NUS National University of Singapore | SERIS Solar Energy Research Institute of Singapore

ANNUAL REPORT 2023

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

ENERGY MARKET AUTHORITY
Our Clean Energy Future

EDB SINGAPORE

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

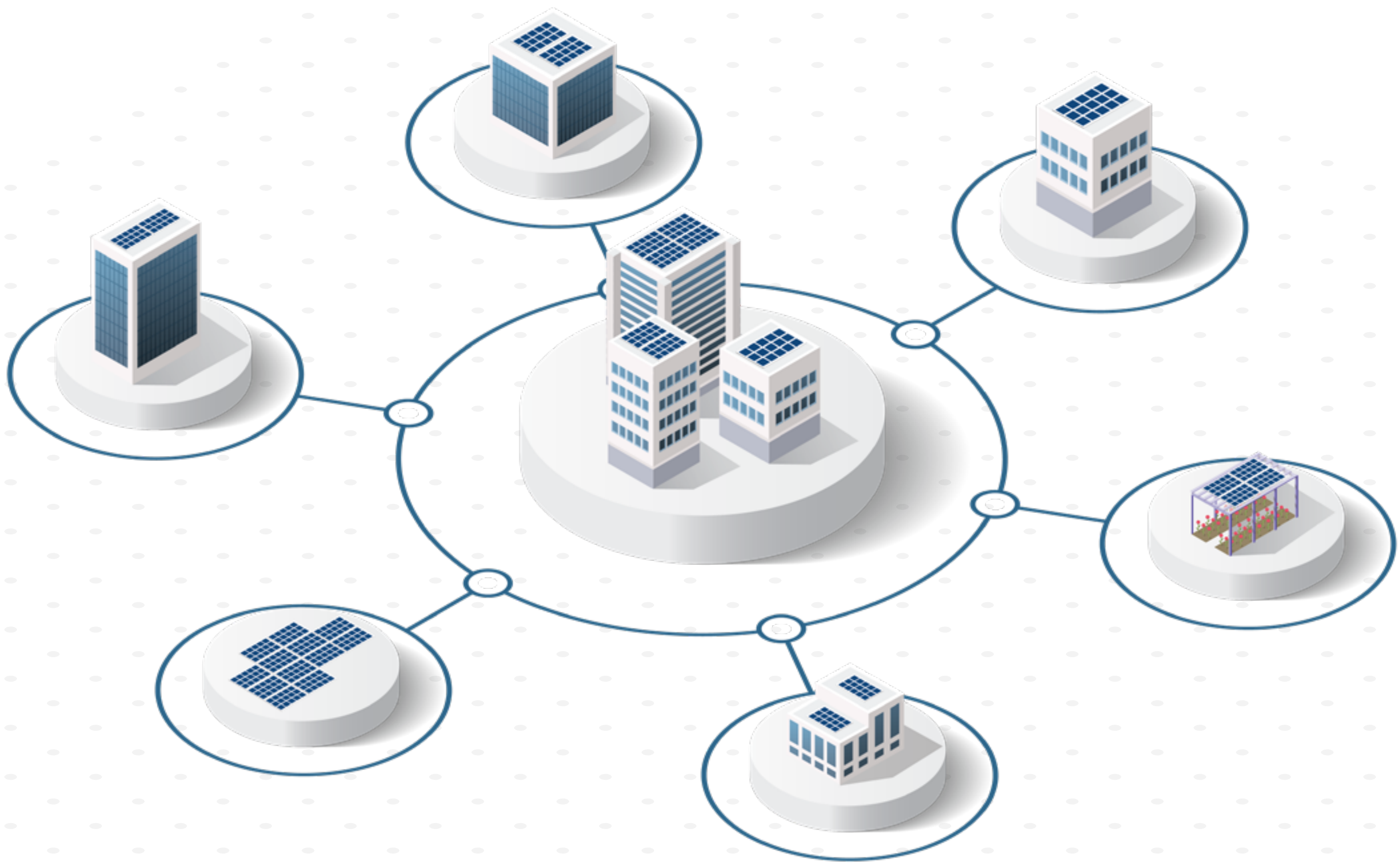
SOLAR ENERGY RESEARCH INSTITUTE OF SINGAPORE
SERIS

Vision

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

Mission

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



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Feedback from **Key Stakeholders**

National University of Singapore (NUS)

Solar energy remains fundamental in the global transition to green, low-carbon energy solutions. With new materials and architectures bringing increased efficiency to solar cell technologies, the potential for solar to reduce our reliance on carbon-based energy sources remains high. For over 15 years SERIS has led the way in Singapore's solar energy research and development efforts, and continues to provide critical leadership and expertise as the nation seeks a green, sustainable future.

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

National Research Foundation Singapore (NRF)

Since 2008, SERIS has consistently pushed the boundaries of solar energy technologies with high-efficiency solar solutions such as building-integrated photovoltaics (BIPV) and floating solar PV on our reservoirs. These solutions have maximised solar technology deployment nationwide, which echoes the fruits of our vibrant research, innovation and enterprise ecosystem, and support our nation's sustainability goals under the Singapore Green Plan 2030. With the launch of the REC@NUS Corporate R&D Laboratory in June this year, we are confident that SERIS will continue to support Singapore's solar industry transformation and in turn, accelerate global energy transitions for a brighter 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' commitment to end-to-end research and development makes the organisation an invaluable partner of both industry and policymakers in Singapore's energy transition. In addition to SERIS' commendable efforts to increase the efficiency of PV cells, which is essential for land scarce Singapore, it has supported the ecosystem of solar players through its research in innovative urban solar deployment. SERIS has also contributed to national outcomes: by developing a solar forecasting tool, which helps to predict solar intermittency and maintain Singapore's grid reliability as we scale up solar deployment in 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 continues to play a key role in the solar sector by driving technological innovations across the value chain in collaboration with industry partners, supporting renewable energy project developers and financiers with quality assurance, and developing standards such as for Floating Solar Systems or Renewable Energy Certificates (RECs). This will support Singapore's ambition to become a renewable energy hub in the region.

Mr LIM Wey-Len, Senior Vice President, Head, Energy & Resources, and Environmental Sustainability, Singapore Economic Development Board (EDB) and member of the SERIS Supervisory Board

CEO's **Foreword**

The transition to a net-zero energy future in Singapore and Southeast Asia requires zero-carbon energy sources to be widely deployed by 2050. While the region is disadvantaged in terms of wind resources, it is blessed with an abundant solar resource ("tropical sun belt") that shows small seasonal variations. Since 2010 the cost of solar photovoltaic (PV) electricity has fallen by about 15% per year, as a result of a steady flow of technical innovations and rapid growth (~25%/year) of the installed global PV capacity. According to a recent study by the International Renewable Energy Agency (IRENA), the weighted average cost of global PV electricity (without storage) has dropped to 4.9 USD cents per kilowatt-hour by 2022, which is now below the lowest-cost fossil options. If solar PV continues to innovate it will become the dominant electricity source in many countries, whereby its intermittent nature will be mitigated by energy storage solutions to ensure a stable and reliable electricity supply around the clock.

