enabling the detection of any discrepancies or deviations.

The deployment of SERIS' PV monitoring solution at the NUS campuses has resulted in significant improvements, including:

Enhanced Fault Detection: The fault detection capability has reduced the average response time of the maintenance team to system anomalies, thereby significantly decreasing unplanned downtime.

Maintained/improved Energy Output: Through continuous real-time monitoring, the overall energy output of the PV systems has improved, ensuring the optimal utilisation of the PV assets.

Targeted Performance Optimisation: Analysis of the collected data has enabled the identification of specific inverters or sections of the PV arrays that were underperforming, enabling targeted interventions to enhance overall system performance.

Configuration Alignment: Routine evaluations have revealed inconsistencies between the anticipated and actual PV system configurations, prompting necessary adjustments to ensure alignment with the initial design parameters.

5. Conclusions

The NUS campus-wide solar PV installation project represents a significant achievement in the university's ongoing commitment to sustainability and environmental stewardship. Through a strategic collaboration with SERIS, NUS has successfully deployed an extensive network of PV panels across its campuses, establishing itself as a leader in renewable energy within the educational sector. SERIS' innovative PV monitoring solution not only enhances system performance but also ensures optimal operation and swift reaction to system faults.

The project's impacts extend beyond mere energy generation, as it embodies a comprehensive approach to asset management and operational efficiency. By continuously monitoring PV system health and performance, the proactive measures implemented have effectively minimised downtime and maximised the lifespan of critical infrastructure. As organisations worldwide strive to meet their sustainability goals, NUS serves as an inspiring example, demonstrating that educational institutions can drive significant environmental change while maintaining operational excellence.

As the university continues to explore further avenues for rooftop solarisation and advances in renewable technologies, it positions itself at the forefront of the global movement toward sustainable development. The success of this project not only contributes to the university's ambitious goal of reducing carbon emissions, but also reinforces its role as an influential player in fostering a sustainable future through education, innovation, and collaborative efforts.

Selected **R&D Project**

Estimating global horizontal irradiance using regional satellite imagery

Dr Gokhan Mert YAGLI

1. Background

Energy meteorology, a field dedicated to optimising the utilisation of renewable energy sources, relies heavily on precise global horizontal irradiance (GHI) data for planning and monitoring solar energy systems. Applications include estimating energy yields for photovoltaic (PV) systems, analysing PV performance, resource assessment, solar forecasting, and integrating solar energy into electrical grids. As the importance of solar energy continues to grow [1], the need for high-quality GHI data is expected to intensify, supporting the efficient integration of renewable energy into global energy systems. Hence, there is a need to develop a regional high-quality GHI estimation model.

2. Scope of project & objectives

High-quality regional GHI data are essential for the efficient integration of renewable energy into global energy systems. This project focuses on developing and validating a satellite-based image-to-irradiance method for estimating GHI, with a particular emphasis on the Asia-Pacific region. The primary objectives are:

a. Develop a robust methodology for converting satellite images to GHI values.
b. Implement this methodology in the Asia-Pacific region using images from the Himawari-9 satellite.
c. Validate the accuracy of the satellite-derived GHI estimates against ground-based sensor measurements.

3. Significance & impact of project

The significance of this project lies in its potential to provide accurate, spatio-temporal GHI data over a large geographical area which are entirely based on satellite images. The key benefits are:

a. Improved spatial coverage: While ground-based sensors provide the most accurate GHI measurements, their spatial distribution is typically sparse. Satellite-derived GHI can fill these gaps, providing continuous coverage over large areas.
b. Cost-effectiveness: Maintaining and calibrating extensive networks of ground-based sensors is costly and often impractical. Satellite-based methods offer a more cost-effective alternative for comprehensive GHI monitoring.
c. Support for renewable energy integration: As the share of solar energy in the global energy mix continues to grow, high-quality GHI data becomes increasingly important for efficient planning and integration of solar power systems.
d. Improved solar forecasting: High-quality GHI information can contribute to more accurate PV power forecasts and predictions of weather patterns and extreme events to support grid operations.

4. Methodology & Results

The Himawari-9 satellite provides Asia-Pacific snapshots every 10 minutes in 16 different wavelengths, ranging from 0.47 to 13.3 micrometres. This study primarily utilises the visible band at 0.64 micrometre.

Raw satellite images are in the unit of digital numbers, which should be converted to GHI values. The conversion of satellite images into GHI values involves several steps. First, raw satellite sensor readings are converted to reflectance values using a calibration table generated from the header information contained in the Himawari-9 Himawari Standard Data. Second, reflectance values are converted to cloud albedo (CAL) using the following equation:

$$CAL = (\rho - \rho cs) / (\rho cal - \rho cs),$$

where ρ is the observed reflection for each pixel and time, ρcs is the clear-sky reflection (or surface reflectance), ρcal is a calibration value representing maximum reflection over a period (typically 20-30 days). ρcal and ρcs are also commonly referred to as upper and lower bounds, respectively.

One should derive the upper and lower boundaries for reflectance-to-CAL conversion. The upper boundary calculation identifies large reflectance observations (cloudy conditions), while the lower boundary calculation identifies low reflectance observations (clear-sky conditions). These boundaries are derived using a data-driven model based on 20 days of historical 10-minute resolution reflectance images.

For the upper boundary calculation, all reflectance values are sorted, and the 98th percentile of the maximum reflectance value per UTC hour is identified. For the lower boundary calculation, the lowest observed reflectance value for each hour for each pixel is used so that surface reflectance can be derived.

Boundary values are updated daily to reflect the most recent reflectance changes, such as snow events or dense regional cloud observations, in the image-to-irradiance conversion.

Figure 1 shows an example image of Asia-Pacific surface reflectance estimations at 02:00 UTC on July 15, 2024.

These boundaries are then used to convert new reflectance values to CAL values. CAL values can be used as a proxy for sky cloudiness. These values are then converted into clear-sky index (CSI) values using a piecewise equation [2].

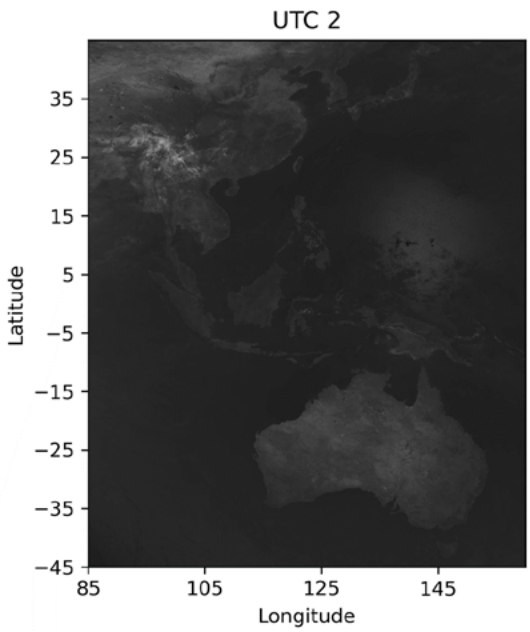


Fig. 1: Data-driven Asia-Pacific ρcs estimations at 02:00 UTC on July 15, 2024: the minimum value of each pixel over the previous 20 days is recorded as surface reflectance.

At this stage, raw satellite images with digital counts are converted to regional CSI estimations. To convert CSI values into final GHI values, clear-sky GHI estimations for the entire Asia-Pacific region are calculated. Then, by multiplying regional CSI values by regional clear-sky GHI estimations, raw satellite images are converted to regional GHI values. Figure 2 shows an example image illustrating the conversion from reflectance values to GHI values at 11:30 AM Singapore time on June 24, 2024.

The accuracy of the SERIS satellite model has been validated against 15 ground-based sensors distributed across Singapore and 2 overseas sensors located in Cambodia and Malaysia.

For the Singapore stations, the validation covers 6 months, from June 1, 2023, to December 31, 2023, whereas for the overseas stations, the validation period runs from April 1, 2024, to June 30, 2024. One-minute GHI sensor readings are quality controlled, after which high-quality sensor measurements and the GHI data from the corresponding satellite pixel are aggregated to an hourly resolution for accuracy checks.

In addition to point-specific forecasts, the accuracy of the Singapore island-wide average GHI is also calculated. For this, GHI sensor readings from the 15 ground sensors are averaged to obtain the island-wide average GHI, and the same is done for satellite-derived GHI. Both are then aggregated to an hourly resolution, and the accuracy is calculated.

For validation, three error metrics are chosen: normalised mean bias error (nMBE), normalised mean absolute error (nMAE), and normalised root mean square error (nRMSE), where the normalisation factor is the range of hourly sensor readings. The validation results are given in Table 1.

As seen from the results, nRMSE and nMAE at hourly resolution are around 10% and 7%, respectively, in most of the stations. Although the model-led bias observed in satellite-derived GHI data shows some variability, the observed bias is within the -1% to 1% range in most stations. Since spatial variability is smoothed out after island-wide averaging, the results are more accurate. Model output statistics (or more generally, post-processing) can be considered to mitigate the bias and improve the general accuracy of the satellite model. We are, therefore, working on a general and scalable post-processing approach to address the bias observed in satellite-derived GHI.

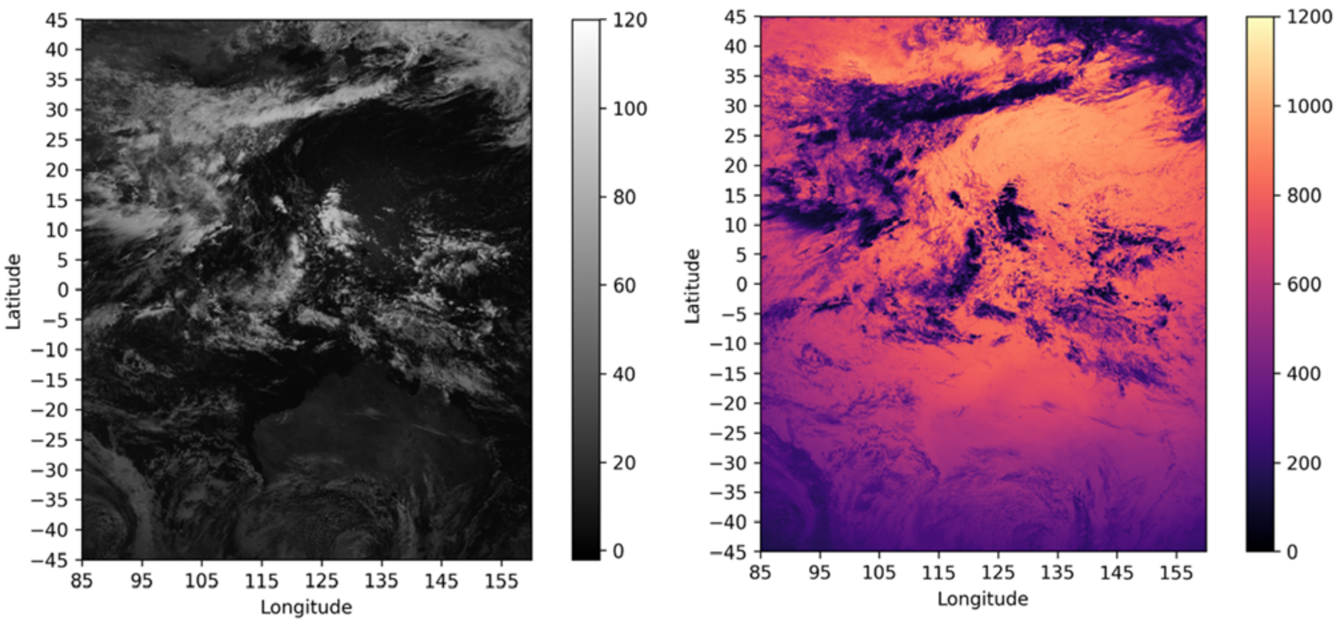


Fig. 2: Satellite image in units of reflectance (left) and converted GHI image in units of W/m^2 (right). The images were taken at 11:30 AM Singapore Time on June 24, 2024.

Table 1: Hourly validation results of the satellite-to-irradiance conversion model were validated against 15 ground stations distributed across Singapore and 2 overseas stations. Singapore-wide average results were also calculated.

Station	nMBE [%]	nMAE [%]	nRMSE [%]
SG-1	-0.11	7.60	10.71
SG-2	-1.26	8.18	11.46
SG-3	-0.53	7.63	10.97
SG-4	-1.41	8.38	11.50
SG-5	-1.72	8.02	10.20
SG-6	1.02	7.08	10.20
SG-7	1.39	7.99	11.07
SG-8	-1.15	7.29	10.28
SG-9	-1.19	6.73	9.50
SG-10	-0.77	7.08	10.34
SG-11	0.77	7.44	10.62
SG-12	-0.69	7.77	11.00
SG-13	-0.79	7.33	10.34
SG-14	-0.75	7.03	10.22
SG-15	-0.21	7.77	10.77
Island-wide	0.51	5.53	7.69
Cambodia	-0.73	7.36	10.69
Malaysia	-0.77	9.54	14.03

5. Conclusions

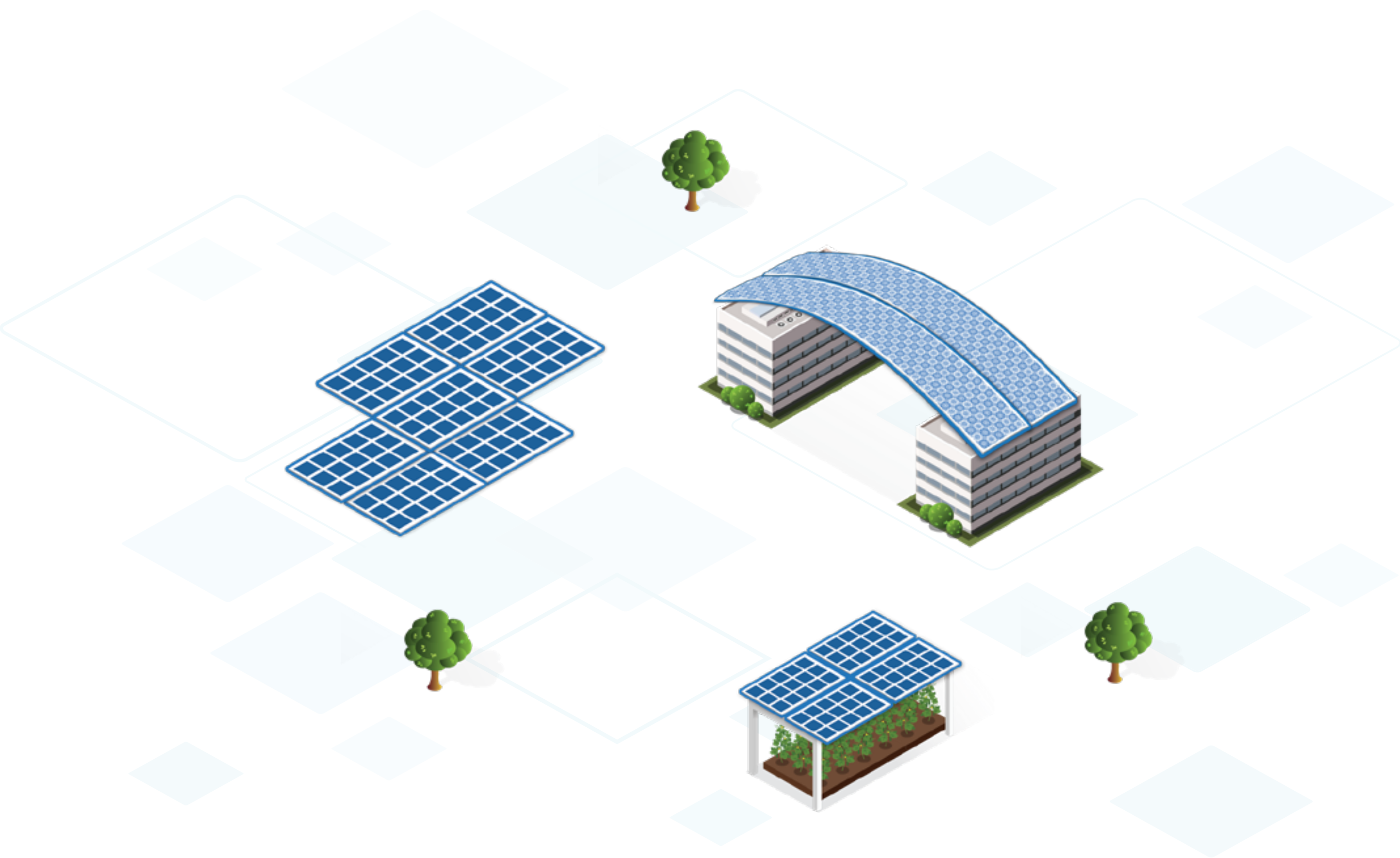
The increasing importance of solar energy in the global energy mix drives the need for accurate and reliable spatio-temporal complete GHI data. The methods developed and validated by the SERIS team using satellite images represent a significant advancement in the field of solar energy resource assessment and forecasting. The conversion of satellite images into GHI values through a detailed methodological process, and the validation against ground-based sensors, demonstrate the potential for high accuracy in regional satellite-derived GHI estimations. This approach offers a cost-effective and scalable solution for GHI estimation over large geographical areas, addressing the limitations of ground-based sensor networks. The scalability of the model and ongoing efforts to improve post-processing techniques hold promise for future enhancements.

The overall success of the project underscores its significance in supporting the efficient integration of renewable energy into energy systems, contributing to more effective solar energy system planning, solar forecasting, and site monitoring.

References

[1] World energy outlook 2024, International Energy Agency. https://iea.blob.core.windows.net/assets/86ede39e-4436-42d7-ba2aedf61467e070/WorldEnergyOutlook2023.pdf

[2] Müller, R. and Pfeifroth, U., 2022. Remote sensing of solar surface radiation–a reflection of concepts, applications and input data based on experience with the effective cloud albedo. Atmospheric Measurement Techniques, 15(5), pp.1537-1561.



SERIS FACILITIES AND LABORATORIES

PEROVSKITE **SOLAR CELL LABORATORY**

This 190-m^2 class-100,000 cleanroom 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 Atomic Layer Deposition System (Kemicro)

This atomic layer deposition system is used for the deposition of oxide-based functional thin films, e.g. tin oxide (SnO) onto various substrates (glass sheets, silicon wafers) of a wide range of sizes up to 230 mm x 230 mm. The desired film can be as thin as 15 nm with a non-uniformity of only ±3%. The depositions are carried out via sequential gas-phase chemical reaction of two precursor sources. The chamber is designed to enable a wide range of processing temperatures (80-150 °C), depending on the material composition and quality of the desired film. To achieve high-quality films with low contamination levels, a very low base pressure is required in the vacuum chamber, which is achieved with a high-performance pump system that reaches < 10^{-2} Torr. 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).

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)
- Low-damage low-temperature sputtering system
- Photoluminescence quantum yield tool (QYB)
- 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

Contact: Dr Firdaus Bin SUHAIMI (serfs@nus.edu.sg)

SILICON **SOLAR CELL LABORATORY**

This laboratory is located on levels 1 and 2 of the E3A building on the main NUS campus. Industrial tools with throughput of more than 100 wafers per hour enable industry-relevant solar cell R&D using monocrystalline silicon wafers.

Silicon Cleanroom Lab 1A:

Lab 1A is used for wet-chemical processing of silicon wafers. It is equipped with highly versatile R&D equipment to develop advanced processes for 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 were custom-built by MediaMac and include 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.

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 processes such as etching, alkaline texturing, and cleaning of silicon wafers (up to M10 size and half-cut G12). It consists of several baths with automated bleed and feed function that help maintain the concentration of chemicals in the bath, resulting in excellent process control based on feedback from several sensors. The tool also has state-of-the-art O_3-based wet-chemical process baths for advanced wafer cleaning, producing tailored surface morphologies and growing thin oxide films. The robotic arms enable automated, fast and safe processing with consistent performance.

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

The InPilot tool from RENA Technologies provides inline wet-chemistry for single-side processing of silicon wafers (up to M10 size and half-cut G12). This is a semi-automated 1-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 water rinses separating the chemical baths. The HF and alkaline baths can be heated.

Silicon Cleanroom Lab 1B:

Lab 1B houses several chemical vapour deposition tools that can deposit various 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 R&D inline plasma-enhanced CVD (PECVD) machine MAiA 2.1 from Meyer Burger is a quasi-continuously operating high-throughput PECVD reactor (> 1000 wafers/hr for some processes). The deposition process uses a 'remote' plasma energised by 2.54-GHz microwaves, inducing less damage to the Si wafers than the conventional parallel-plate approaches. The loading module is equipped with an infrared lamp array for rapid substrate heating to the process temperature (350-550 °C). The machine deposits silicon nitride, silicon oxide and aluminium oxide films onto large silicon wafers (M2 to G12).

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

The Manual ALD Lab tool from SoLayTec is a pioneering R&D system developed 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. The tool is able to deposit layers on a wide range of substrate types and sizes (up to G12 size wafers or 21 cm x 21 cm glass panes). While Al_2O_3 films are critical for further development of current silicon solar cell technologies, ZnO and SnO-based films will enable the development of transparent conductive oxides or transparent metal oxides for application in high-efficiency large-area perovskite-silicon tandem solar cells.

Versatile Tube furnace (TS81254 / Tempress Systems, Netherlands)

The TS81254 tube furnace from Tempress Systems is a 4-stack R&D high-throughput furnace featuring various process options: Low-pressure chemical vapour deposition (LPCVD) of doped & intrinsic poly-Si films for passivated-contact solar cell applications (double-sided deposition), doped & intrinsic silicon nitride deposition, oxidation for surface passivation applications.

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

The CAiA Lab tool is a unique prototype PECVD tool for the ultra-fast deposition of intrinsic and doped silicon thin films and associated stacks, as well as doped transparent metal oxide films. The CAiA is the result of a joint development project by SERIS and Meyer Burger during the period 2017-2020. It has two process chambers to prevent cross-contamination. The tool enables the single-sided deposition of thin high-quality interfacial oxide layers and low-absorbing and dense doped-layer stacks on silicon wafers up to size M6. The tool is used for R&D on single-junction silicon solar cells as well as tandem devices with silicon bottom cells.

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

The Octopus II is a 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 wafers and is designed in a cluster form to provide process flexibility needed for the R&D purposes. 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 has a versatile laser tool and an inkjet printing tool that are used to create advanced features on solar cells.

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

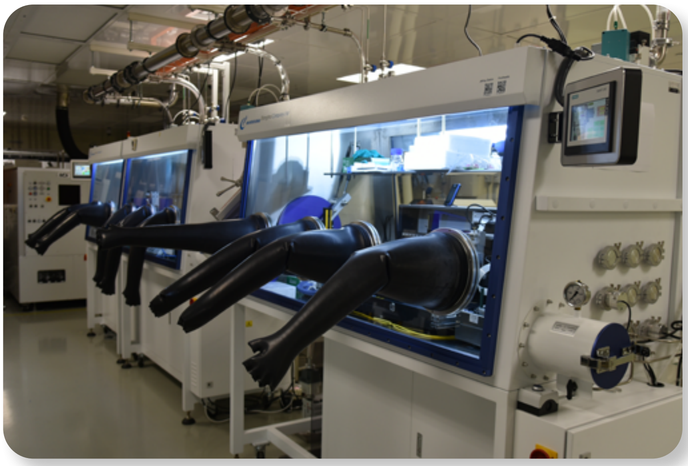
The ILS LT is an R&D laser processing workstation for high-precision applications in PV. The machine features three laser sources to provide excellent flexibility: a 2-W UV continuous source, a 20-W green ns source, and a 30-W fs source that can be tuned to operate at either UV, green or IR wavelengths. 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 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 avoiding cross contamination. An ink evaluation module with disposable cartridges allows to test 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 is utilised to create a controlled, moisture-free environment essential for processing 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.

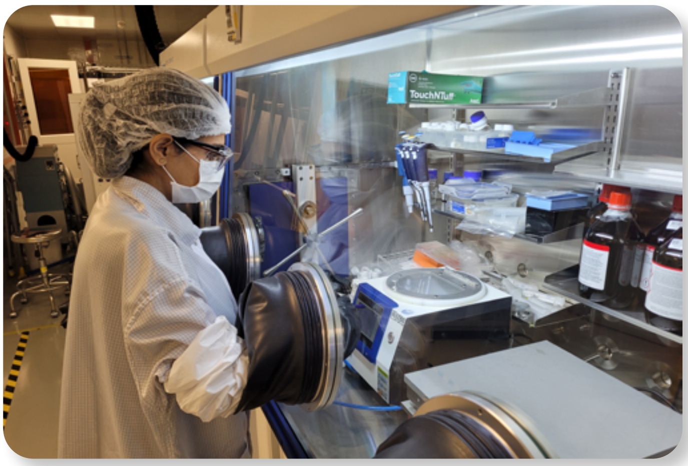


Pilot-Scale Inkjet Printer (PiXDRO / SUSS MicroTec, Netherlands) in a glovebox

The PiXDRO inkjet printer, positioned in one section of the 3-section glovebox, operates in a controlled moisture-free environment. This pilot-line tool is capable of handling substrates up to G12 size (210 mm), making it ideal for the precise deposition of moisture-sensitive layers such as perovskite, ETL and HTL for industrial-size tandem solar cells. The printer also supports a wide range of functional inks and allows rapid switching between ink types with minimal risk of cross-contamination.

Spin Coater (LEBO Science, China) in a glovebox

The spin coater, together with a hotplate, is housed in a separate section of the 3-section glovebox. This configuration ensures uniform deposition and curing of perovskite and other functional layers.



Solar Cell Metallisation Lab 2B:

This laboratory facilitates metallisation and contact formation for different types of solar cells. It has multiple tools for advanced metallisation processes, suited for both high- and low-temperature applications.

R&D screen printer (ASYS, Germany)

This versatile R&D screen printer from ASYS, Germany is capable of screen printing metal contacts onto a wide range of substrate sizes, ranging from small (50 mm x 50 mm) to very large (210 mm x 210 mm, G12). The printer is also capable of stencil printing. The system is equipped with a patented vision alignment lens capability, i.e. smart assistance system, that 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 Si wafers (up to M6 size) within a temperature range of 300-1000°C. 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 and other materials (Al, Ag, etc) 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. The SV-540 tool has dedicated processing chambers for the sputtering of metallic, dielectric and TCO/TMO layers. The chambers 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 400°C. 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, Cu, In, ZnO and thin oxide and oxynitride tuned to specific requirements. The Line540 tool has three planar magnetron sources, of which two 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 dielectric films such as iZnO and $MgZnO_4$. Substrates of sizes up to 30 cm x 40 cm or up to six M6-size wafers can be processed per run at substrate temperatures of up to 200°C.

Contact person: Dr Selvaraj Venkataraj (s.venkataraj@nus.edu.sg)

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.

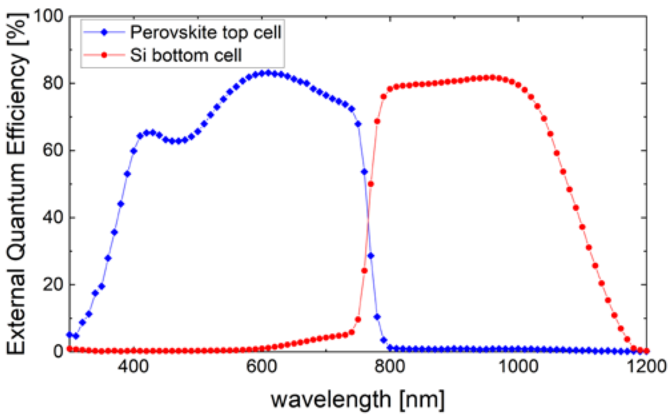
Materials Characterisation Laboratory

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 wafer thickness & resistivity measurement 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, and a contactless corona-voltage measurement system for interface defect characterisation.

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 allows quick and localised measurements of both EQE and R over a wavelength range of 300-1700 nm for various types of solar cells.



Measured EQE of a monolithic perovskite-Si tandem cell made by SERIS

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.

Contactless corona-voltage (C-V) measurement and µ-PCD lifetime mapping tool (SEMILAB, PV-2000)

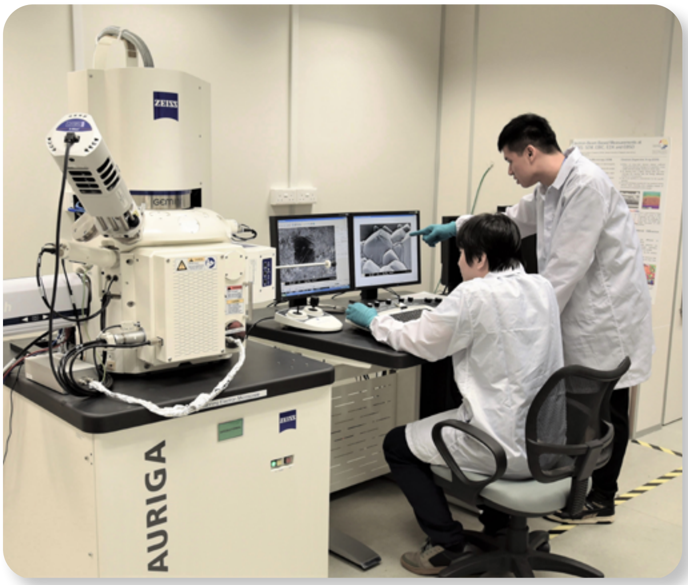
This technique provides fast contactless measurement of interface parameters that affect the passivation quality of dielectric films for PV applications. The metrological capabilities include the mapping of contact potential (in the dark or under illumination), band bending at the semiconductor/dielectric interface, fixed charge in the dielectric, and interface defect density. Microwave-detected photoconductance decay (µ-PCD) is a time-resolved method to determine and map the effective carrier lifetime of silicon wafer samples with a spatial resolution of 5 mm.

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, 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 less than 1 kV. It is ideal for imaging sub-micron morphologies, cell surface textures, and micro- and nanopatterned 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

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 the thickness of thin optical coatings. The ellipsometer has an additional tilted sample stage, which is ideal for measurements of the pyramid facets of textured monocrystalline silicon solar cells.

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

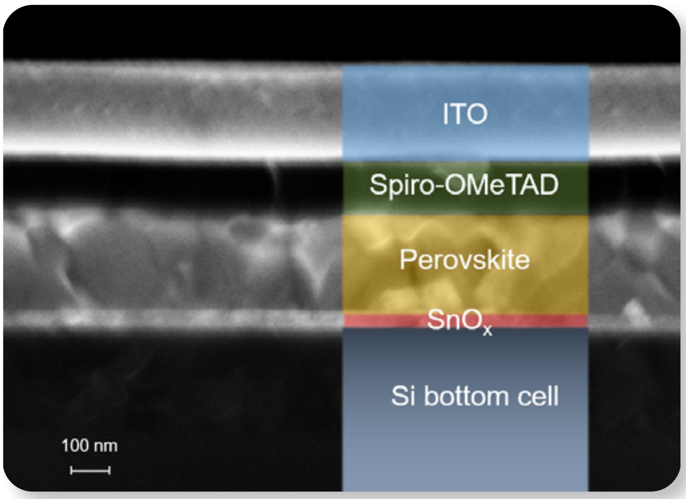
The UV-VIS-NIR optical spectrophotometer enables the determination of the specular and diffuse reflectance and transmittance of materials/devices in the 190-2500 nm wavelength range. These measurements are routinely used to assess cell front texture quality, antireflection layer properties, and transparency 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.

Solar Cell Measurement Laboratory

This laboratory focuses on measuring solar cell efficiency, 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 ISO 17025:2017 SAC-SINGLAS accredited high-precision I-V and spectral responsivity measurements to determine the efficiency of solar cells provided by SERIS researchers and 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.



Cross-sectional SEM image of a monolithic perovskite-Si tandem solar cell made by SERIS

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 300 - 1100 nm. These solar simulators are capable of measuring solar cells with metallisation grid patterns ranging from traditional H-patterns to newer busbarless designs.

Large-area spectral response analyser (Enlitech, SR-156)

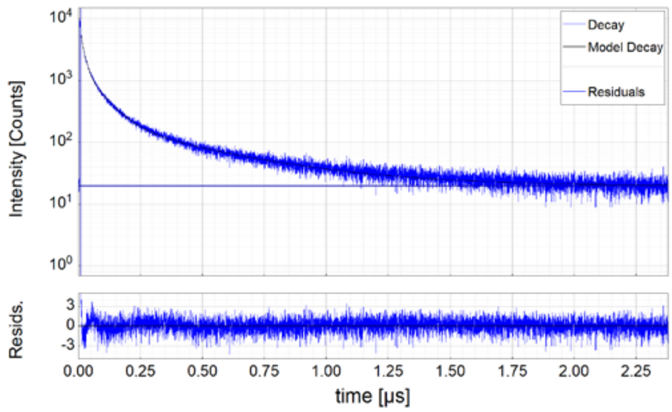
This system projects a large monochromatic beam that overfills the solar cell area for differential spectral response measurement up to 1-Sun bias light intensity. The external quantum efficiency (EQE) extracted from the measured spectral response curve enables the determination of the spectral mismatch correction factor.