Necessity is the mother of invention

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. One challenge for PV deployment in Southeast Asia is the tropical climate with its high temperature and humidity throughout the year. This requires tailor-made PV panels that can cope with these tough operating conditions for 25 years or more. Another challenge is the land scarcity in Southeast Asia, and in particular in the City-state of Singapore where there is very little open land available for PV deployment. For Singapore this means that the installed PV panels should have very high efficiency of 22% or more, to maximise the solar energy production per m^2 and year. Such high-performance panels are now commercially available, for example from our Singapore-based industry partners REC Solar and Maxeon Solar Technologies. Another challenge is the integration of the distributed and highly variable solar power into the electric grid. Furthermore, Singapore has to think "outside the box" and develop novel urban PV deployment options such as BIPV, Floating PV, solar canopies (water canals, carparks, etc) and Agri PV.

The *Singapore Green Plan 2030* describes the transformation of Singapore into a "Global City of Sustainability" by the end of this decade. Solar energy is a crucial element of this initiative, with a target of 1.5 gigawatt-peak (GW_p) of PV power installed locally by 2025, and at least 2 GW_p by 2030. In 2023, the total installed PV capacity in Singapore has passed 1 GW_p, and the nation is on track to reach the 2025 and 2030 PV deployment targets.

SERIS is presently in its fourth funding cycle, which runs for 5 years (FY 2022 - 2026) and provides core funding for three flagship projects (thin-film on silicon tandem solar cells, BIPV modules & systems, floating solar systems) and the development & testing of several "Urban Solar" deployment options. This report presents SERIS' major achievements in calendar year 2023 and the R&D plans for 2024. It also describes our research departments ("clusters") and groups, as well as our facilities & laboratories, services, and outreach activities.

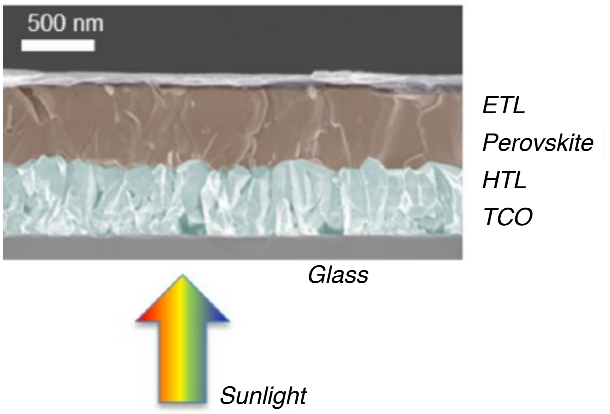
Notable SERIS achievements in 2023 include a certified new world record of 24.35 ± 0.5 % for perovskite thin-film solar cells (≥1 cm^2), the upscaling of the perovskite-silicon tandem solar cell technology to substrate sizes of 244 cm^2 (with efficiencies of over 17%, whereby both the bottom and the top sub-cells were fully made by SERIS), the official launch of a SGD 77 million 5-year REC@NUS Corporate Laboratory project aiming for the world's first low-cost large-area (440 cm^2) solar cell with 30% efficiency (perovskite-silicon tandem), and the opening of two SERIS testbeds for novel agrivoltaic technologies at the Yuhua Agritech Solar (YAS) Living Lab.

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 industry partners and supporters 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.

The globally installed solar PV capacity grew by about 30% in 2023, and the PV industry is on track to reach a deployment rate of 1 TW_p/year by 2030. A large share of both the manufacture and deployment of these PV systems will occur in the Asia-Pacific region. By 2040, solar PV will likely be the dominant electricity source in Southeast Asia, as its costs and rate of growth far undercut all alternatives. Interestingly, this solar revolution is no longer driven by subsidies or the concerns about global warming. The key driver is now pure economics, as solar power in the region has become cheaper than anything else and thus offers good profits. To further accelerate the energy transition, SERIS and NUS will continue to develop innovative solar energy technologies and services, transfer them to industry, and contribute to the solarisation of Singapore and Southeast Asia.

With sunny regards,
Prof Armin ABERLE
SERIS CEO
18 December 2023

Highlights **2023**

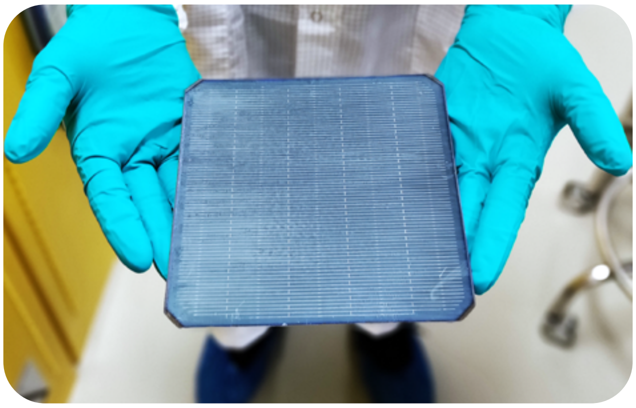


April

China's National PV Industry Measurement and Testing Center (NPVM) measures a certified efficiency of 24.35 ± 0.5 % for a SERIS-made single-junction perovskite solar cell with an area of 1.0 cm^2. In June 2023 this result is included as the **new perovskite solar cell world record** in the Solar cell efficiency tables (version 62) of the journal Progress in Photovoltaics. The solar cell was made by Dr LI Jia and PhD student WANG Xi from SERIS' Perovskite-based Multijunction Solar Cells Group headed by Assistant Prof HOU Yi.

June

Official launch of the **REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics** by Deputy Prime Minister Mr HENG Swee Keat. This SGD 77 million 5-year project of NUS-SERIS and REC Solar researches, develops and commercialises disruptive solar PV technologies based on perovskite-silicon tandem solar cells. A brief report on the official launch event can be found on page 7 of this Annual Report.



August

SERIS' Advanced Solar Cells Group in the NISCM Cluster successfully developed **fully in-house fabricated large-area (244 cm^2) 2-terminal perovskite-silicon tandem solar cells** with 1.7-eV perovskite top cells integrated with double-side textured silicon heterojunction bottom cells made on M2-size Cz silicon wafer substrates, as shown in the photograph. All layers of the perovskite cells were deposited using industrially compatible deposition processes. These tandem solar cells exhibit 1-Sun efficiencies of more than 17% (measured in-house with a class AAA I-V tester). This makes SERIS the only facility in Singapore, and one of the few laboratories in the world, capable of producing fully in-house fabricated perovskite-silicon 2T tandem solar cells on industrial-size (M2) silicon wafer substrates.

(Photo credit: PII)

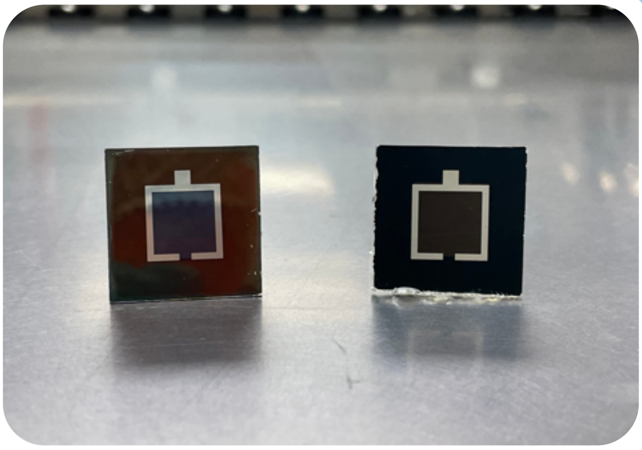
August

SERIS signs a MOU with Persatuan Insuinyur Indonesia (PII, The Institution of Engineers Indonesia) to jointly establish the "Indonesia Solar Energy Research Centre" (ISEREC). The planned initial activities of ISEREC include trainings, consultancy, and targeted R&D activities for the "Green Corridor" project which aims for a sustainable industry development in Riau province including GW-scale solar projects, the establishment of a solar PV value chain, and also the export of green electricity to Singapore.

(Photo credit: Yuhua Citizens' Consultative Committee)

November

Supported by the SG Eco Fund and initiated by the Yuhua Citizens' Consultative Committee, the Yuhua Agritech Solar (YAS) Living Lab was officially opened by Minister for Sustainability and the Environment Ms Grace FU on 4 Nov 2023. In collaboration with research partners Arianetech, ClearVue PV, Life3 Biotech, and V-Plus Agritech, and implemented by JML, SERIS operates two Agri-photovoltaic (PV) testbeds at the YAS Living Lab to study the balance among crop yield, clean energy generation and energy consumption, and to engage residents. Rotatable PV modules are used to track the sun during the day for maximised power generation, rainwater management, and microclimatic control around the plants.



November

A team of scientists comprising researchers from SERIS, NUS, EMPA (Switzerland) and Forschungszentrum Jülich (Germany) reports a new **world record efficiency of 29.9% for a 4-terminal perovskite-CIS tandem solar cell** (perovskite sub-cell 0.05 cm^2, CIS sub-cell 0.5 cm^2). The perovskite sub-cell was made at SERIS.

November

Assistant Prof HOU Yi, Head of the Perovskite-based Multijunction Solar Cells Group at SERIS, and Asst. Prof at the NUS Department of Chemical and Biomolecular Engineering, College of Design and Engineering, is named by analytics company Clarivate as one of the world's most highly cited researchers in 2023.

Official Launch of the **REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics**

The official launch of the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics at the National University of Singapore was graced by Deputy Prime Minister HENG Swee Keat (third from left)

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) and REC Solar (REC) officially launched the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics ("REC@NUS Corp Lab") on 16 June 2023. The event was graced by Mr HENG Swee Keat, Deputy Prime Minister and Coordinating Minister for Economic Policies, and Chairman of the National Research Foundation Singapore.

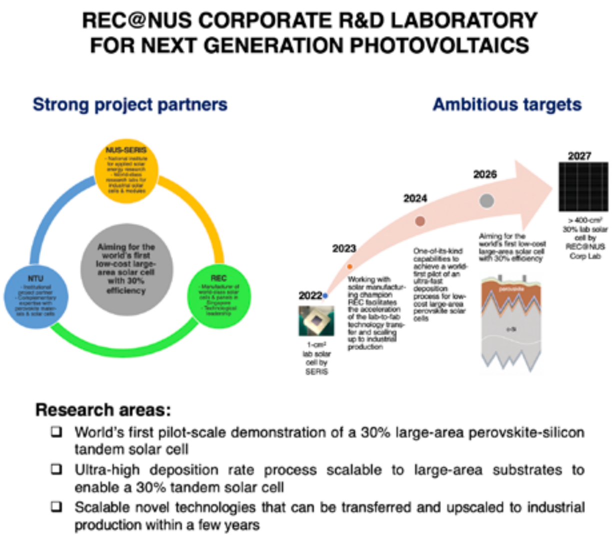
The REC@NUS Corp Lab resides in SERIS at NUS. Supported by Singapore's Research, Innovation and Enterprise (RIE) 2025 Plan, the new SGD 77 million research initiative will research, develop and commercialise disruptive solar photovoltaic (PV) technologies based on perovskite-silicon tandem solar cells over the next five years.

Currently, the energy conversion efficiency of commercial single-junction silicon solar cells is around 24-25%. The REC@NUS Corp Lab aims to develop cost-effective ultra-high-performance solar cells with 30% efficiency or more, by adding a perovskite cell on top of a silicon cell to form a two-junction tandem solar cell. The research team also strives to develop one-of-its-kind capabilities to manufacture these advanced solar cells cost-effectively to facilitate industry adoption. The targeted product is a low-cost, large-area (> 400 cm^2) 30% perovskite-silicon tandem solar cell well suited for urban environments like Singapore.

The REC@NUS Corp Lab is led by two Co-Directors: Professor Armin ABERLE, CEO of SERIS, and Dr Shankar G. SRIDHARA, Chief Technology Officer of REC. The project is also in partnership with the Nanyang Technological University (NTU) in Singapore and aims to train up to 20 PhD students over the next five years.

More information about the Corp Lab can be found at: www.seris.nus.edu.sg/recnus-corp-lab/

SERIS CEO Prof Armin ABERLE (right) describing the Corp Lab's research activities, challenges and targets to DPM HENG Swee Keat.



SERIS key numbers in **CY2023**

(as of 30 Nov 2023, unless otherwise stated)

Headcount & Educational background

121
Staff, Adjuncts & Students

70
With university degrees

PV Module Reliability / Quality Index

26
Golden Modules* Tested (Jan-Dec 2023)

**SERIS' lab is accredited for the electrical characterisation of secondary reference standards (known as "Golden modules") according to IEC 60904-2. More details on page 107 of this Annual Report*

World record perovskite solar cell

24.35 ± 0.5%
certified efficiency
New world record for perovskite solar cells with an area of at least 1.0 cm^2

Glare analysis for PV installations

Assessed
>40
locations in Singapore

Floating Solar projects

~1.8 GW_p
Feasibility studies or design consultancies carried out

Research publications

29
Journal & conference papers published / in press

Industry Income (FY2023, projected)

~SGD **3 Million**

Conferences, Symposia, Workshops & Webinars

>60
talks & posters presented

Links with academia, industry, government & other bodies

>30
memberships in technical and/or advisory committees

Outreach Activities

Hosted
>20
visits from schools and companies

Customers **Feedback**

The Asian Photovoltaic Industry Association (APVIA) consists of a diverse range of individuals, corporate entities and non-profit stakeholders from the solar industry. It includes manufacturers, developers, research institutes, think-tanks and industry associations from the Asia-Pacific region who are committed to develop the solar PV markets, increase the global share of solar energy in the renewable energy space, and contribute to the worldwide decarbonisation efforts. APVIA has members that span the Asia-Pacific region, in particular from the Philippines, Malaysia, Vietnam, Indonesia, Singapore, China and Australia.

SERIS has been an important partner of APVIA for many years. It consistently shares its knowledge and expertise in the field of solar PV and has been collaborating with APVIA since 2012 to co-organise SNEC – the world's largest solar conference and exhibition held annually in Shanghai. SERIS' active participation in APVIA meetings and roundtable dialogues allow us to gather updates, trends and forecasts in the solar PV sector. Thus, APVIA greatly values the collaboration with SERIS and we look forward to the continuation of our strategic partnership in the years to come.

Mdm Tetchi CAPELLAN
Secretary-General
Asian PV Industry Association (APVIA)

Dai Nippon Printing Co., Ltd. (DNP) is one of the world's largest printing companies and its corporate philosophy is "Connecting individuals and society to provide new value". As one of our activities, we have been providing solutions to the renewable energy industry by supplying high quality and high barrier PV component materials. It is one of our important missions to contribute to a sustainable future that reduces environmental impact and enables people worldwide to coexist harmoniously with the earth. The partnership between SERIS and DNP is very important in achieving this goal. We will support SERIS in their tremendous efforts to develop the future solar cells with our barrier film and encapsulation technology. We are more than excited to achieve our goals very soon with our outstanding partner.