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 includes 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.



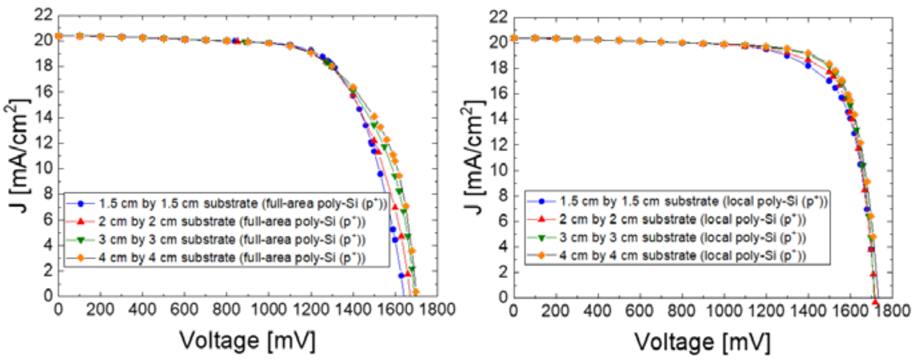
Time-resolved photoluminescence (PL) of a perovskite film showing the PL decay, and fitted model decay. The residual trace (bottom panel) indicates good agreement between the fitted and measured data.

Contact person: Dr CHOI Kwan Bum (serckb@nus.edu.sg)

PV DEVICE **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 n-PERT and passivated-contact (TOPCon) silicon solar cells as well as perovskite solar cells and perovskite-silicon tandem cells. Via 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	n-PERT, 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 in Puqun Wang, Tianyuan Liu, Laxmi Nakka, Armin G. Aberle, Fen Lin, 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 n-PERT and 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.

Metrology simulation

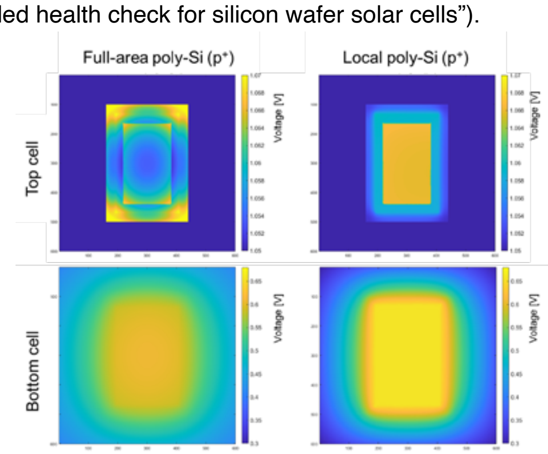
We have developed various programmes for reliable simulations of the PV device characterisation methods in use at SERIS. For example, we can simulate injection dependent carrier lifetime measurements, bias and injection dependent quantum efficiency (EQE/IQE) measurements, as well as injection and bias 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").

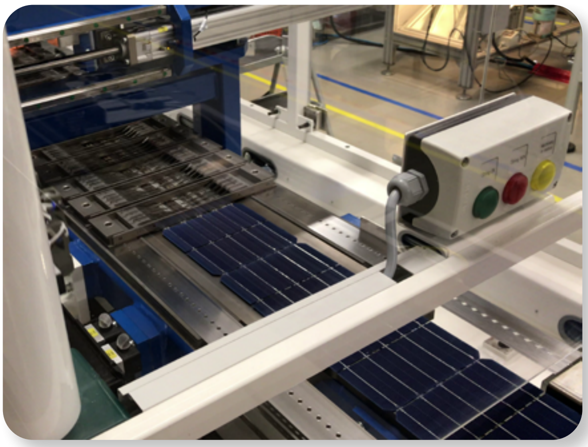


The simulated diode voltage map of the top perovskite cell and the Si bottom cell for perovskite-biPoly™ tandem devices featuring full-area poly-Si (p⁺) and local poly-Si (p⁺) layers. (Image source: Fig. 6 in Puqun Wang, Tianyuan Liu, Laxmi Nakka, Armin G. Aberle, Fen Lin, Unlocking the full potential 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).

Contact person: Dr CHOI Kwan Bum (serckb@nus.edu.sg); Assoc Prof Erik BIRGERSSON (mpebke@nus.edu.sg)

PV MODULE **DEVELOPMENT LABORATORY**

Located at CleanTech Park, SERIS' 300-m² PV Module Development 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 located at CleanTech Park

Thermal Laser Separation (TLS) cell cutter (3D-Micromac, 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 vapourised. 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 plant (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 plant

Contact person: Dr Carlos Enrico CLEMENT (carlos.clement@nus.edu.sg)

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 to measure and characterise 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.

Complementary coloured light bias system in one of SERIS' Class A+A+A+ solar simulators

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.

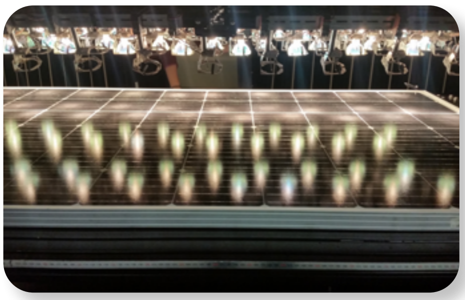
"Golden module" certificates can be produced by combining the results from both simulators, giving the world-class uncertainty of ± 1.4% for the module's measured maximum power.

"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

PV module characterisation

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 2025.

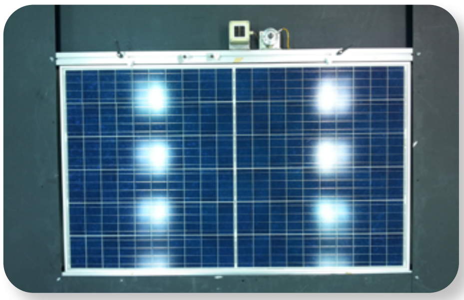
Measurement of the IAM of a commercial-size PV module

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.

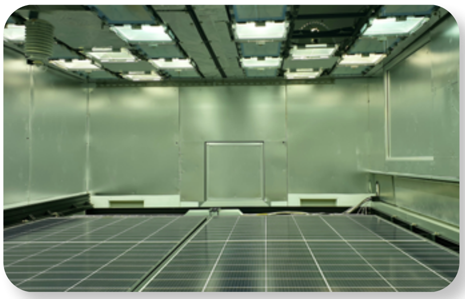


Module stabilisation

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

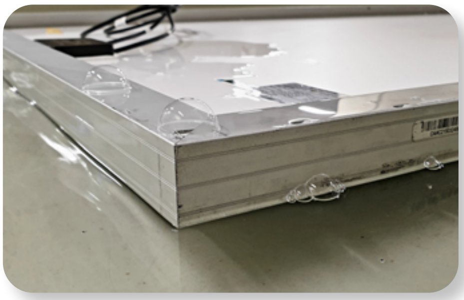
PV module reliability and durability testing

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

Mechanical stress tests

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

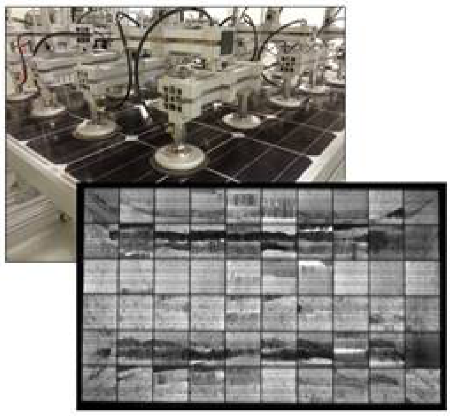
"Mechanical Load Test" (MLT) to simulate for extreme weather stress conditions (e.g., heavy winds, snow): a static load of up to 5400 Pa is chosen for a certain duration.

"Dynamic Load Test" (DLT) uses lighter loads but is repeated 1000 times. This simulates 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.swing' into a module from 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 novel 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

Contact person: Aziz NAIRI (a.nairi@nus.edu.sg)

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 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)

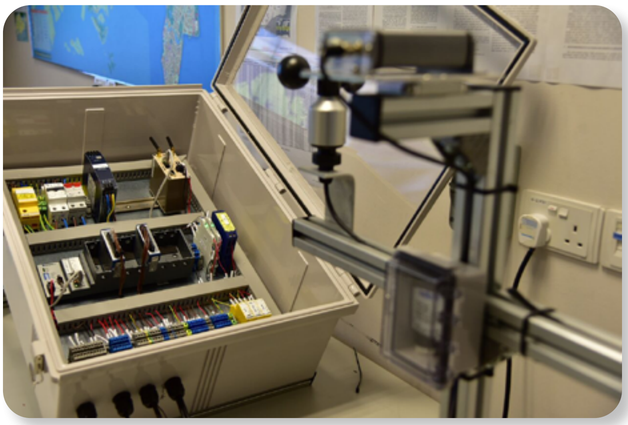
Contact person: Dr Jaffar Moideen YACOB ALI (jaffarmoideen@nus.edu.sg)

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 specific project requirements. It has been deployed successfully in numerous projects across Asia-Pacific and Europe, and it fulfills the stringent data requirements of EMA PSO, Singapore's power system operator, for PV systems 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), 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 the 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 variowus 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 network
- 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 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 (left) and a motion monitoring sensor for floating PV systems (right)

Contact person: SOE Pyae (soepyae@nus.edu.sg)

ELECTRONICS **LABORATORY**

SERIS' Electronics Laboratory is a general-purpose workshop and laboratory space that enables research and development in areas including meteorological observations, PV system monitoring, power electronics, and programming of embedded systems. The following processing and testing equipment is available in this laboratory.

General purpose workshop

Mechanical and electronic tools and workspaces allow general construction and development of devices for diverse research purposes. The lab houses tools and components for the analysis of PV systems and the support of SERIS' network of meteorological and system monitoring stations.

3D printer

Three-dimensional solid objects can be fabricated from digital files with our 3D printer in order to perform detailed analyses and propose novel designs related to PV system mounting structures and other components.

Programmable multipurpose tester (National Instruments)

The programmable multipurpose tester is a computer-controlled platform for measurement and automation. It combines a chassis with interchangeable hardware modules which make it highly adaptable for different testing procedures of electronic components.

Lead-free solder stations for SMD (Surface Mounted Device) soldering (Weller), equipment for testing and wiring

All types of surface mounted device components can be soldered with high-precision solder stations, and electrical circuits can be tested and verified after soldering. SERIS' monitoring stations are developed, assembled and tested in the laboratory before they are deployed at different project locations.

Computer stations for microcontroller programming

Microchip programming interfaces and debuggers are available for developing the firmware for embedded systems such as measurement equipment or solar charge controllers.

3D printer

Multiple Lab equipment for electrical works

Contact person: Dr Jaffar Moideen YACOB ALI (jaffarmoideen@nus.edu.sg)

SERIS SERVICES

PROCESSING SERVICES **FOR SILICON SOLAR CELLS**

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

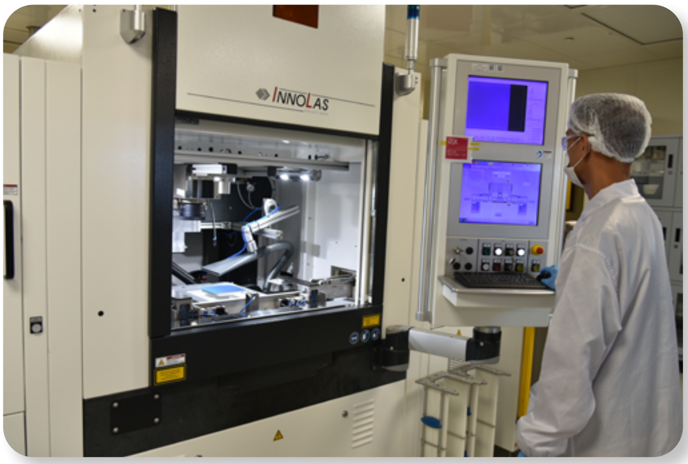
Processing of large-area silicon solar wafers and cells:

- M2 to G12 wafer size (up to 210 mm x 210 mm)
- Batch-type wet-chemical processes including cleaning, etching and texturing
- Inline wet-chemical processes (both acid and alkaline chemistries) including cleaning and etching
- PECVD of dielectric layers (SiN_x, AlO_x, SiO_x, SiO_xN_y etc)
- PECVD 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 silicon heterojunction 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 processes including oxidation, forming gas anneal, co-annealing
- 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 applications in heterojunction solar cells.

Inline wet-chemical processes (both acid and alkaline chemistries) including cleaning and etching.

The PVD sputtering platform at SERIS is used for depositing metal layers, transparent conductive oxides and multi-layer stacks for silicon and thin-film solar cells, as well as heterojunction silicon wafer solar cells.



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

Contact person: Dr Selvaraj VENKATARAJ (s.venkataraj@nus.edu.sg)

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.

The PVD sputtering platform at SERIS 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 × 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 400ºC. This allows to deposit thin layers of metals, TCOs and dielectrics onto various substrates. It is also possible to deposit graded layers, 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, the 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 Si 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, Cu, In, ZnO 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

Contact person: Dr Selvaraj VENKATARAJ (s.venkataraj@nus.edu.sg)

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 (e.g. 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)

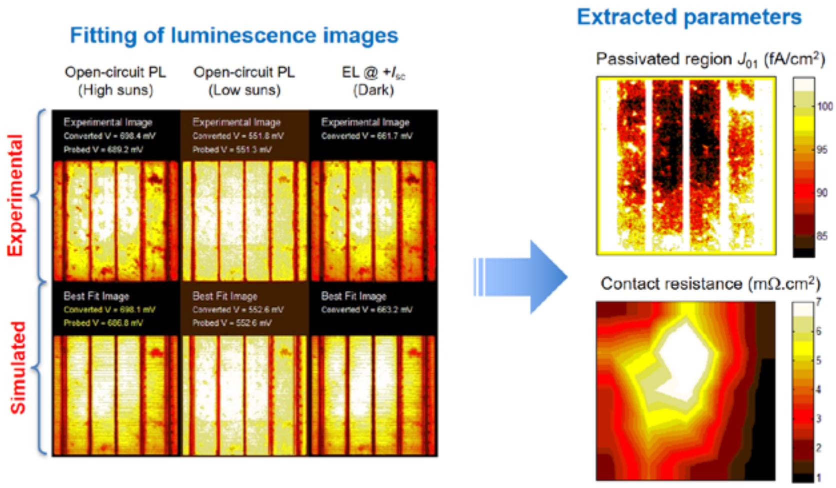
- High-precision steady-state light I-V and spectral response measurements for solar cell devices
- Solar Cell Doctor: Detailed health check for solar cells
- Photoluminescence and electroluminescence imaging
- Determination of thickness and optical properties of thin films by spectroscopic ellipsometry
- 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

PV product validation and improvement

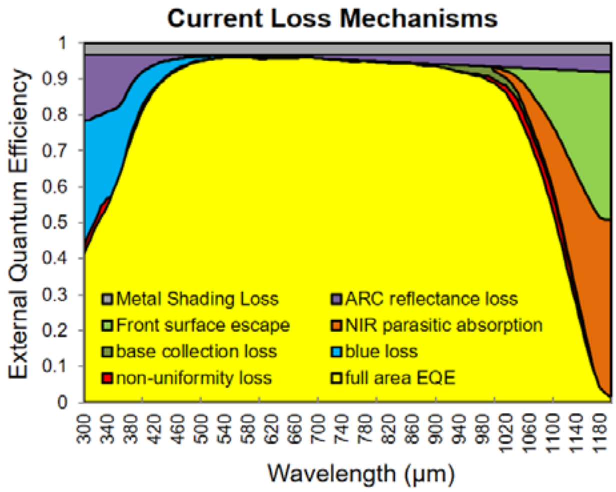
- Technical consultancy for industrial silicon solar cell development, process optimisation, metal grid design, production yield improvement
- Analysis and simulation of advanced silicon solar cell concepts such as the heterojunction architecture, passivated contacts (TOPCon), local back-surface-field (PERC/PERL), and bifacial configurations
- Accelerated inspection, characterisation and analysis (for solar cell manufacturing and research applications) by artificial intelligence techniques

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.

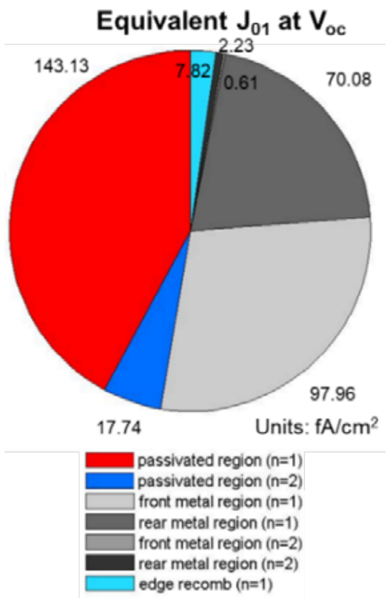


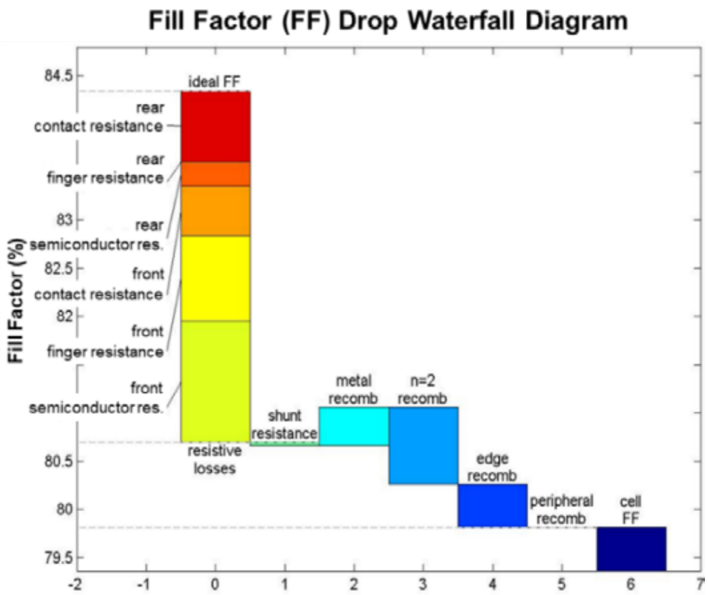
Fitting of Griddler simulated luminescence images to experimental data allows the extraction of device parameters in this p-type multicrystalline silicon solar cell. This includes the spatial distribution of the saturation current density J_{01} of the passivated region and the contact resistance.



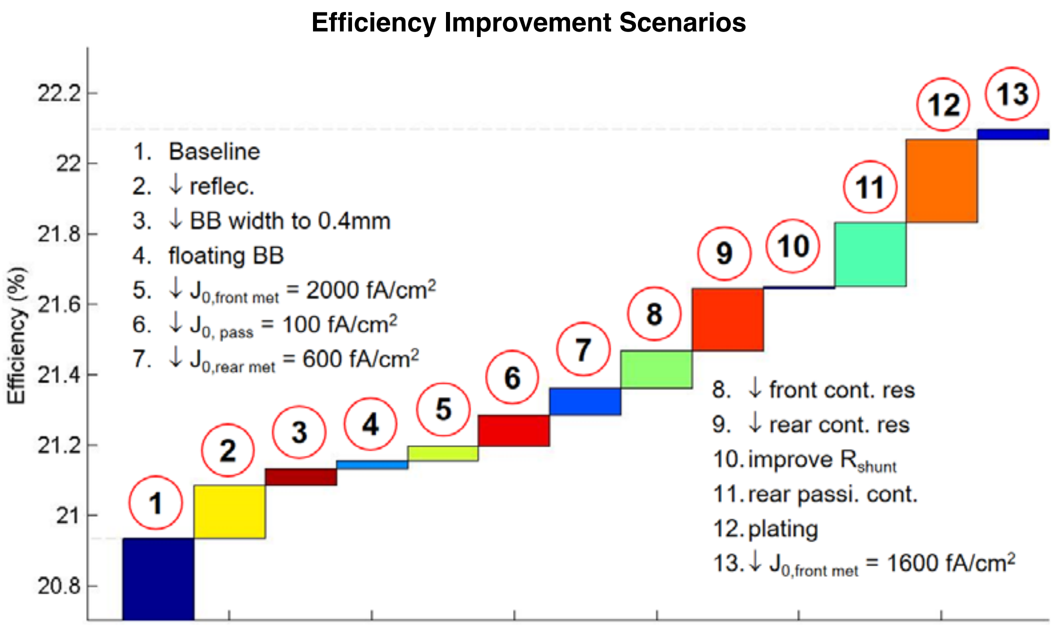
J_{sc} Breakdown (mA/cm²)	
Cell Current	40.062
Base collection loss	0.314
NIR parasitic absorb	1.550
Front surface escape	1.287
ARC reflectance	0.977
Blue loss	0.464
Metal shading	1.567
Non-uniformity loss	0.207
WAR (300-1000nm) %	1.762
Base eff. diffusion length (μm)	3478

Elucidation of the short-ciruit current density (J_{sc}) losses of a monocrystalline silicon solar cell by analysing spectral response and reflectance measurements. Knowing the shortfalls in J_{sc} facilitates better solar cell design and optimisation.





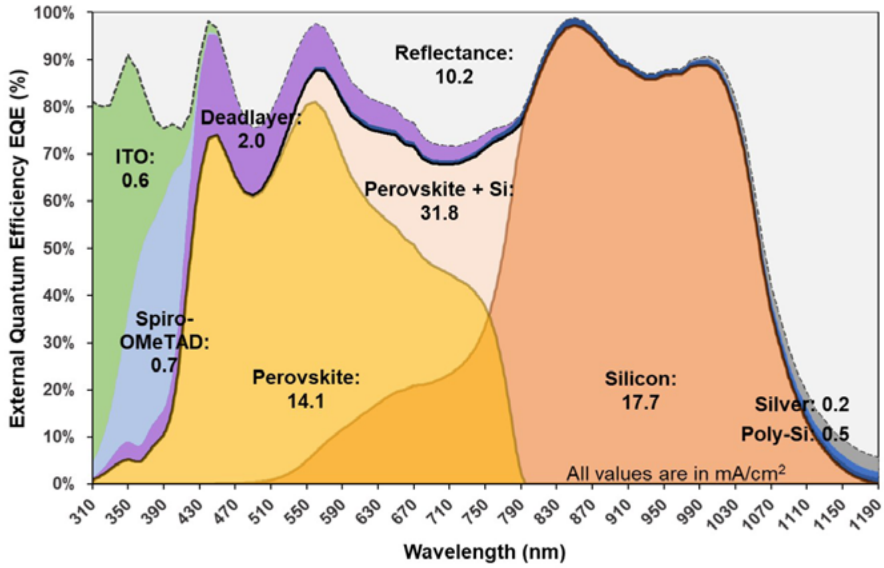
The accurate representation of a crystalline silicon solar cell allows the precise quantification of the various recombination currents at open circuit that affect its voltage, as well as the myriad of factors which influence its fill factor.



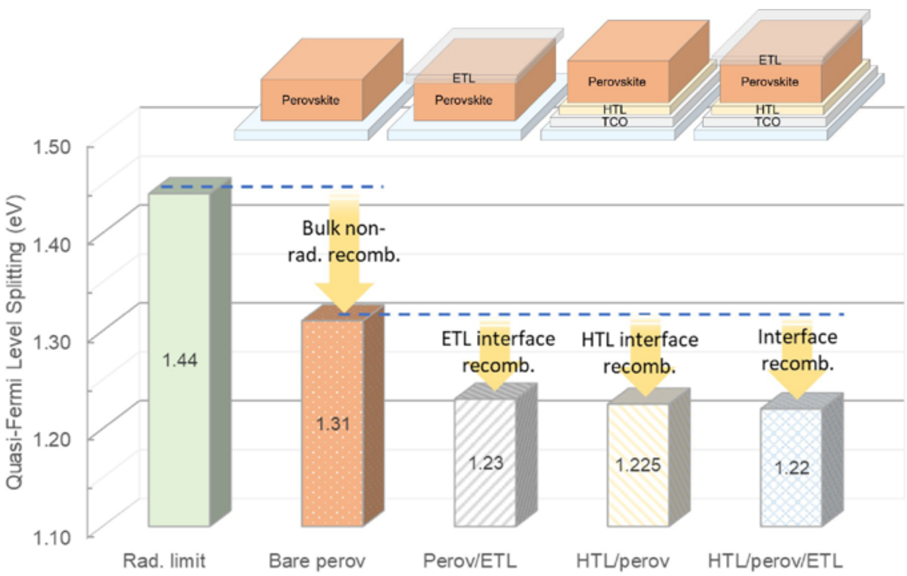
Griddler prediction of incremental silicon solar cell efficiency improvements due to specific process or cell design changes

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 presents 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.



Analysis of absolute luminescence quantum yield measurements of a bare perovskite film, a perovskite/electron transport layer (ETL) stack, a hole transport layer (HTL)/perovskite stack, and a HTL/perovskite/ETL stack allows the quantification of voltage losses associated with the bulk and carrier transport layer interfaces. "Rad. limit' is the radiative limit. (values shown are for illustration purposes.)

Contact person: Dr CHOI Kwan Bum (serckb@nus.edu.sg)

DEVELOPMENT **OF PV MODULES**

SERIS operates a PV Module Development and Application Laboratory where PV modules ranging from small single-cell modules for testing purposes up to full-size 72-cell 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 visually appealing PV modules (Peranakan PV, pointillism PV, etc)
- Integration of BIPV onto 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 perform 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***

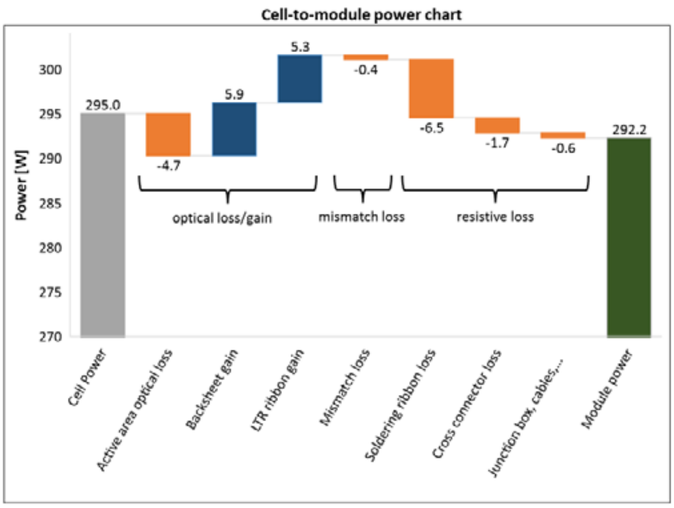
Quantify the light harvesting from inactive areas of a PV module (e.g. cell-gap area, ribbon) using EQE line scans.

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.

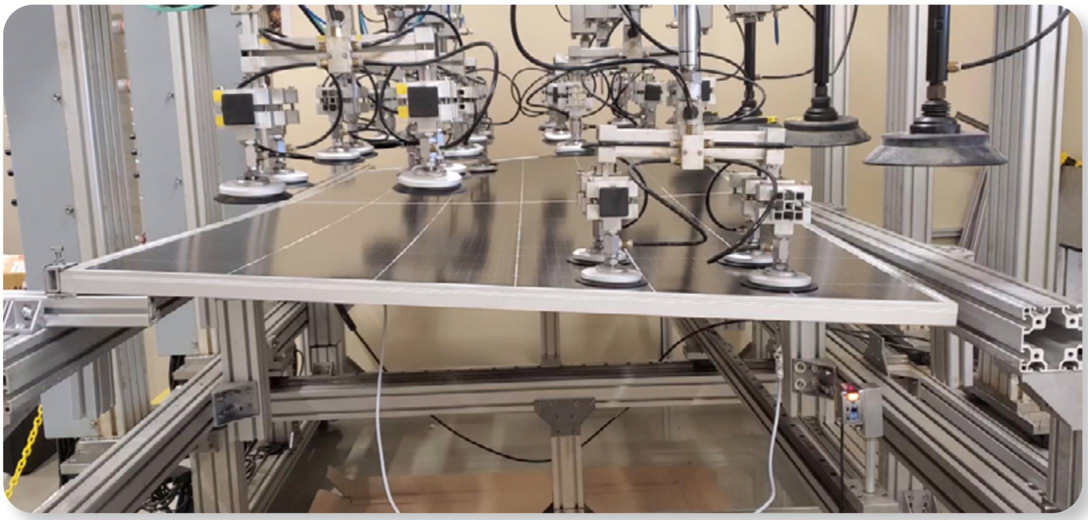


Cell-to-module (CTM) power loss analysis at SERIS

Contact person: Dr Carlos Enrico CLEMENT (carlos.clement@nus.edu.sg)

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. 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

PID is one of the most damaging degradation processes of PV modules in field conditions, and its effects can be exacerbated in the maritime environment. 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

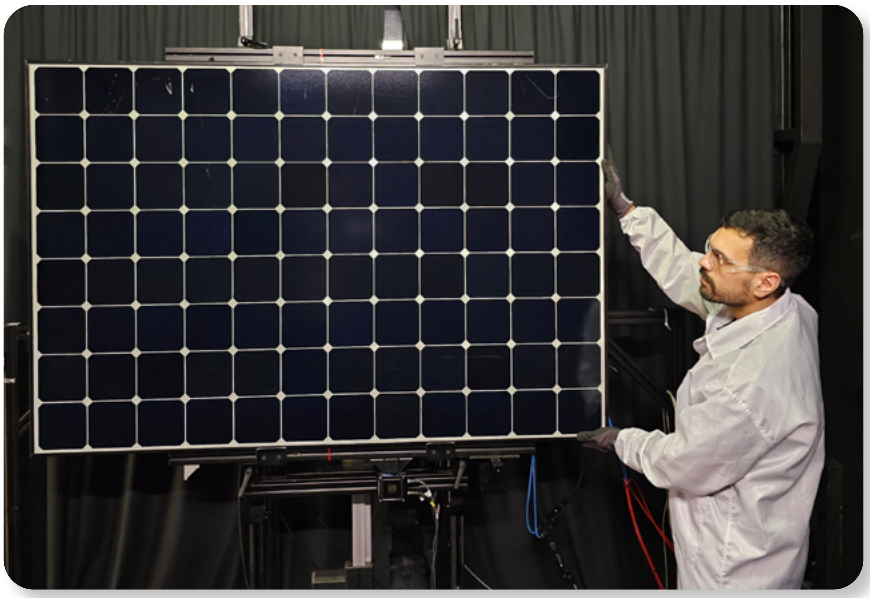
Contact person: Aziz NAIRI (a.nairi@nus.edu.sg)

CHARACTERISATION **AND RELIABILITY 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 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 research partners. The laboratory has ISO 17025 accredited 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.

Secondary reference standards, temperature coefficients, and irradiance dependence

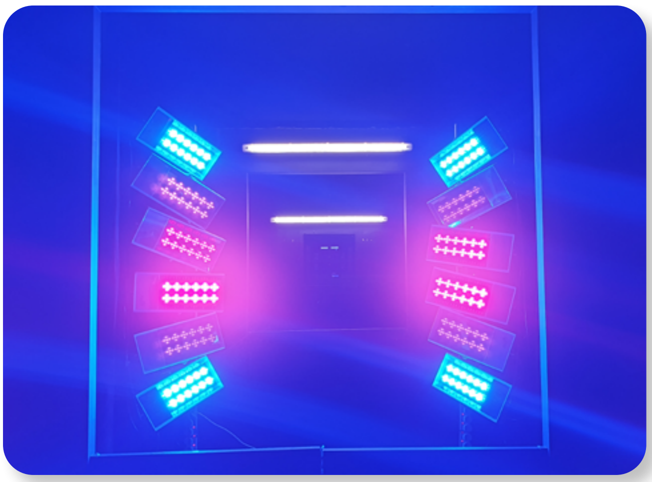
Equipped with two Class A+ large-area pulsed solar simulators (a 10-ms Pasan SunSim 3B and a 100-ms Halm solar simulator), the laboratory can characterise all types of commercially available PV modules at Standard Test Conditions (STC), including bifacial and heterojunction modules. This is particularly 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 demand from the industry to measure and characterise such modules.