Taiki TAKAYAMA
General Manager of PV Management Division
Dai Nippon Printing Co., Ltd.

As a leading German engineering and consultancy service provider, Dornier Group has been supporting the development of > 17 GW of renewable projects across the globe. Our Business Unit Renewables, which includes Dornier Suntrace, has been collaborating with SERIS since 2019 for Floating Solar (FPV) advisory projects in various locations, including Vietnam, the Philippines, Sri Lanka, Suriname, and other countries. We always strive to provide innovative concepts for our clients in their projects, and thus are often collaborating with different research organisations such as SERIS to complement our advisory offering.

I wanted to take a moment to express our appreciation for the outstanding service we have been receiving from the SERIS team. From the beginning of our partnership, SERIS has consistently impressed us with their professionalism, expertise, and proactive approach. Our SERIS colleagues have gone above and beyond to understand our unique needs, contributing significantly to the success of our projects. We value our partnership and look forward to achieving even greater milestones together.

Mr Martin SCHLECHT
Director Strategy
Dornier Group - Business Unit Renewables

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

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

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

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 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 over the next 2 years. 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)

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

Quantified Energy Labs Pte Ltd (QE-Labs)

Quantified Energy Labs (QE-Labs) is a Singapore-based deep-tech start-up company that specialises in using drone technology to provide electroluminescence (EL) testing of fielded solar PV panels. The company was founded by a team of experienced researchers and engineers from SERIS/NUS who recognised the need for a more efficient and effective method of solar panel inspection. QE-Labs' solution involves the use of high-sensitivity shortwave infrared (SWIR) cameras mounted on drones to capture EL images of PV panels at a throughput of 10,000 panels per night shift at a ground-mounted utility-scale solar farm. The captured raw EL data are then processed using QE-Labs' proprietary software solutions, which use A.I. algorithms to detect and analyse cell cracks, faulty soldering, dark cells, and other defects that may affect the performance of the PV panels. The result is a stitched EL map that provides the exact location of defective panels in a PV farm, along with quantitative scores in the 0 - 100 range that represent the PV system's actual quality condition.

QE-Labs' autonomous drone EL mapping solution is a game-changing tool in the solar PV industry, providing a remarkable solution for quality control on a vast scale for field-installed PV modules. By analysing installed PV modules at the actual site, this innovative technology delivers exceptional results, enabling the allocation of liabilities to various parties such as manufacturers, transporters, EPCs, O&M (Operations and Maintenance) teams, insurance companies, and investors. This disruptive innovation is a first of its kind in the PV industry and has the potential to transform the way solar PV asset operation is monitored and maintained. In 2023, QE-Labs has expanded its operations to the EU, USA, China, Australia, Southeast Asia, and Taiwan markets, establishing a global presence to meet the growing demand for its cutting-edge technology.

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

QE-Labs' interactive dashboard provides a powerful user-friendly interface to visualise and manage geo-referenced EL big data. With advanced A.I. and quantitative scoring algorithms, this tool empowers users to gain valuable insights for data-driven decision-making.

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 services for PV system owners developed by SERIS in recent years that are now being offered to industry through the spin-off company. The SERIS team has completed a project portfolio of 40 MW_p in Thailand, Malaysia, Indonesia, and Singapore - from large solar farms (> 20 MW_p) to industrial, commercial, residential, and off-grid PV systems - to gain real-world experiences and build a robust track record before venturing into the spin-off. The PV DOCTOR™ comprises a broad range of remote and on-site "health checks" of PV installations as well as fault diagnostics and rectification measures that help asset owners, investors, and lenders to verify the operational health of PV systems. The spin-off also offers SERIS-developed proprietary solutions in the areas of real-time monitoring, smart O&M, and solar forecasting.

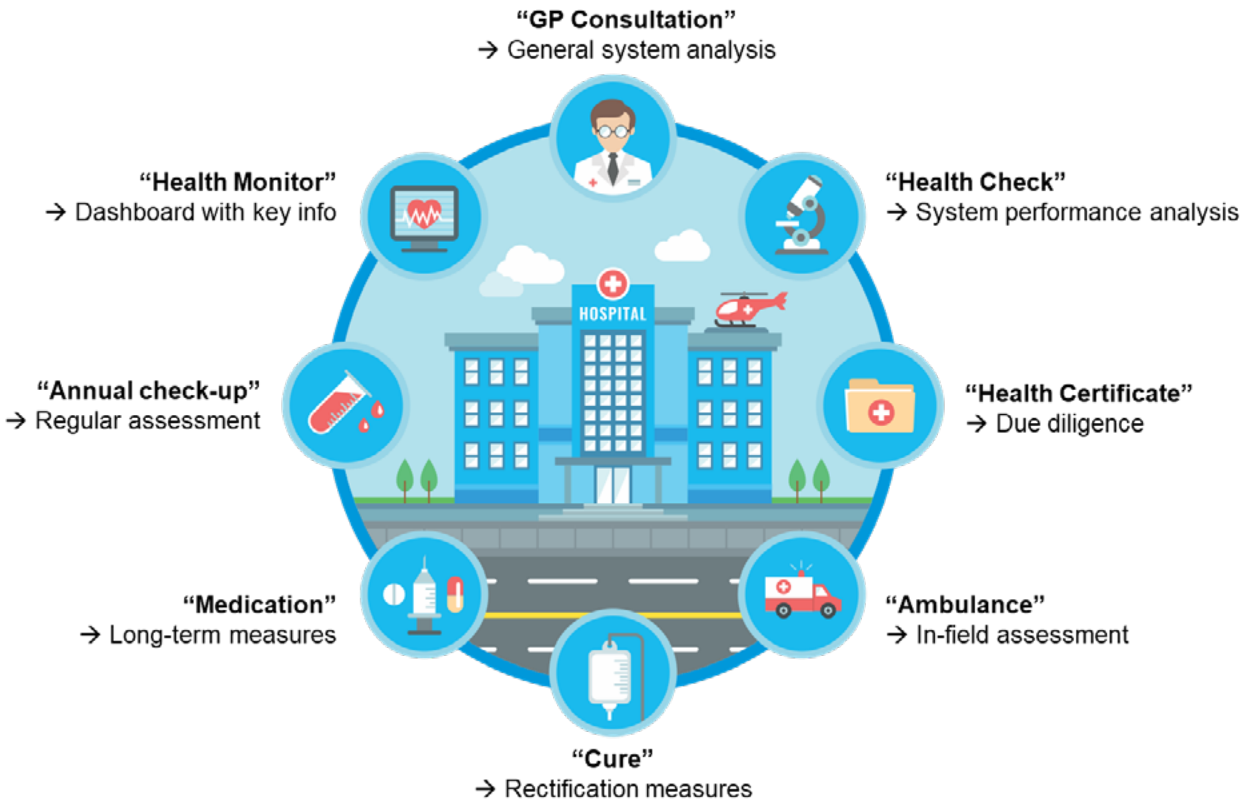
The graphic below provides an overview of the comprehensive services of the PV DOCTOR™.

In 2023, the spin-off managed to sign a major deal for a comprehensive PV monitoring system for a MW-scale rooftop installation of a C&I client in Singapore. In collaboration with SERIS, the team also carried out a detailed assessment of a newly installed PV system in Singapore where the owner suspected mishandling of PV modules during installation (i.e., workers had been spotted walking over the PV modules that are installed directly on the slightly tilted metal roof).