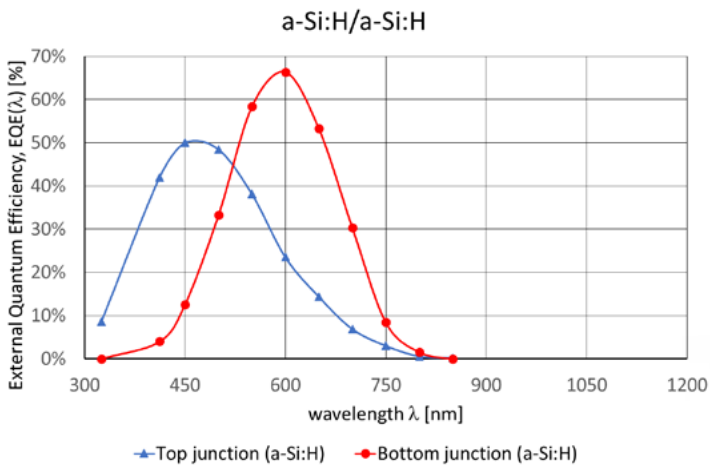


"Golden module" characterisation at SERIS

Electrical characterisation of multi-junction modules

In view of the possible emergence of mass-produced multi-junction terrestrial PV modules, and aligned with new frontiers of research on perovskite-silicon tandem solar cells, SERIS' laboratory is equipped with an External Quantum Efficiency (EQE) measurement system for multi-junction modules using additional coloured bias light. Validation was performed on an "old-generation" amorphous silicon double-junction PV module.

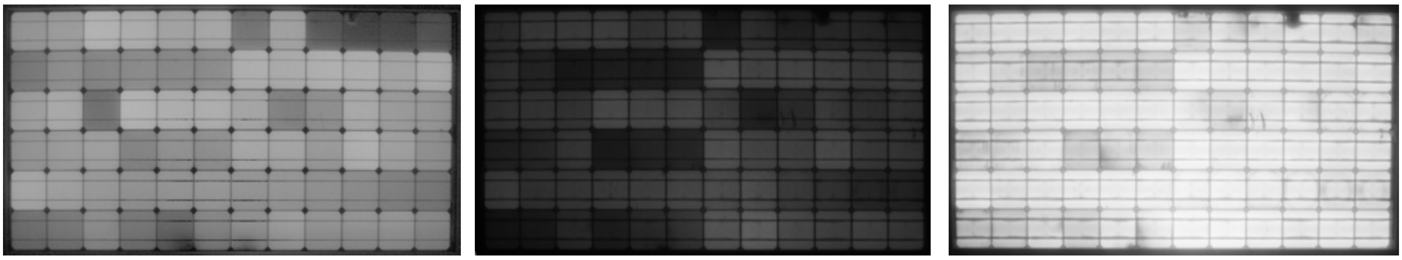




Coloured bias light system and example of an EQE measurement of a double-junction amorphous silicon PV module

Photoluminescence (PL) of PV modules

Reliability studies often require to detect the origin of failures or degradations in module performance. Electroluminescence (EL) is a well-known imaging technique that allows to easily identify defects such as microcracks, corrosion, or missing/delaminated contacts. In EL the infrared (IR) emission from the cells in a module is triggered by current injection from the module terminals, and hence the method highlights with low IR emission any cell (or parts of a cell) where current flow is missing for any reason. Alongside EL, at SERIS we also perform photoluminescence (PL) analysis, where the IR emission is triggered by photon absorption in open-circuit conditions. The light is generated by powerful LEDs that illuminate the module uniformly. In PL images, the low emissivity areas are not caused by missing current flow, but more inherently caused by cell defects. The combination of PL and EL imaging on the same module can give more insight on the quality of the tested module, and also gives an indication of the root cause for power losses.

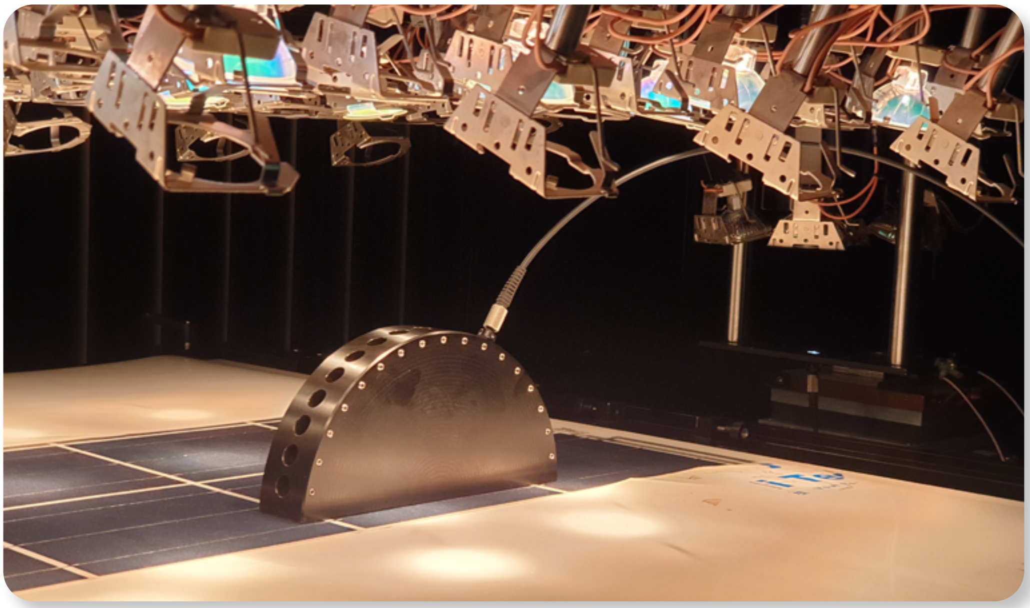


(a) (b) (c)

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 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 IEC61853-2 which is expected to be adopted in early 2025.



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

Contact persons: Aziz NAIRI (a.nairi@nus.edu.sg) for PV module characterisation and reliability
Dr CHOI Kwan Bum (serckb@nus.edu.sg) for PV module characterisation

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 (available in 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 seven 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 Jaffar Moideen YACOB ALI (jaffarmoideen@nus.edu.sg)

PV SYSTEM **DESIGN AND EVALUATION**

SERIS can help project owners and developers design their PV systems to maximise performance and fulfil the highest quality requirements, particularly for tropical climates. SERIS, for example, designed and commissioned a photovoltaic (PV) system in Singapore that has been functioning with an extraordinarily high performance ratio (PR)* of 85-90% since 2011. SERIS project services begin with initial design and energy yield analyses, and continue throughout the project duration until the PV systems are fully operational and performing as expected.

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 performance ratio (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 projects
Bottom row: Rooftop PV installations on metal roof and installed over water tanks

Contact person: Rachel TAN (racheltan@nus.edu.sg)

PV SYSTEM **PERFORMANCE MONITORING**

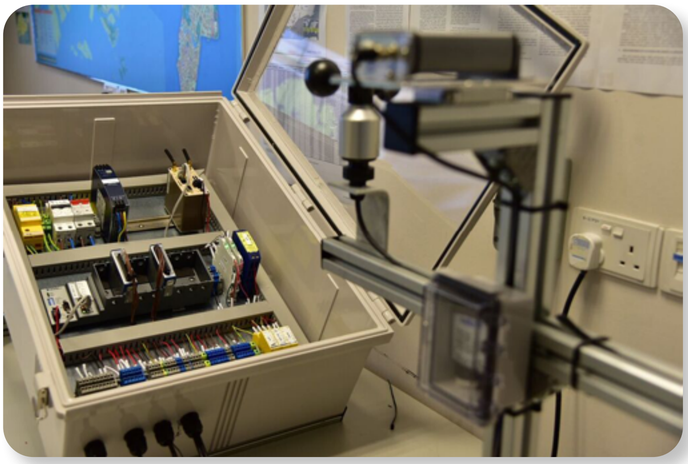
We offer a cloud-based real-time Analytical Monitoring of PV installations - from small rooftop systems to large ground-based PV power plants and floating PV systems in the multi-MW range. SERIS has developed a highly reliable and scalable monitoring platform to accommodate multiple deployments in different regions across the world. We have successfully deployed over 100 systems to-date and our monitoring capabilities are operational in Singapore, Australia, Cambodia, China, Germany, India, Indonesia, Malaysia, Philippines and Vietnam.

Analytical monitoring consists of a detailed measurement of critical system parameters and their analysis through mathematical modelling and scientific-technical evaluation. The monitoring system provides instant output verification, failure detection and alarm triggers. The features of the system, which can be customised to individual requirements, include:

- 1-second temporal resolution for various DC and AC parameters 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
- Central Data Management – A cloud-based Web portal for customers to access the acquired real-time and historical data from PV systems
- Tailoring of alarms according to the customer's needs (e.g. upon inverter trips, grid outages, system underperformance, etc), including SMS service
- High-quality visualisation of measured data online or on screens for various target groups: operations managers, engineers, general public (e.g. through displays in corporate entrance areas)
- Automated daily download and data back-up routines through a secure virtual private network over 4G connection
- Highest data security through VPN connections over 4G network
- Submission of live power and irradiance data compliant with requirements from power system operators (PSO), e.g. the Energy Market Authority of Singapore (EMA)
- ± 150 ms time synchronisation with cloud-based time servers

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

PV Monitoring Display Panel with live display of irradiance, sky images, and weather parameters



Example of a monitoring system with electrical components (in the background) and sensors (foreground)

Stand-alone analytical monitoring solution for small rooftops and residential PV systems

Contact person: SOE Pyae (soepyae@nus.edu.sg)

ON-SITE PV **SYSTEM ASSESSMENTS**

On-Site PV System Performance Testing and Commissioning

SERIS provides SAC-SINGLAS-accredited on-site PV system performance testing and commissioning services. This allows key stakeholders to independently verify the actual system installation against original design drawings and best practices, as well as its performance level versus predicted values. Calibrated measuring equipment is utilised for ISO/IEC 17025 compliance assessment of key PV system characteristics. These metrics can be adjusted to account for environmental factors such as module temperature and irradiance. The inspection and testing findings are also compared to local and/or IEC standards. Our services include:

- System verification against design / as-built drawings
- Independent measurement of the system's power output
- String-level DC measurements
- Module temperature measurements
- Irradiance measurements
- Verification tests as per the local standard SS601 and/or international standard IEC62446, with SAC-SINGLAS accredited reports

On-site measurement of PV system performance

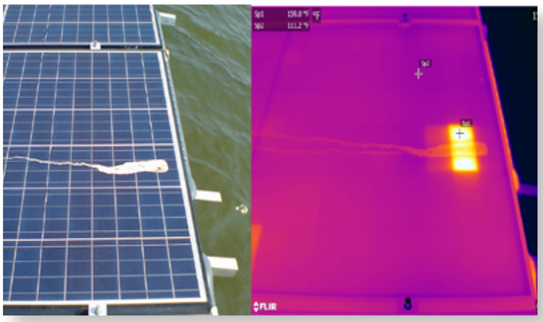
On-site inspection / verification of PV system installations

Contact person: Rachel TAN (racheltan@nus.edu.sg)

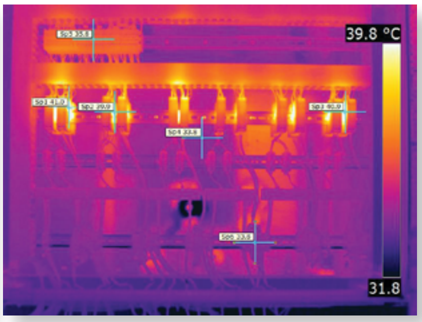
Thermographic Analysis of PV Systems

SERIS provides thermographic analysis of PV systems at both system and component levels. This enables the identification of different types of thermal stresses inside a PV system. Thermal stress can be a sign of an underlying problem with the PV system, affecting system performance or posing safety risks. We typically focus on:

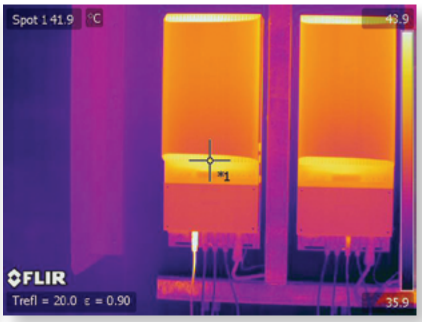
- PV string and module temperature measurements: This helps in determining if a DC string contains damaged PV modules or faulty/overheated solar cells within a PV module (top left picture). Module junction boxes can also exhibit unusual heat behaviour.
- Component temperature measurements: Component failures not only create PV system downtime, but they can also pose a fire risk. Proper fuse ratings and component selection for hot temperature conditions are critical but sometimes overlooked. Thermographic analysis allows for an in-depth examination of component operating temperatures ranging from DC field junction boxes to AC distribution boards (top middle image).
- DC and AC cable operating temperature measurements: Hot spots can be detected not only in system elements that are exposed to sunlight, but also in the wiring configuration. Overheated parts can result from loose connectors and undersized cables (top right image), an overloaded cable tray (bottom left image), improper cable routing (for example cables dangling and touching a metal roof; bottom middle image), and AC cables entering the electric switchgear as a bundle rather than through proper cable glands (bottom right image). These issues reduce the performance of the PV system and increase the risk of a fire.



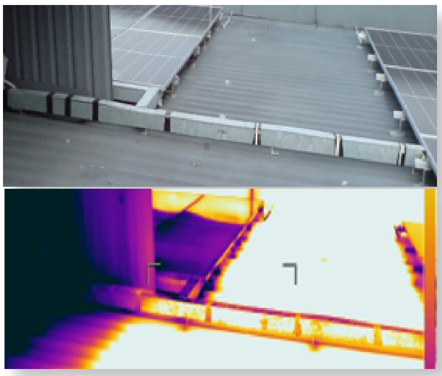
Silicon PV modules in operation, with some solar cells having a significantly increased temperature ("hot spot") due to a bird dropping. Left: Photograph. Right: Thermographic image



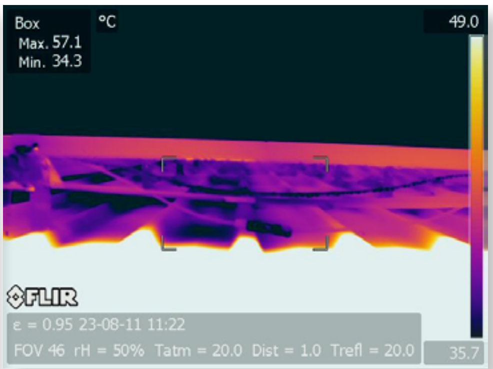
Thermographic image of overheated components in a DC distribution box



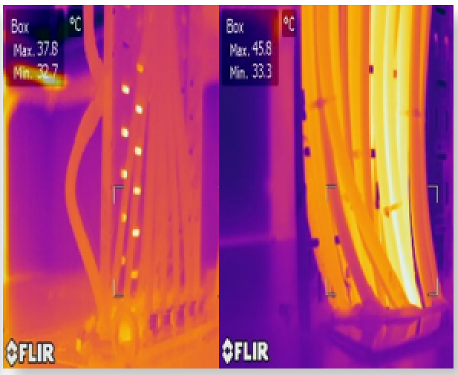
Thermographic analysis showing the overheating of a DC cable and a connector



The main drop-down cable trunking (from the roof to the inverter at ground) is overheating due to overloaded cable trays (all 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

Contact person: Rachel TAN (racheltan@nus.edu.sg)

SPECIALISED **SERVICES**

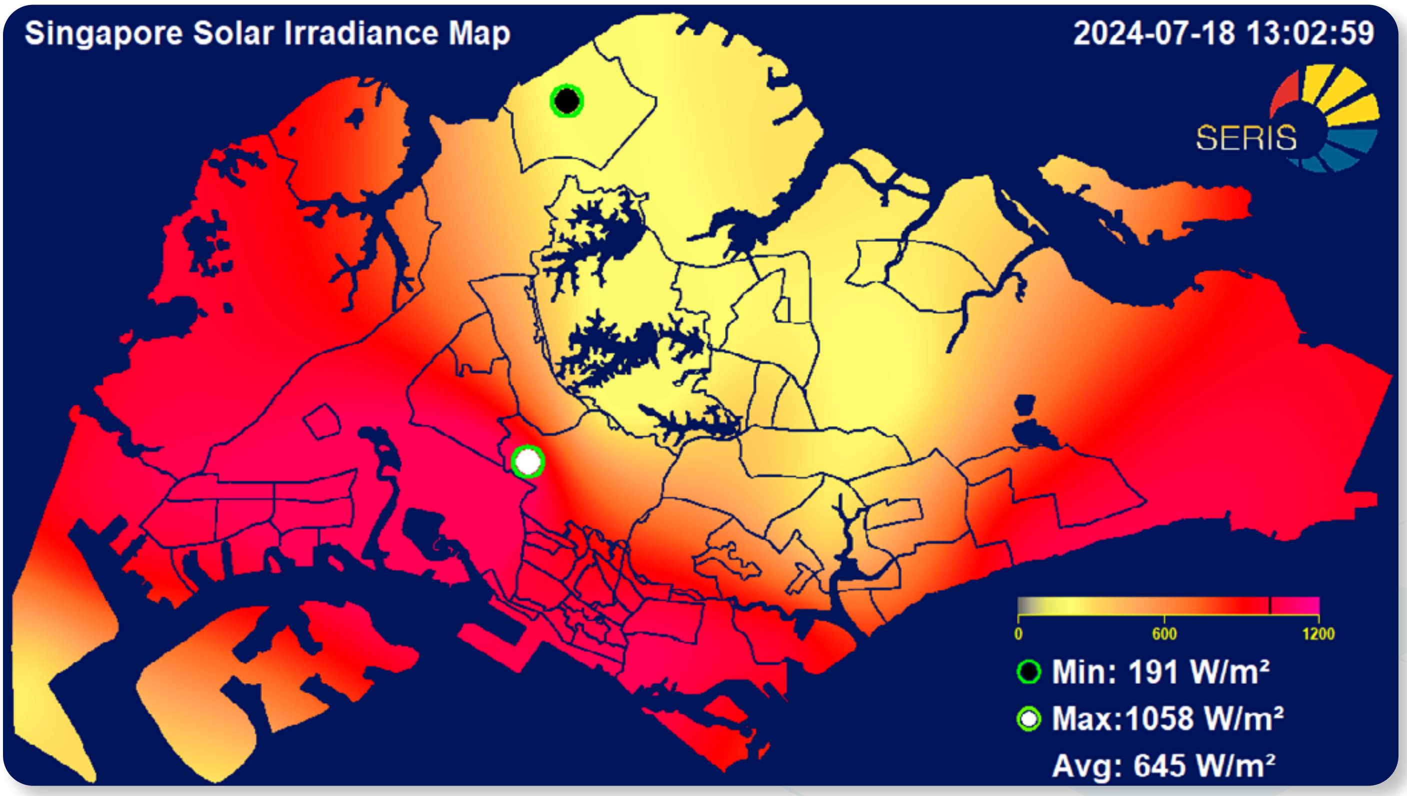
Real-Time Monitoring System of Meteorological Parameters

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

Contact person: SOE Pyae (soepyae@nus.edu.sg)

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. Please see page 76 for more details on this project.

For the 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 have been deployed in the testbed, which are described in more detail 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 in 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 panels in real-time.
- Various DC and AC parameters of the two PV systems are collected from 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.

Contact person: SOE Pyae (soepyae@nus.edu.sg)

SPECIALISED **SERVICES**

Glare Analysis of PV Installations

With increasing deployment of Solar PV systems, potential glare from the glass surfaces of 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. In 2015, SERIS published a report on glare arising from PV modules in Singapore as part of the SolarNova programme. 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 – 140 locations
   ii. Malaysia – 28 locations
   iii. Cambodia – 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)

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

** ATCT: Air Traffic Control Tower*

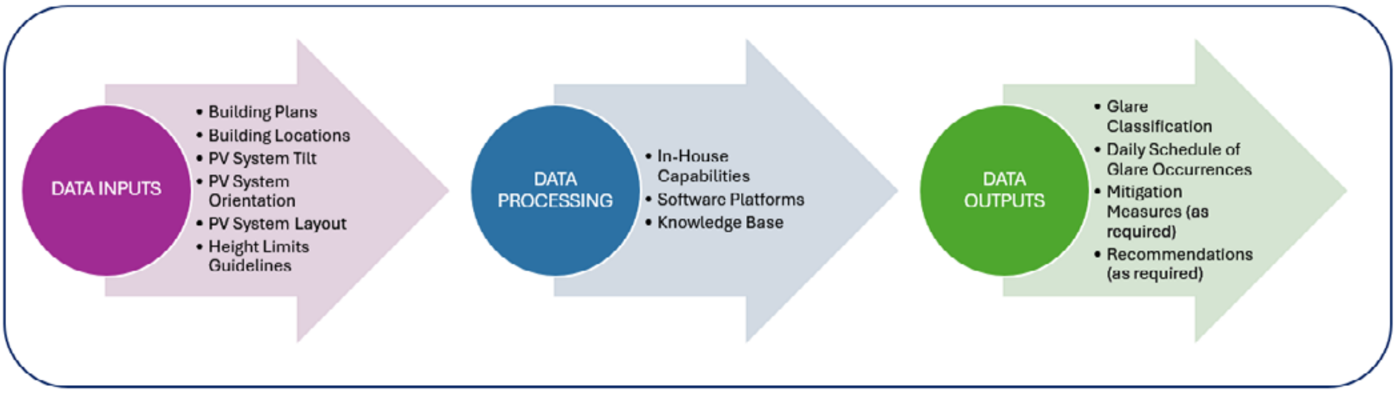


Fig. 1: Glare analysis framework at SERIS. Customised solutions can be designed to suit the needs of individual clients.

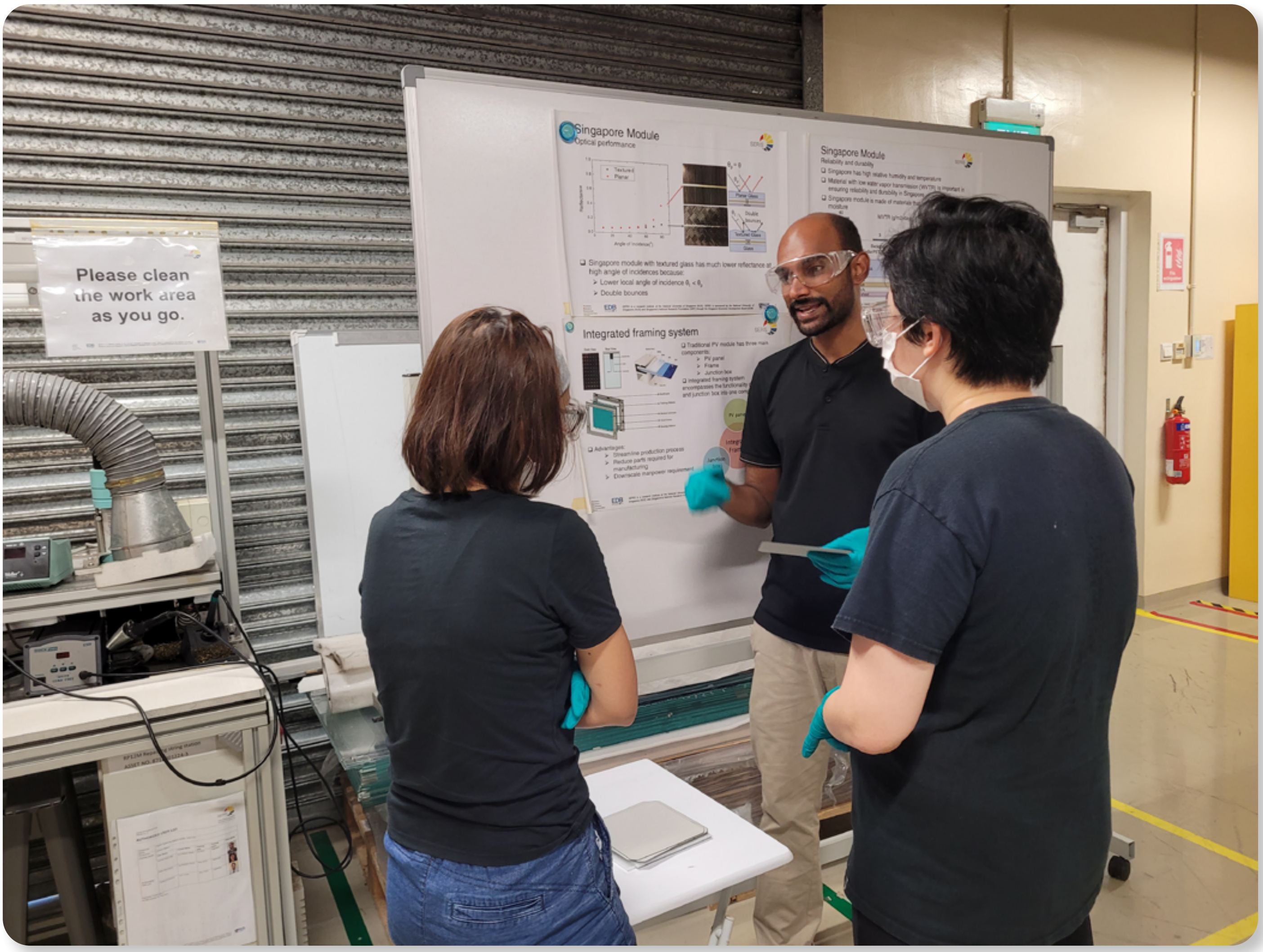
Contact person: David LEE (david.lee@nus.edu.sg)

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

Scientific Conferences, Symposia, Workshops and Webinars **Co-organised by SERIS**

3rd International Integrated-PV Workshop (IPV), Haikou, China, 19 April 2024

Building on the great success of the two previous IPV Workshops held virtually, the 3rd edition of the workshop highlighted innovative advancements in this fast evolving field. Topics encompassed Building-integrated PV (BIPV), Floating PV (FPV), Agrivoltaics, Vehicle-integrated PV (VIPV) and the use of Artificial Intelligence in PV Development (AIPV). The workshop brought together 15 speakers and experts from all over the world, providing them with a platform to share state-of-the-art technologies, current trends, future research needs and a comprehensive views of integrated PV technology.

The workshop aimed to facilitate interdisciplinary discussions and industry-wide comprehension of IPV technologies. It also sought to address "non-technical" challenges faced by IPV, including legal, regulatory, environmental, and societal acceptance issues.

The 3rd IPV workshop was jointly organised by the Yangtze Institute for Solar Technology (YIST), Forschungszentrum Jülich, Solarbe Global, Solar Energy Research Institute of Singapore (SERIS), and the European Energy Research Alliance (EERA-PV).

The 3rd IPV Workshop (hybrid session) was well attended by participants both on-site and online. The event was live-streamed on 19 Apr 2024 and accessible by a global audience.

Dr Thomas REINDL (Deputy CEO, SERIS, NUS) delivering his online talk on "Latest trends in Floating PV"

17th Global Advanced PV Technology Conference at the SNEC 17th (2024) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition, Shanghai, China, 11-15 June 2024

SERIS co-organised the 17th Global Advanced PV Technology Conference at the world's largest PV tradeshow in 2024, the SNEC 17th (2024) 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, cells, modules, systems and quality assurance to smart grid technologies. The program consisted of 2 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.

Conference Chairman Prof Armin ABERLE, CEO of SERIS, welcoming all participants at the Opening Ceremony of SNEC 2024 Photo credit: Asian Photovoltaic Industry Association (APVIA)

Dr Thomas REINDL, Deputy CEO of SERIS, giving a talk on "Overview and Latest Trends in Floating Solar" in the Plenary Session of the 17th Global Advanced PV Technology Conference Photo credit: Asian Photovoltaic Industry Association (APVIA)

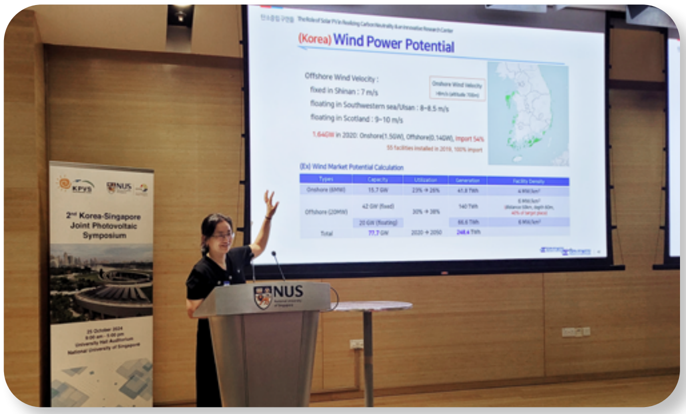
2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024

Building on the success of the 1st Korea-Singapore Joint Photovoltaic Symposium held last year in Gwangju, Korea, organised by the Korea Photovoltaic Society (KPVS), the National University of Singapore (NUS), through its Solar Energy Research Institute of Singapore (SERIS), hosted the 2nd Symposium at the NUS University Hall, Singapore this year, in collaboration with KPVS. South Korea and Singapore strongly support academic excellence, and both have a rich background in the development of photovoltaic materials, devices and systems. The Symposium program included plenary and invited talks on the latest developments in solar energy research in both countries from upstream to downstream, covering topics like perovskite solar cells and perovskite-silicon tandems, building integration and recycling of solar PV, and exploring new applications of solar PV like agrivoltaics and floating PV. The event was well received and attended by close to 100 participants from the NUS community and members of the general public and the solar industry.

Prof Armin ABERLE, CEO of SERIS, welcoming the speakers from Korea and all Symposium attendees in his Opening address

Symposium Co-organiser Prof Min Jae KO giving a presentation on "Diffusion-assisted lamination process for semi-transparent perovskite solar cells"

Deputy CEO of SERIS, Dr Thomas REINDL, giving a plenary talk on the status of R&D and industry in PV in Singapore



Plenary speaker Dr Jihye GWAK from the Korea Institute of Energy Research (KIER) giving an overview of PV in South Korea

The Symposium had close to 100 attendees from the NUS community and members of the general public and the solar industry

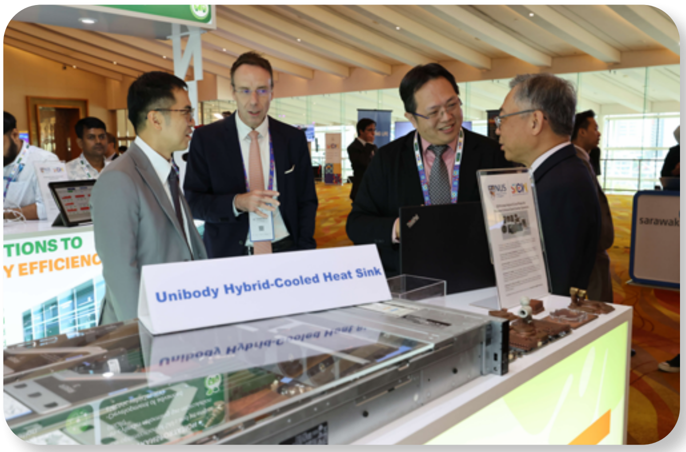
Group photo of the Symposium speakers after the afternoon session

SERIS Booths at
Conferences & Exhibitions

Singapore International Energy Week (SIEW) Conference & Exhibition, Singapore, 21-25 Oct 2024

As the SIEW Energy Showcase sponsor, NUS officially launched a new research initiative called NUS Energy Solutions Hub (NESH) at SIEW 2024, and set up a booth to showcase NUS' latest innovations in energy transition solutions. SERIS, a research institute of NUS and also part of NESH, showcased a next-generation tandem solar cell prototype with scalable novel technologies that can be transferred and upscaled to industrial production within the next few years. SERIS also displayed its leading-edge solar energy forecasting platform (developed with support from the Energy Market Authority of Singapore, EMA) that is now fully operational inside Singapore's power system operating centre.

NUS booth at the SIEW 2024 exhibition, introducing a new research initiative called NUS Energy Solutions Hub (NESH) and showcasing a selection of the University's research projects and innovations that contribute to Singapore's net zero energy goals. NESH is an integrative platform at NUS that transcends disciplinary boundaries, fostering collaboration among the university's various research entities and faculties.



Deputy Prime Minister Mr GAN Kim Yong (right) and EMA's CEO Mr PUAH Kok Keong (left) at the NUS booth with Prof LEE Poh Seng, Executive Director of NUS' Energy Studies Institute and Dr Thomas REINDL, Deputy CEO of SERIS (Image: Courtesy of Energy Market Authority of Singapore)

Asia Clean Energy Summit (ACES) Conference & Exhibition, Singapore, 22-23 Oct 2024

SERIS set up an 18-m^2 booth to showcase selected R&D results, prototypes and projects in the areas of PV cells, modules and systems, including next-generation tandem solar cells, "Peranakan" PV modules suitable for BIPV applications, the PV pixel concept for BIPV, PV module recycling using the shock wave fragmentation method, and a display of real-time solar power forecasting tailored for tropical Singapore and the Asia-Pacific region.

SERIS researchers in discussions with visitors at the SERIS booth at ACES 2024

Other **Outreach Activities**

SERIS constantly engages in outreach activities targeting students at schools & universities and interested members of the general public to increase their awareness of solar energy research and deployment in Singapore. Our researchers give talks and organise laboratory tours for students and visitors from Singapore and abroad to demonstrate the solar research capabilities at SERIS, and to inform about the progress of solar energy research and deployment in Singapore. The photos below are a collection from selected outreach activities organised by SERIS in 2024. A full list of our outreach activities can be found in the Facts and Figures chapter of this Annual Report.