The team carried out on-site testing using various methods, ranging from visual inspection to string I-V curve measurements, infrared (IR) analysis and selected electroluminescence (EL) measurements. While the alleged mishandling may have caused some contrasts and micro-cracks visible in the EL pictures, they didn't affect the system performance, which turned out to be according to expectation. Here, 'expectation' includes the fact that the operating temperatures of the PV modules are higher than for raised-up structures, reaching around 65°C at full sunshine conditions. This leads to ~12% yield loss compared to the theoretical system performance at standard test conditions (STC). Close monitoring of the system's behaviour was advised, given the presence of micro-cracks found in more than 70% of the samples.

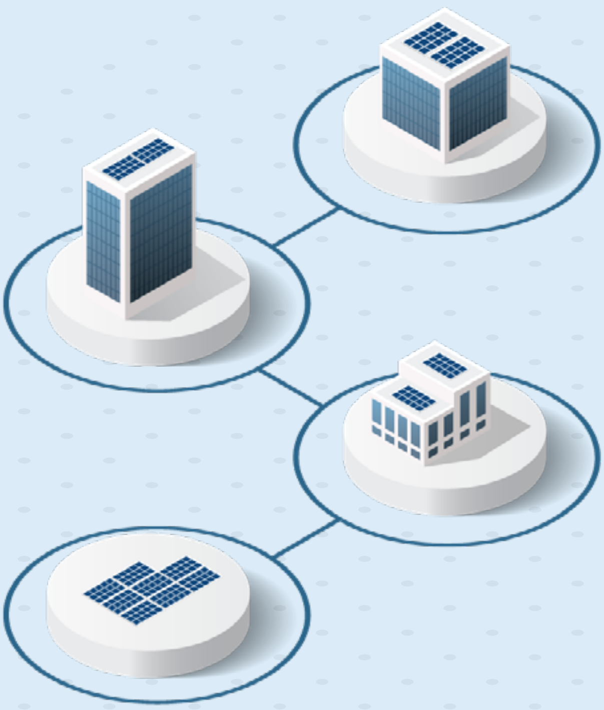
In the area of solar forecasting, the fully operational solar forecasting system developed for EMA's Power System Operation Centre has been adjusted for individual solar farms as a so-called "point forecast" that is being integrated into the SERIS Asset Management platform, which will be commercialised through the PV DOCTOR™ spin-off.

For further information please contact:
Ms YANG Ping, CEO, PV DOCTOR™ spin-off,
e0669537@u.nus.edu



Overview of the services offered by the PV DOCTOR spin-off for the assessment of the "health" of a PV system, detecting under-performances, and implementing suitable rectification measures. Image source: SD Global Tech.

INSTITUTE IN **BRIEF**



Introduction

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) was founded in April 2008. It has the stature of a NUS University-level Research Institute and is endowed with considerable autonomy and flexibility, including an industry-friendly IP policy. 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 need for solar adoption and industry development, and also supports the government's pledge to reduce the nation's carbon emissions. The institute has been instrumental in driving several strategic government initiatives aiming at fostering the solarisation of Singapore, for example the nation-wide SolarNova programme, the Floating Photovoltaics (PV) Testbed at Tengeh reservoir, the Update of the Solar PV Roadmap for Singapore, and the implementation of a fully operational Solar Forecasting tool to enhance Singapore's solar adoption and grid reliability.

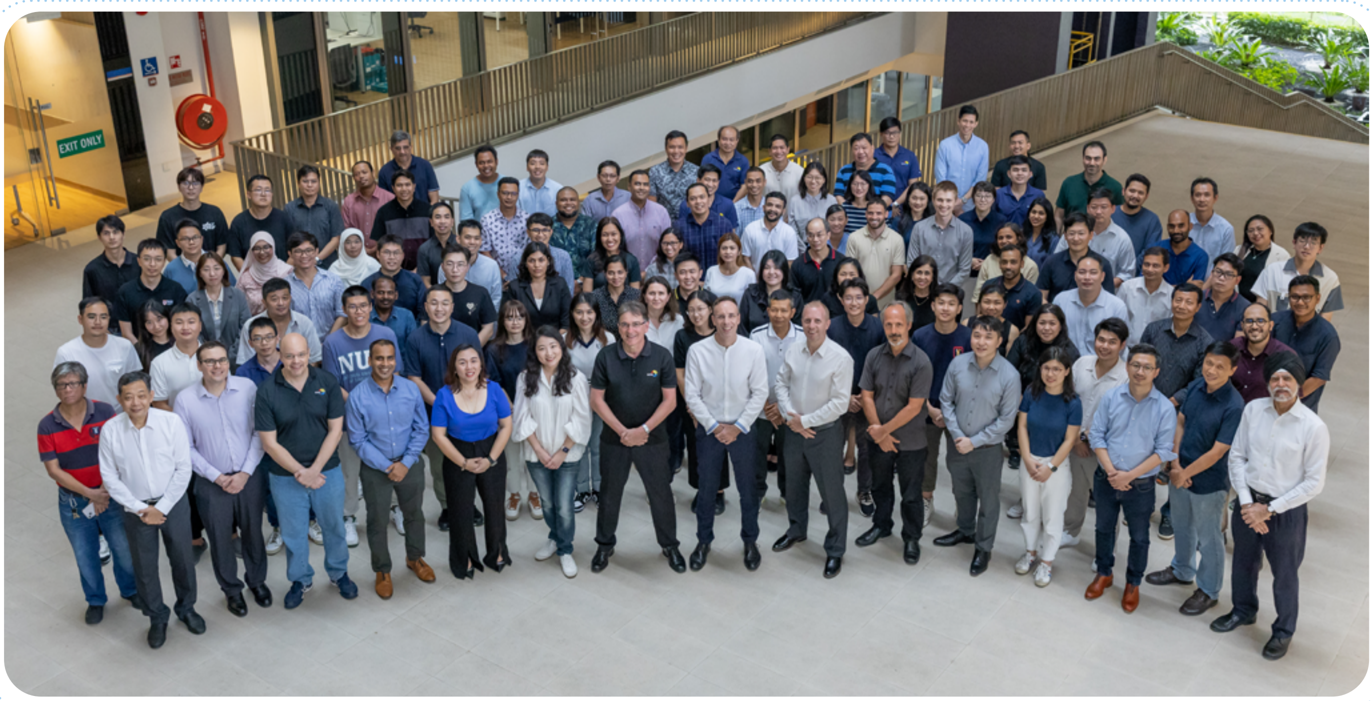
SERIS conducts research, development, deployment, testing and consulting on solar energy technologies and their integration into urban infrastructures, buildings, and power systems. It's R&D spectrum covers industrially relevant materials, components, processes, systems, and services, with an emphasis 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).

SERIS Flagship Projects:

- Thin-film on silicon tandem solar cells – to develop high-efficiency thin-film on silicon tandem solar cells
- Building Integrated Photovoltaics (BIPV) – to develop low-cost high-efficiency and reliable BIPV modules and systems for integration into the facades of buildings
- Floating Solar Systems – to develop single- and multi-purpose floating PV systems for inland water reservoirs and marine areas (near-shore, off-shore)

The institute operates world-class laboratories and facilities for solar R&D & testing services, of which the electrical testing of PV Modules (indoor characterisation and reliability), Grid Tied Solar PV Systems measurement (up to 1000 V) and the 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. The collaborations with companies from the solar sector span from small start-ups to industry leading heavyweights. To date, 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
- 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

An aerial view of the Yuhua Agritech Solar (YAS) Living Lab located on the rooftop of an HDB carpark at Jurong East, Singapore. The YAS Living Lab has 10 test-bedding projects run by institutes, companies and heartlanders to study the combination of solar panels and urban farming for the optimum balance between crop yield and renewable energy generation on the same area. The solar roof invented by SERIS features moveable louvers that allow to track the sun during the day and are also used for rainwater management and control of the microclimate around the plants. More information on SERIS' novelties and research in this project can be found on page 80 and page 115 of this Annual Report.

Finances

For Financial Year (FY) 2023, 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 12.4 million. The core funding is complemented by grants from public competitive R&D programmes and funds from industry contracts of approximately SGD 7.7 million and SGD 2.9 million, respectively. These are projected amounts, as FY 2023 will end on 31 March 2024. The breakdown of the projected SERIS funding of SGD 23.0 million for FY 2023 is displayed in Figure 1.

Figure 2 shows the usage of the projected available SERIS funding of SGD 23.0 million in FY 2023: SGD 10.1 million for manpower, SGD 3.8 million for equipment, SGD 7.5 million for operating expenses, and SGD 1.6 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 9 financial years is shown in Figure 3.

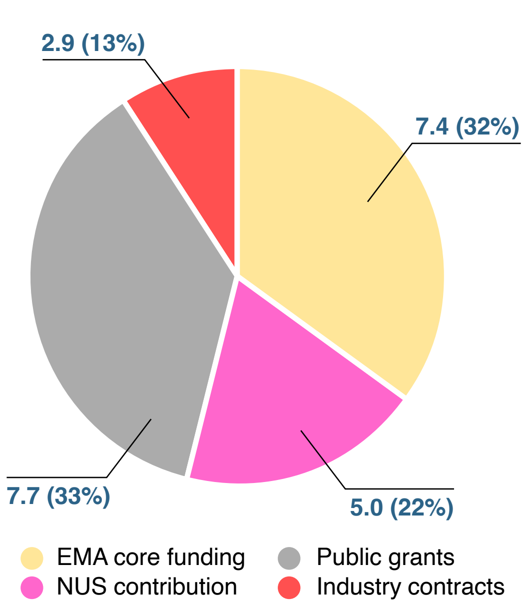


Fig. 1: Projected SERIS funding for FY 2023 (1 Apr 2023 to 31 Mar 2024, in SGD million)

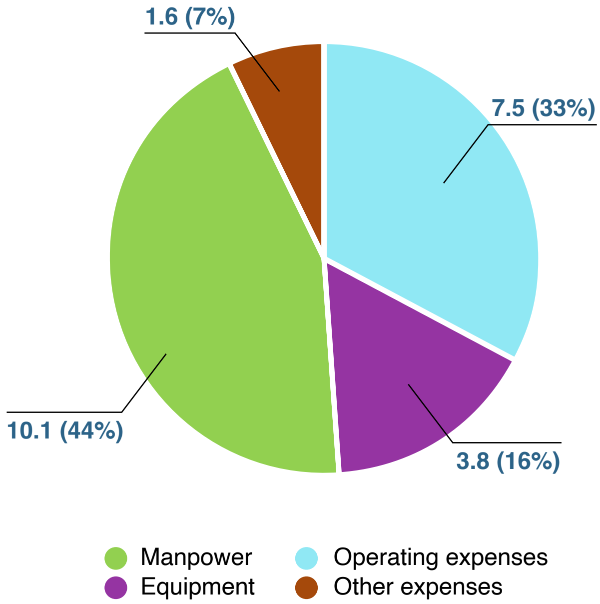


Fig. 2: Projected expenses for FY 2023 (1 Apr 2023 to 31 Mar 2024, in SGD million)

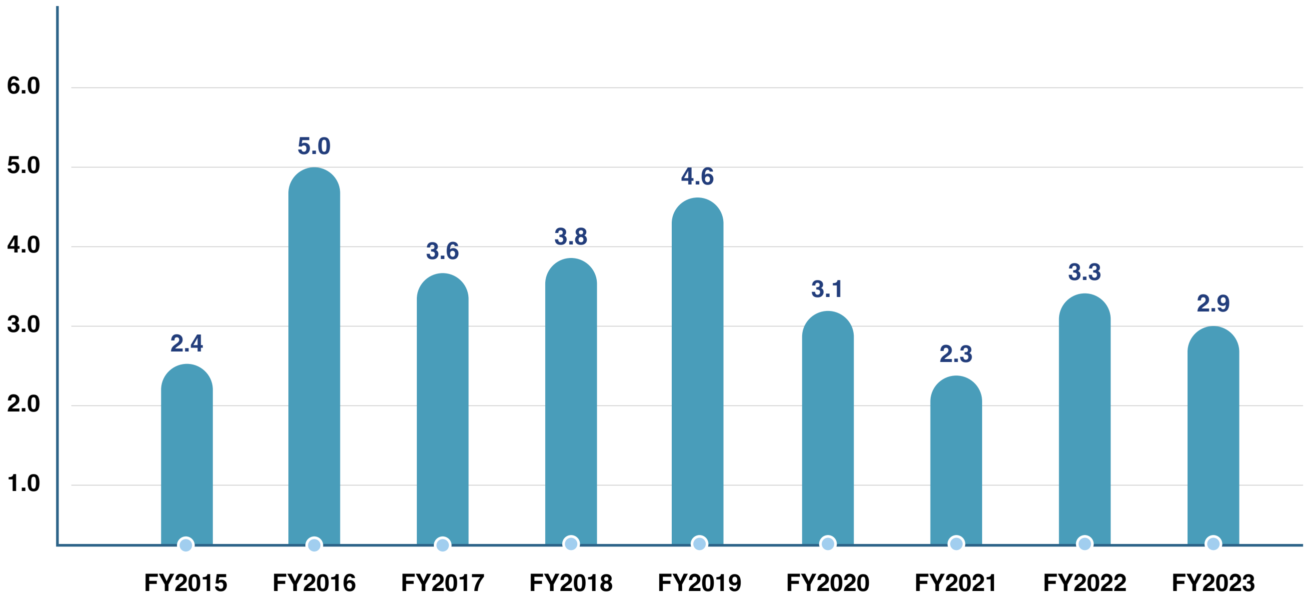
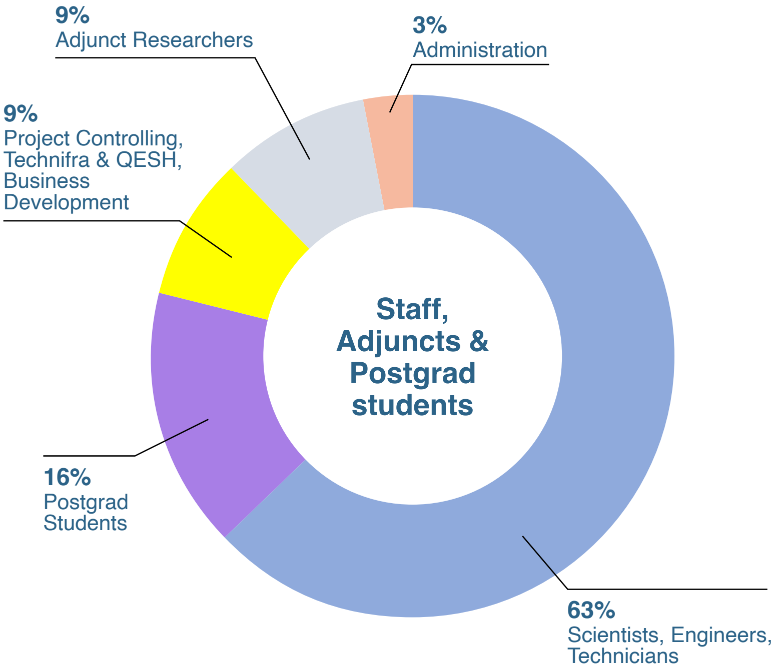