Visit by students from UC Berkeley College of Engineering, USA, 9 Jan 2024

SERIS Senior Research Fellow Dr WANG Puqun conducted a guided tour of the PV Devices Characterisation Lab for the students.

Visit by members from the Student Energy NUS, Singapore, 5 Feb 2024

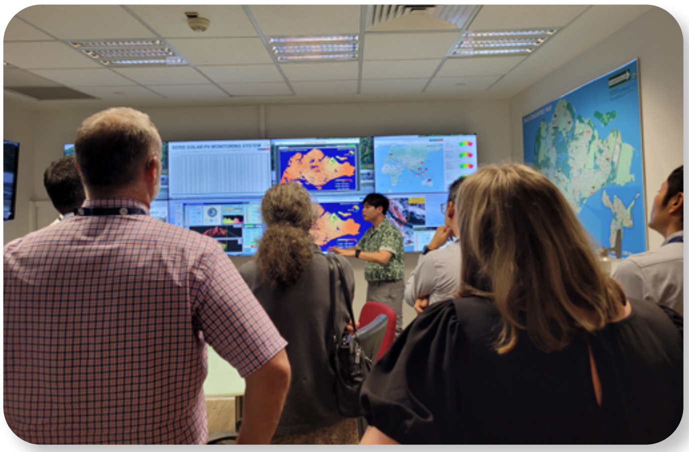
Guided by SERIS Adjunct Researcher Assoc Prof Stephen TAY, the students visited SERIS to learn about solar energy research and deployment in Singapore.

NUS Career Fest 2024, Singapore, 20-22 Feb 2024

SERIS researchers sharing with NUS undergrad and postgrad students about internship opportunities and sustainability-related careers in SERIS. This annual event was organised by the NUS Centre for Future-ready Graduates.

Visit by Hitachi team, Singapore, 28 Feb 2024

SERIS Deputy CEO Dr Thomas REINDL hosting a group of Hitachi's mid-career leaders from different geographies in a workshop format, which included a group activity for the participants to brainstorm and explore the need for Digital Solutions for Solar PV in Singapore.



SOE Pyae, Team Leader in SERIS' Digitisation of Energy Group, conducting a guided tour of SERIS' PV System Monitoring Lab for the participants.

Visit by students from the Methodist Girls' School, Singapore, 19 Mar 2024

SERIS' Senior Research Fellow Dr Donny LAI informing the students about SERIS and career opportunities for women in the green energy sector.

Assembly talk at Boon Lay Secondary School, Singapore, 22 Apr 2024

SERIS' Senior Business Development Manager Eddy BLOKKEN visiting Boon Lay Secondary School Singapore and informing the students about solar energy research & adoption in Singapore. (Photo credit: Boon Lay Secondary School Singapore).

Visit by students from Kent Ridge Secondary School, Singapore, 7 May 2024

As part of the visit program, Dr CHOI Kwan Bum conducted a guided tour of SERIS' PV Devices Characterisation lab, including "hands-on" activities for the students to learn about the importance of measurements and characterisation in solar energy research & development.

Visit by students from the University of Texas, Singapore, 31 May 2024

SERIS' Senior Business Development Manager Eddy BLOKKEN giving a tour of SERIS' PV System Monitoring Lab to the students from University of Texas, who were on a short-term study abroad program to Singapore (with a focus on biotechnology and sustainability).

Participation in SEAS' Beach Clean-up event, Singapore, 29 Jun 2024

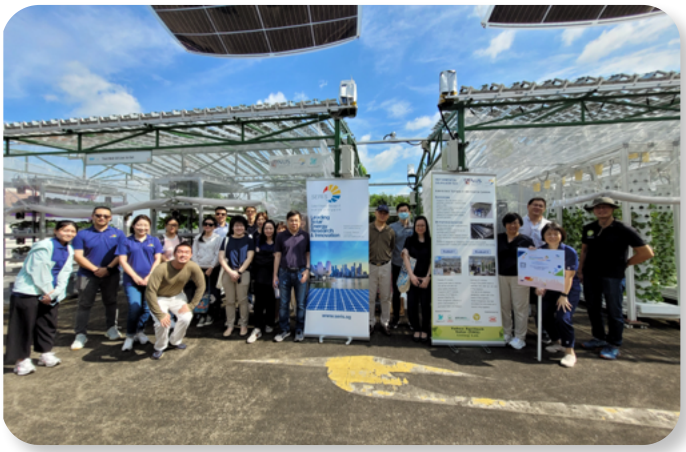
SERIS had an educational booth at SEAS' Beach clean-up event to promote solar energy as a promising form of renewable energy for environmental sustainability. Several solar R&D projects currently being conducted by SERIS were also displayed at the booth.

SERIS researcher Jeffrey ISON collecting waste from the beach. The event, which was organised by the Sustainable Energy Association of Singapore (SEAS), had more than 100 attendees from SEAS member organisations and the general public.

NUS-CDE Career Fair, Singapore, 10-11 Sep 2024

SERIS exhibited in the product/innovation showcase segment of the NUS CDE Career Fair to inform the NUS community about innovations in solar energy projects and exciting career opportunities in the solar energy research sector.

NUS Sustainability CONNECT 2024, Singapore, 16 Sep 2024



One of the highlights of this year's NUS Sustainability CONNECT was a visit to the Yuhua Agritech Solar (YAS) Living Lab located on an HDB rooftop carpark in western Singapore. The visit was organised by SERIS and provided participants with the opportunity to learn about SERIS' innovative urban farming concepts and to harvest vegetables from the two agrivoltaics testbeds set up and operated by SERIS.

FACTS AND FIGURES

AWARDS AND ACHIEVEMENTS

Apr 2024: SERIS' publication "Analytical review of spiro-OMeTAD hole transport materials: paths toward stable and efficient perovskite solar cells" in Advanced Energy and Sustainability Research, authored by SERIS' researchers Laxmi NAKKA, Yuanhang CHENG, Armin G. ABERLE and Fen LIN is "recognised as one of the top-10 most cited publications of Advanced Energy and Sustainability Research", among work published between 1 Jan 2022 - 31 Dec 2023.

Jun 2024: Prof Armin ABERLE, CEO of SERIS, was recognised as one of the Global Solar Scientists who have made outstanding contributions to the development of the photovoltaic industry over the past 2-3 decades. In his 38-year career in 3 continents (Europe, Australia, Asia), Prof ABERLE has been a prolific researcher, educator, mentor and leader in the global solar PV community. His research covers the full spectrum from fundamental materials and device research to the industrial evaluation of novel PV technologies at the pilot line level and their transfer to industry. He supervised more than 60 PhD students to successful completion of their degrees. He published more than 500 scientific-technical papers which have received more than 19,000 citations (h-index 65).

Jul 2024: Dr Thomas Reindl won the award in the category Floating Solar at the Sustainability Open Innovation Challenge (SOIC) 2023 for the innovative floating PV module and system deployment approach which has the potential to revolutionise the way how floating PV systems are designed and implemented in the future. SOIC 2023 saw almost 400 entries from 80 countries to address 21 challenge statements and an open category.

MEDIA COVERAGE

14 Feb 2024: S'pore's largest single-site rooftop solar panel system to be installed at Changi Airport by 2025. Straits Times

04 Mar 2024: Researchers invent new triple-junction tandem solar cells with world-record efficiency. Science Daily

05 Mar 2024: NUS develops triple junction tandem solar cells with record efficiency. Optics.org

05 Mar 2024: New triple-junction tandem solar cells with world-record efficiency invented. Lab Manager.com

05 Mar 2024: NUS researchers develop triple-junction perovskite/silicon cell with conversion efficiency of 27.1%. PVTech.org

05 Mar 2024: NUS researchers invent new triple-junction tandem solar cells with world-record efficiency. PR Newswire

05 Mar 2024: NUS researchers invent new triple-junction tandem solar cells with world-record efficiency. PressBee.net

05 Mar 2024: Revolutionising solar energy: NUS team hits record efficiency with triple-junction cells. Bnnbreaking.net

05 Mar 2024: Researchers invent new triple-junction tandem solar cells with world-record efficiency. Lifelong technology.com

09 Apr 2024: Frasers Property to install solar panels in six shopping malls by end-2024. CNA news (youtube)

10 Apr 2024: Researchers achieve 'certified world-record' efficiency with new type of solar cell — here's how it works. thecooldown.com

18 Apr 2024: Sunny Side Up: 5 things you may not know about solar energy in Singapore. EMA website – news/featured stories.

19 Apr 2024: 裕华农光实验室测试新方法 助农场产出多余电源增加收入来源. Zaobao news

26 Apr 2024: [World IP Day 2024] Innovations on Singapore's HDB rooftops, youtube video by IPOS

27 Apr 2024: Global Green Energy Development Center & GCL Photoelectric R&D center unveiled in Singapore. GCL Group Press release

05 May 2024: 专家:外墙垂直安装太阳能板可提高利用率, Zaobao news

26 Jun 2024: The future of netzero solar urban food production with V-Plus and SERIS. Youtube video produced and published by dmtr

28 Jul 2024: Renewable power: Exploring use of solar canopies at Jurong, Tuas ports. Sunday Times

31 Jul 2024: 四年半共13起太阳能板火患 全因电流引起, Zaobao

08 Aug 2024: 我国将探讨沙都姆岛海上再生能源发展 预计第四季开展. Zaobao

09 Aug 2024: 红白色彩太阳能板 制成国旗欢庆国庆, Zaobao

09 Aug 2024: 本地大学与业者合力研制太阳能板国旗 为国庆生, 8world.com

13 Sep 2024: Singapore's solar deployment on track to hit 2030 target: Energy Market Authority, Singapore Tonight, CNAindependensi.com

02 Oct 2024: Indonesian Solar Energy Research Center (ISEREC) and E20: Delivering Indonesia Towards a Global Clean Energy Future, independensi.com

22 Oct 2024: Sun Cable gains conditional approval to import 1.75GW of low carbon electricity. CNA news (youtube)

04 Dec 2024: NUS scores major sustainability milestone with landmark solar power project across campus. NUS news

PRESS RELEASES / JOINT PRESS RELEASES

05 Mar 2024: NUS researchers invent new triple-junction tandem solar cells with world-record efficiency

09 Aug 2024: REC Solar and the Solar Energy Research Institute of Singapore (NUS-SERIS) celebrate National Day 2024 with a Special Edition "Singapore Flag made of Solar Panels" – displayed at NDP 2024 Heartland Exhibition at Bishan

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 2024) (Prof Armin ABERLE, 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 17th (2024) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2024), 17th Global Advanced PV Technology Conference (Prof Armin ABERLE, Chairman)
- International Scientific Committee of European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2024) (Dr Thomas REINDL, member)
- Steering Committee of the 3rd Integrated PV (IPV) Workshop (Dr Thomas REINDL, member)
- MPA Steering Committee for the Design and Develop Electric Harbour Craft in Singapore (Dr Thomas REINDL, invited member)
- Executive Committee of the International Energy Agency, Photovoltaic Power Systems Programme (IEA-PVPS), SERIS joined PVPS as sponsor, represented by Dr Thomas REINDL and Eddy BLOKKEN as members of the ExCo)
- Member of the "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 Enrico Cobar CLEMENT, attendee)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 19 (Rachel TAN, attendee)
- International Electrotechnical Commission (IEC) Technical Committee (TC) 82 ("Solar Photovoltaic Energy Systems"), (Dr Thomas REINDL (Singapore representatives)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/WG 2 and IEC-TC82/WG 6 (Dr LEOW Shin Woei, 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)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/PT 600 (Dr LEOW Shin Woei, member)
- National IEC Mirror Committee TC 1 WG10 ("Solar PV Product & Accessories"), Enterprise Singapore (Dr LEOW Shin Woei, 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)
- "BAPV Working Group" organised by SCDF, Singapore (Dr Thomas REINDL, Dr Carlos Enrico Cobar CLEMENT, members)
- "Roof-mounted solar PV installation working group" working group organised by SCDF, Singapore (Dr Thomas REINDL, Dr Carlos Enrico Cobar CLEMENT, Rachel TAN, 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)
- Scientific Committee of the 12th Metallisation and Interconnection Workshop, MIW 2024 (Dr Nitin NAMPALLI, member)

SERIS MEMBERSHIPS / PARTNERSHIPS

- Asian Photovoltaic Industry Association (APVIA)
- International Solar Energy Society (ISES) – Silver Institution Membership
- Sustainable Energy Association of Singapore (SEAS)

VISITORS

09 Jan 2024: Student delegation from UC Berkeley College of Engineering

12 Jan 2024: Student delegation from University of Twente, Netherlands

05 Feb 2024: Members from the Student Energy NUS, lead by Assoc Prof Stephen Tay

28 Feb 2024: Delegation from Hitachi

01 Mar 2024: Delegation from 3M

14 Mar 2024: Prof Dorota Anna Krawczyk, Bialystok University of Technology, Poland

19 Mar 2024: Student delegation from Methodist Girls School, Singapore

12 Apr 2024: Prof Norbert Willenbacher, Karlsruher Institut für Technologie (KIT), Germany

17 Apr 2024: Student delegation from St Joseph Institution, Singapore

22 Apr 2024: Industry talk at Boon Lay Secondary School, Singapore

23 Apr 2024: Visit by Prof Ignacio Sanchez, President of Pontificia Universidad Católica de Chile (UC), Chile

23 Apr 2024: Visit by delegation from Indonesia Coal Company, organised by NUS Business School

07 May 2024: Student delegation from Kent Ridge Secondary School, Singapore

31 May 2024: Visit by student delegation from the University of Austin, USA

12 July 2024: Visit by delegation from India, lead by Vice Chancellor / Director General Pandit Deendayal Energy University, Gandhinagar, Gujarat, India

07 Aug 2024: Visit by delegation from the Sino-Singapore Tianjin Eco-City (SSTEC), China

02 Sep 2024: Visit by students and teachers from the Institute of Technical Education, ITE College East, Singapore

13 Sep 2024: Visit by delegation from the Ministry of Trade & Industry (MTI), NCCS and PMO Singapore

24 Oct 2024: Visit by overseas government officials organised by MFA Singapore

11 Nov 2024: Visit by delegation from the Technological University of Braunschweig, Germany

18 Nov 2024: Visit by delegation from Tsinghua University, China

19 Nov 2024: Visit by delegation from the Rising Stars women in engineering event organised by College of Design and Engineering, National University of Singapore

02 Dec 2024: Visit by final year project student from the National University of Singapore

11 Dec 2024: Visit by delegation from USyd Department of Architecture, University of Sydney, Australia

CONFERENCES / SYMPOSIUM / WORKSHOPS CO-ORGANISED OR SUPPORTED BY SERIS

19 Apr 2024: 3rd Integrated PV (IPV Workshop), China (hybrid)

12-14 Jun 2024: 17th Global Advanced PV Technology Conference at the SNEC 17th (2024) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition, Shanghai, China

22-24 Oct 2024: Asia Clean Energy Summit (ACES 2024), Singapore

25 Oct 2024: The 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore

TEACHING / GUEST LECTURES AT UNIVERSITIES

Prof Armin ABERLE, for Electrical and Computer Engineering Course EE4438 Solar Cells and Modules, AY23/24 Semester 2, National University of Singapore (NUS)

Dr CHOI Kwan Bum. Seminar for SUTD PhD students from Science, Mathematics and Technology Research, 04 Oct 2024 (invited)

PATENT APPLICATIONS IN 2024

Tianyuan LIU, Fen LIN, Puqun WANG. Method to realise well-defined local doping profile for solar cells or semiconductor devices. Non-provisional, Singapore, application number 10202400005Q, filing date 02 Jan 2024

Naomi NANDAKUMAR, Shubham DUTTAGUPTA, Pradeep PADHAMNATH. High-efficiency solar cells and the fabrication methodology. Non-provisional, Singapore, application number 10202400698P, filing date 13 Mar 2024

Min Hsian SAW, Srinath NALLURI, Kong Fai TAI, Mauro PRAVETTONI, Yong Sheng KHOO, Gavin Prasetyo RAHARJO, Shin Woei LEOW. A cover member for a photovoltaic device. Nationalised PCT, Singapore, application number 11202402491S, filing date 12 Apr 2024

Kong Fai TAI. A building integrated photovoltaic panel. Nationalised PCT, Singapore, application number 11202402631S, filing date 17 Apr 2024

Kong Fai TAI. A building integrated photovoltaic panel. Nationalised PCT, Australia, application number 2022383908, filing date 19 Apr 2024

Kong Fai TAI. A building integrated photovoltaic panel. Nationalised PCT, China, application number 202280075337.1, filing date 11 May 2024

Jai Prakash SINGH, Shubham DUTTAGUPTA, Carlos Enrico Cobar CLEMENT, Nitin NAMPALLI. Solar cell fabrication. Nationalised PCT, Singapore, application number 11202403498W, filing date 23 May 2024

Jai Prakash SINGH, Shubham DUTTAGUPTA, Carlos Enrico Cobar CLEMENT, Nitin NAMPALLI. Tandem solar module fabrication. Nationalised PCT, Singapore, application number 11202403597T, filing date 27 May 2024

Jai Prakash SINGH, Shubham DUTTAGUPTA, Carlos Enrico Cobar CLEMENT, Nitin NAMPALLI. Solar cell fabrication. Nationalised PCT, United States, application number 18/715,527, filing date 31 May 2024

Jai Prakash SINGH, Shubham DUTTAGUPTA, Carlos Enrico Cobar CLEMENT, Nitin NAMPALLI. Two-terminal tandem solar module. Nationalised PCT, United States, application number 18/715,497, filing date 31 May 2024

Nitin NAMPALLI, Krishna SINGH. Method of forming boron-containing thin films and devices made thereof. PCT application number PCT/SG2024/050399, filing date 14 Jun 2024

Shubham DUTTAGUPTA, Jeremie WERNER, Nitin NAMPALLI. Electrodes for halide perovskite devices. PCT application number PCT/SG2024/050430, filing date 28 Jun 2024

Shubham DUTTAGUPTA, Nitin NAMPALLI. Multi-layer contact structure, photovoltaic cell and method of fabrication of multi-layer contact structure. Nationalised PCT, Singapore, application number 11202406142R, filing date 05 Sep 2024

Huixuan SUN, Thomas REINDL. AI-powered software for visual impact assessment (VIA) of coloured building facades. Non-provisional, Singapore, application number 10202403074W, filing date 03 Oct 2024

Stella HADIWIDJAJA, Puqun WANG, Jian Wei HO, Kwan Bum CHOI. Method for luminescence characterisation of optoelectronic materials and devices based on modulated optical excitation. PCT application number PCT/SG2024/050663, filing date 16 Oct 2024

Nitin NAMPALLI, Krishna SINGH. Hole selective contacts, photovoltaic devices made thereof and methods of formation. International application number PCT/SG2024/050738, filing date 15 Nov 2024

Nitin NAMPALLI, Krishna SINGH. Carrier selective contacts, photovoltaic devices utilizing them and methods of forming thereof. International application number PCT/SG2024/050739, filing date 15 Nov 2024

PUBLICATIONS

Journal papers

Li, J., Liang, H., Xiao, C. et al. Enhancing the efficiency and longevity of inverted perovskite solar cells with antimony-doped tin oxides. Nat Energy 9, 308–315 (2024), doi: 10.1038/s41560-023-01442-1

Shi, Z., Guo, R., Luo, R. et al. “T-shaped” carbazole alkylammonium cation passivation in perovskite solar cells. ACS Energy Lett. 9, 419–427 (2024), doi: 10.1021/acsenergylett.3c02357

Luo, W., Khaing, A.M., Rodriguez-Gallegos C.D. et al. Long-term outdoor study of an organic photovoltaic module for building integration. Prog. Photovolt. Res. Appl., 32(7): 481-491. (2024), doi:10.1002/pip.3791

Brinkmann, K.O., Wang, P., Lang, F. et al. Perovskite–organic tandem solar cells. Nat. Rev. Mater. 9, 202–217 (2024), doi: 10.1038/s41578-023-00642-1

Padhamnath, P., Choi, W.J., De Luna, G. et al. Design and development of front and back contact solar cells with selective poly-Si passivating contact on the front and local Al contact on the rear. Sol. Ener. Mat. and Sol. Cells 269, 112759 (2024), doi: 10.1016/j.solmat.2024.112759

Liu, S., Lu, Y., Yu, C. et al. Triple-junction solar cells with cyanate in ultrawide-bandgap perovskites. Nature 628, 306–312 (2024), doi:10.1038/s41586-024-07226-1

Alvianto, E., Wan, G., Shi, Z. Sustainable manufacturing of perovskite-CIGS tandem solar cells through lamination with metal-free transparent conductive adhesives. ACS Energy Lett. 9, 2057–2064 (2024), doi: 10.1021/acsenergylett.4c00350

Meng, X., Jia, Z., Niu, X. et al. Opportunities and challenges in perovskite-organic thin-film tandem solar cells Nanoscale 16, 8307-8316 (2024), doi: 10.1039/D3NR06602A

Guo, X., Jia, Z., Liu, S. et al. Stabilising efficient wide-bandgap perovskite in perovskite-organic tandem solar cells. Joule 8, Issue 9, 2554-2569 (2024), doi: 10.1016/j.joule.2024.06.009

Choi, W.J., Ok, Y.W., Madani, K. et al. Development of APCVD BSG and POCl3 codiffusion process for double-side topcon solar cell precursor fabrication. IEEE Journal of Photovoltaics 14(5), 727-736 (2024), doi: 10.1109/JPHOTOV.2024.3423814

Wang, X., Li, J., Guo, R. et al. Regulating phase homogeneity by self-assembled molecules for enhanced efficiency and stability of inverted perovskite solar cells. Nat. Photon. (2024), doi: 10.1038/s41566-024-01531-x

Pravettoni, M., Saw, M.H., Bardizza, G. et al. Incidence angle effect: validation of new measurement methods for IEC 61853-2. Progress in Photovoltaics: Research and Application, doi: 10.1002/pip.3850

Kaur, G., Sridharan, R., Dutta, T. et al. Enhanced carrier selectivity and superior passivation in cost-effective heterogeneous hybrid transport layers for next generation silicon solar cells. Advanced Functional Materials, doi: 10.1002/adfm.202409070

Rodríguez-Gallegos, C.D., Gandhi, O., Sun, H.X. et al. Global floating PV status and potential. Progress in Energy, doi: 10.1088/2516-1083/ad9074

Chen, J., Wang, X., Wang, T. et al. Determining the bonding–degradation trade-off at heterointerfaces for increased efficiency and stability of perovskite solar cells. Nat. Energy (2024). https://doi.org/10.1038/s41560-024-01680-x

Conference papers / proceedings

Padhamnath, P., Arcebal, J.D., Dasgupta, S., De Luna, G., Rohatgi , A., Aberle, A. Investigation of contact properties and device performance for bifacial, double-side textured solar cells with polysilicon based passivating contacts. Proceedings of the 14th International Conference on Crystalline Silicon Photovoltaics 2024 (SiliconPV), France, 15-19 Apr 2024

Padhamnath, P., De Luna, G., Zhong, R., Arcebal, J.D., Aberle, A. Investigation on the impact of the wafer resistivities on double side passivated contact silicon solar cells. Proceedings of the 14th International Conference on Crystalline Silicon Photovoltaics 2024 (SiliconPV), France, 15-19 Apr 2024

Choi, W.J., Ok, Y.W., Kwan, H.M., Zhong, R., Dasgupta, S., Upadhyaya, V.D., De Luna, G., Arcebal, J.D., Padhamnath, P., Rohatgi, A. Fabrication and detailed analysis of 22.0% rear junction double-side TOPCon solar cell with front SiOX/polysilicon selective emitter. Proceedings of the IEEE PVSC, USA, 09-14 Jun 2024 (in press)

Zhong, R., Padhamnath, P., De Luna, G., Arcebal, J.D. et al. Characterisation and modeling of thin n-type and thick p-type polysilicon passivated contacts for back-junction solar cells. Proceedings of the IEEE PVSC, USA, 09-14 Jun 2024 (in press)

TALKS AT CONFERENCES, WORKSHOPS AND SEMINARS

(Speaker's name underlined)

Reindl, T. Status and trends in solar PV. Event organised by Bank of America, Singapore, 31 Jan 2024 (invited)

Blokken, E. Solar 101. Workshop organised by the Community Foundation of Singapore, 14 Mar 2024 (invited)

Reindl, T., Gandhi, O., Moideen, J. Latest trends in floating PV. 3rd Integrated PV (IPV) Workshop, China (hybrid), 19 Apr 2024 (invited)

Reindl, T., Gandhi, O., Moideen, J. Overview and latest trends in floating solar. SNEC 17th Global Advanced PV Technology Conference, China, 11-14 Jun 2024 (invited, plenary)

Chen, T., Clement, C., Reindl, T. Streamlining BIPV projects by integrating digital workflows with building information modeling (BIM). SNEC 17th Global Advanced PV Technology Conference, China, 11-14 Jun 2024 (invited)

Hou, Y. Unlocking the potential of perovskite solar cells: from single-junction to tandem. SNEC 17th Global Advanced PV Technology Conference, China, 11-14 Jun 2024 (invited)

Lin, F. Urban Agrivoltaics: PV & food generation in dense settings like Singapore. SNEC 17th Global Advanced PV Technology Conference, China, 11-14 Jun 2024 (invited)

Aberle, A. Status of solar PV in Singapore APVIA Annual General Meeting, 3rd General Meeting of the 5th Council, China, 13 Jun 2024 (invited)

Reindl, T. Jobs in Renewable Energy Sector. APVIA Annual General Meeting, 3rd General Meeting of the 5th Council, China, 13 Jun 2024 (invited)

Reindl, T. Pitch session at SOIC2023 Award closing Ceremony, Singapore, 04 July 2024 (invited)

Reindl, T. Digital resource maps for solar potential analysis and solar asset management. Workshop of Promoting Digital Solar Resources Maps and Management Technologies in APEC Region. Hong Kong, 08 July 2024 (invited, keynote)

Reindl, T. Status and outlook of the solar industry: a critical review and possible opportunities. NUS Global CEO Programme: Sustainability Challenges; Digital Opportunities, Singapore, 11 Sep 2024 (invited)

Reindl, T. Lecture on Floating PV. "PV Academy" as part of the European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC), Vienna, Austria, 22 Sep 2024 (invited lecture)

Reindl, T. European Photovoltaic Solar Energy Conference and Exhibition (EUPVSEC) Panel Discussion: Social Acceptance of Ubiquitous-PV: The Era of Integrated Photovoltaics, EU PVSEC, 25 Sep 2024 (invited panellist)

Reindl, T. Latest developments at SERIS and solar PV in Singapore. 10th East Asia Summit - New Energy Forum, China, 27-28 Sep 2024 (invited, pre-recorded)

Gandhi, O., Ali, J.M.Y., Reindl, T. The floating solar PV market and future trends in technology. Harvesting Sunshine: Exploring the Future with Floating Solar PV – a symposium organised by the Society of Floating Solutions, Singapore, 26 Sep 2024 (invited)

Reindl, T. 100% Renewable Energy Scenario – what are the options? First International ISEREC Conference: The Building of Large Green Corridors, Indonesia, 02 Oct 2024 (invited)

Reindl, T. BIPV in Singapore – Challenges & Opportunities. SEC Future City Lab (FCL) roundtable on BIPV, Singapore, 15 Oct 2024 (invited)

Nobre, A. The PV DOCTOR™: Smart O&M for maximising returns of solar systems. Asia Clean Energy Summit (ACES), Solar and Storage track, 23 Oct 2024, Singapore (invited)

Reindl, T. Overview of Solar PV in Singapore. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited, plenary)

Aberle, A. Status of perovskite-silicon tandem solar cell R&D at SERIS. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Hou, Y. Unlocking the efficiency potential of perovskite solar cells from single-junction to tandem. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Sharma, R. Scaling up perovskite-silicon tandem modules: from lab-scale (1 cm^2) to M2-sized (244 cm^2) mini-modules. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Clement, C. BIPV in Singapore – outlook and innovations. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Chen, T. Streamlining BIPV projects by integrating digital workflows with building information modeling (BIM). 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Nalluri, S. PV module recycling using novel shock wave fragmentation technology. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Fen, L. Urban Agrivoltaics: balancing the food and energy generation in dense settings like Singapore. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Gandhi, O. Overview of the Floating PV industry. 2nd Korea-Singapore Joint Photovoltaic Symposium, Singapore, 25 Oct 2024 (invited)

Kim, Y.R. Introduction to the Solar Energy Research Institute of Singapore, Asia-Pacific Forum on Renewable Energy 2024, 05-08 Nov 2024, South Korea

Wang, X., Guo, R., Hou, Y. Regulating phase homogeneity by self-assembled molecules for enhanced efficiency and stability of inverted perovskite solar cells. 35th International Photovoltaic Science and Engineering Conference (PVSEC35), Japan, 10-15 Nov 2024

Zhou, Q., Hou, Y. Rationalising Perovskite Crystal Growth on Cz Silicon Wafers for Efficient Tandem Solar Cells. 35th International Photovoltaic Science and Engineering Conference (PVSEC35), Japan, 10-15 Nov 2024

Saw, M.H., Heng, S.L., Leow, S.W., Pravettoni, M. Wave impact load testing of PV modules for floating applications. 35th International Photovoltaic Science and Engineering Conference (PVSEC35), Japan, 10-15 Nov 2024

Lin F., Liu D., Reindl, T. Agrivoltaics in ASEAN Countries – IEA PVPS Agrivoltaics Action Group workshop. 35th International Photovoltaic Science and Engineering Conference (PVSEC35), Japan, 12 Nov 2024 (invited)

Reindl, T. Overview and outlook of solar PV in Singapore. 4th Asian Nations – Japan Workshop, 35th International Photovoltaic Science and Engineering Conference (PVSEC35), Japan, 14 Nov 2024 (invited)

Reindl, T. Singapore - a front-runner in "Urban Solar". Workshop on Singapore and the Energy Transition: Local and Regional Potentials and Challenges for a Sustainable and Just Transition, Singapore, 25-26 Nov 2024 (invited)

Wang, P., Hadiwidjaja, S., Choi, K.B., Aberle, A.G. Advancing the development of back-contact silicon solar cells through simulation and characterisation. 2024 MI Green Power Innovation Conference, China, 10 -14 Dec 2024 (invited)

Reindl, T. Technology readiness and deployment: Solar PV. UNDP knowledge sharing workshop, Singapore, 16-18 Dec 2024 (invited)

POSTERS AT CONFERENCES AND SEMINARS

(Presenter's name underlined)

Padhamnath, P., Arcebal, J.D., Dasgupta, S., De Luna, G., Rohatgi , A., Aberle, A. Investigation of contact properties and device performance for bifacial, double-side textured solar cells with polysilicon based passivating contacts. 14th International Conference on Crystalline Silicon Photovoltaics 2024 (SiliconPV), France, 15-19 Apr 2024

Padhamnath, P., De Luna, G., Zhong, R., Arcebal, J.D., Aberle, A. Investigation on the impact of the wafer resistivities on double side passivated contact silicon solar cells. 14th International Conference on Crystalline Silicon Photovoltaics 2024 (SiliconPV), France, 15-19 Apr 2024

Padhamnath, P., Nalluri, S., Leow Shin Woei, S.W., Kozieł, T., Mirosław Karbowniczek, M. Recycling end-of-life c-Si photovoltaic panels - recovery of high-quality silicon and other valuable materials. Metallisation and Interconnection Workshop for Crystalline Solar Cells (MIW) 2024, France, 23-24 Oct 2024

IMPRINT

EDITOR IN CHIEF
Prof Armin ABERLE (CEO, SERIS)

EDITORS
TAN Mui Koon (Scientific Manager, Corporate Relations, SERIS)
Kesha Jane DRYSDALE (Senior Scientific Executive, Corporate Relations, SERIS)

PHOTOGRAPHERS (SERIS):
Prof Armin ABERLE
Eddy BLOKKEN
Kesha Jane DRYSDALE
Stella HADIWIDJAJA
David LEE
LEE Ling Kai
Dr LEOW Shin Woei
LIANG Haoming
Dr LIN Fen
LIU Tianyuan
Stanley PHUA
Dr Thomas REINDL
Johannes SCHENK (internship student)
SOE Pyae
TAN Mui Koon
Rachel TAN

GRAPHIC DESIGNER
Dexel Pte Ltd

EDITORIAL ADDRESS
Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)
7 Engineering Drive 1
Block E3A, #06-01
Singapore 117574
SINGAPORE
Tel: +65 6516 4119
Fax: +65 6775 1943
seris-info@nus.edu.sg
www.seris.sg

Solar Energy Research Institute of Singapore (SERIS)
PV Modules for Urban Solar Cluster
1 CleanTech Loop
#06-01, CleanTech One
Singapore 637141
seris-info@nus.edu.sg
(+65) 6567 8073
(+65) 6775 1943

Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)
7 Engineering Drive 1
#06-01, Block E3A
Singapore 117574
seris-info@nus.edu.sg
(+65) 6516 4119
(+65) 6775 1943

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).