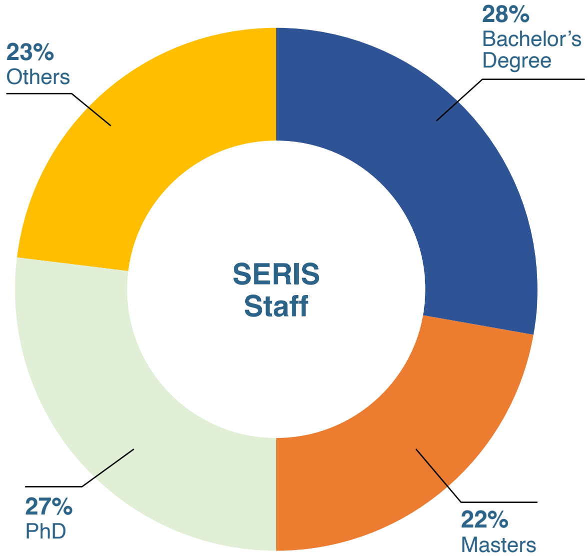
Fig. 3: Evolution of SERIS' industry income since FY 2015 (in SGD million)

Headcount

At the end of calendar year 2023, the SERIS headcount was 121, including NUS-funded postgraduate students and adjunct researchers ("faculty"). The figure 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 9% of the total headcount, while administrative staff represent 3% of the headcount.



Breakdown of SERIS headcount in December 2023



Educational qualification of SERIS staff

Laboratory, Office and Rooftop Space

SERIS occupies approximately 5,160 m^2 of space in the E3A building on the main NUS campus, including offices, laboratories and laboratory support facilities. SERIS also rents about 1,370 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 3,330 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),
Former Director of the National Renewable Energy Laboratory (NREL)
Former Chancellor of New Mexico State University (NMSU)

Dr Nancy HAEGEL

Director, National Centre for Photovoltaics
National Renewable Energy Laboratory
USA
(since Apr 2023)

Prof Sarah KURTZ

Professor
University of California, Merced
USA
(until Mar 2023)

Mr Steve O'NEIL

Chairman, REC Solar Norway
Board Director, Endurans Solar
Executive Advisor, Nel Hydrogen and Solestial
USA

Mr Frank PHUAN

Business CEO
EDP Renewables APAC
Singapore

Dr SHI Zhengrong

Chairman and Founder
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 (since Sep 2023)

Prof LIU Bin

Deputy President (Research and Technology)

National University of Singapore (until Aug 2023)

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

Mr ANG Kian Seng

Group Director

Environmental Sustainability Group

Building and Construction Authority (BCA)

(until Aug 2023)

Mr Ralph FOONG

Deputy Chief Executive

Energy Planning & Development Division

Energy Market Authority, Singapore

(until Sep 2023)

Mr HONG Howe Yong

Head, Group Centre of Excellence

Sembcorp Industries Ltd

(until Aug 2023)

Mr 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 Hospital System (NUHS)

Mr LIM Wey-Len

Senior Vice President and Head

Energy and Resources / Environmental Sustainability

Singapore Economic Development Board (EDB)

Mr LOW Xin Wei

Assistant Chief Executive

Markets & Systems Division

Energy Market Authority, Singapore

(since Oct 2023)

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 Supervisory Board

SERIS International Advisory Panel

Prof Armin ABERLE
Chief Executive Officer

Dr Thomas REINDL
Deputy CEO

Administration
Shakander Singh CHAHAL
Director

Technical Infrastructure & QESH
Peter LIM
Director

Novel PV Concepts
Prof Armin ABERLE
Acting Cluster Director

Next-Generation Industrial Solar Cells & Modules
Prof Armin ABERLE
Cluster Director

PV Modules For Urban Solar
Dr Mauro PRAVETTONI
Cluster Director

Solar Energy Systems
Dr Thomas REINDL
Cluster Director

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):
Mr Shakander Singh CHAHAL, Dr Thomas REINDL, Prof Armin ABERLE, Dr Mauro PRAVETTONI, Mr Peter LIM

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 & Modules

Acting Cluster Director, Novel PV Concepts
armin.aberle@nus.edu.sg

Dr Thomas REINDL

Deputy CEO
Cluster Director, Solar Energy Systems
thomas.reindl@nus.edu.sg

Dr Mauro PRAVETTONI

Cluster Director, PV Modules for Urban Solar
mauro.pravettoni@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 Managers, the Scientific Manager (Corporate Relations), and the SERIS Business Partners for Finance and Human Resources from NUS. The team meets every two months to discuss managerial, operational and strategic matters of the institute.

Extended Management Team

Assoc Prof Karl Erik BIRGERSSON

Head, Emerging Solar Technologies Group, NPVC Cluster

mpebke@nus.edu.sg

Dr CHOI Kwan Bum

Head, PV Devices Characterisation Group

Team Leader, Solar Cell Testing, NPVC Cluster

serckb@nus.edu.sg

Asst Prof HOU YI

Head, Perovskite-based Multijunction Solar Cells Group, NPVC Cluster

yi.hou@nus.edu.sg

Assoc Prof TAN Zhi Kuang

Team Leader, Perovskite Devices Emerging Solar Technologies Group, NPVC Cluster

chmtanz@nus.edu.sg

(until Mar 2023)

Dr WANG Puqun

Team Leader, Advanced Characterisation

PV Devices Characterisation Group

NPVC Cluster

puqun.wang@nus.edu.sg

LAM Yiin Fan

Laboratory Manager, NISCM Cluster

yflam@nus.edu.sg

(since Mar 2023)

Dr Nitin NAMPALLI

Deputy Cluster Director and Head of Corporate Laboratory Group (since Oct 2023)

Team Leader, Heterojunction Solar Cells, Advanced Solar Cells Group, NISCM Cluster (until Sep 2023)

nitin.nampalli@nus.edu.sg

Dr Pradeep PADHAMNATH

Head, Solar Cell Metallisation Group & Laboratory Manager, NISCM Cluster

(until May 2023)

Dr Selvaraj VENKATARAJ

Senior Research Fellow

Corporate Laboratory Group

NISCM Cluster

s.venkataraj@nus.edu.sg

Dr Jeremie WERNER

Team Leader, Large-Area Tandem Cells, Advanced Solar Cells Group, NISCM Cluster

(until Mar 2023)

Dr LEOW Shin Woei

Head, BIPV Group,

PV Modules for Urban Solar Cluster

swleow@nus.edu.sg

Dr LONG Jidong

Laboratory Manager,

PV Modules for Urban Solar Cluster,

SERIS laboratory at CleanTech Park

jidonglong@nus.edu.sg

Extended Management Team

Eddy BLOKKEN

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

Dr Serena LIN Fen

Head, Urban Solar Solutions Group,
SES Cluster (since Jan 2023)
lin.fen@nus.edu.sg

Dr Carlos RODRÍGUEZ

Head, Solar System Technology
Group, SES Cluster
carlos.rodriguez@nus.edu.sg

SOE Pyae

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

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

TAN Mui Koon

Scientific Manager,
Corporate Relations
muikoon.tan@nus.edu.sg

Janet GOH

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

Nicole YAO Baozhen

SERIS Business Partner Finance, NUS
nybz@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.

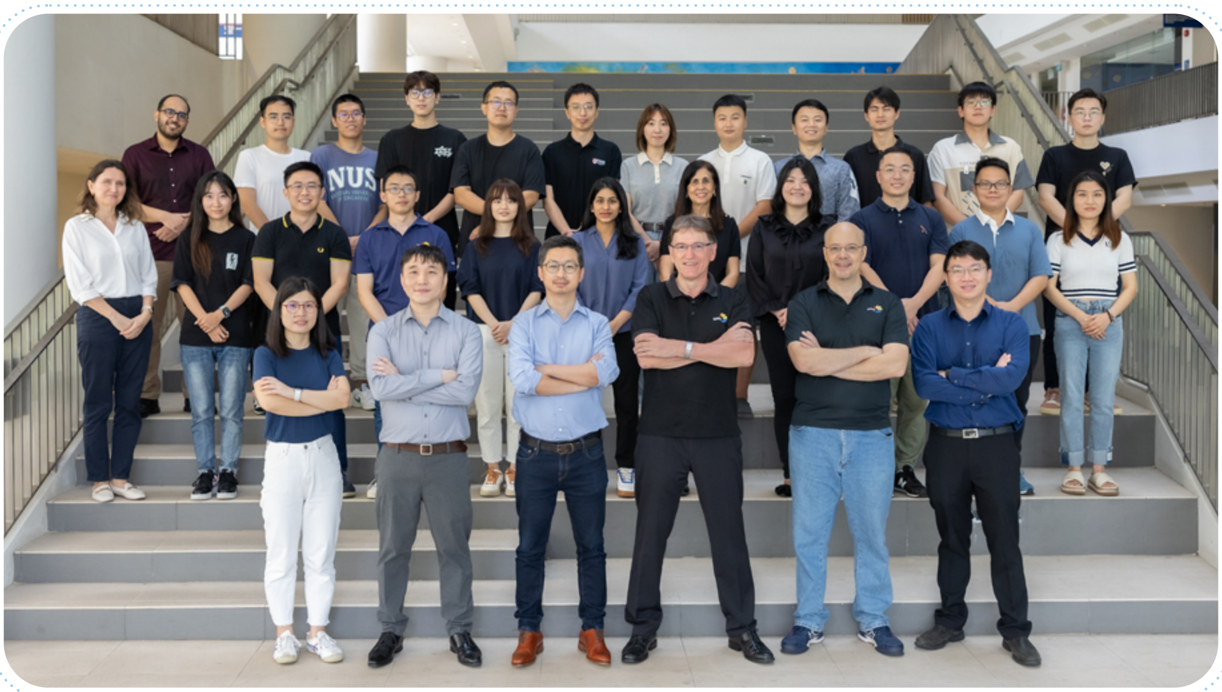
In 2023, the following Adjunct researchers from NUS have been working with SERIS:

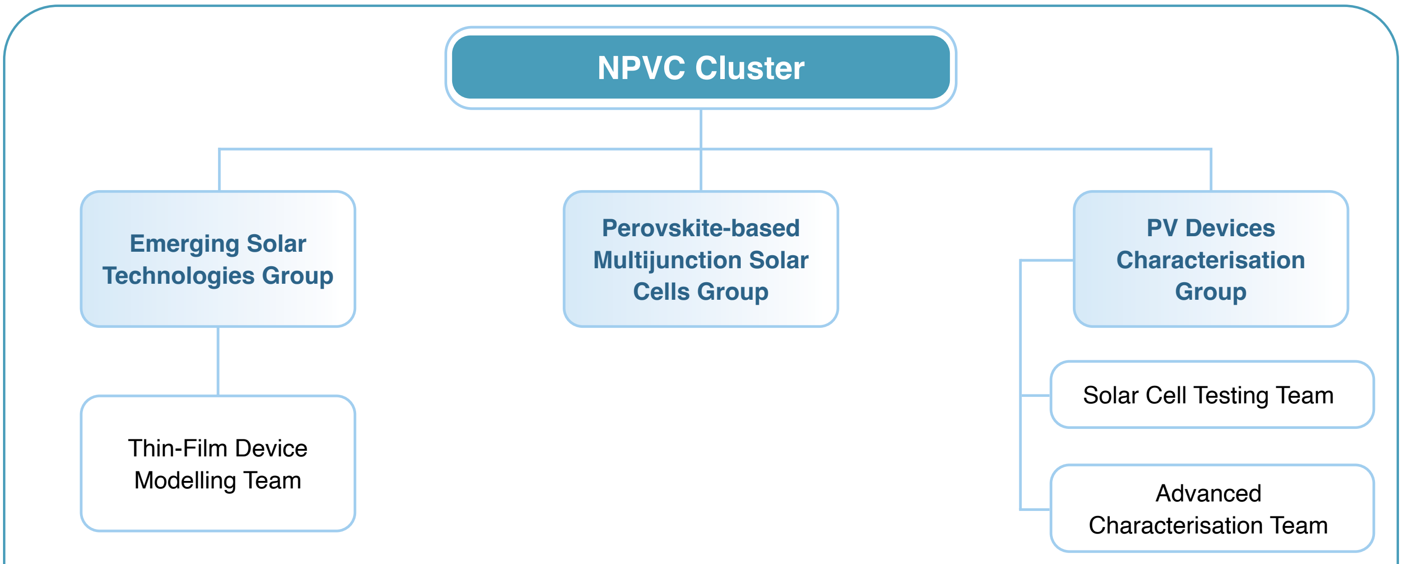
Name	NUS Department	Research Area / Role at SERIS
Prof Armin ABERLE	Electrical and Computer Engineering	Photovoltaic materials, devices and modules / CEO and Cluster Director
Assoc Prof Karl Erik BIRGERSSON	Mechanical Engineering	Modelling, optimisation and characterisation of solar cells; Modelling of PV modules / Head of Emerging Solar Technologies Group
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 / Head of Group
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

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 2023, the Cluster had 31 members (including 15 PhD students) spread over three R&D Groups.





Organisation chart of the Novel PV Concepts Cluster (in Dec 2023)

Cluster Director's Office

Prof Armin ABERLE
Acting Cluster Director

Ann Mythel ROBERTS
Cluster Secretary

Laboratory Manager

Dr Firdaus Bin SUHAIMI

Group Heads

Assoc Prof Karl Erik BIRGERSSON
Emerging Solar Technologies

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 CHOI Kwan Bum
Solar Cell Testing

Dr WANG Puqun
Advanced Characterisation

Adjunct Researchers, NUS

Prof Armin ABERLE
Dept of Electrical and Computer Engineering (Photovoltaic materials, devices & modules)

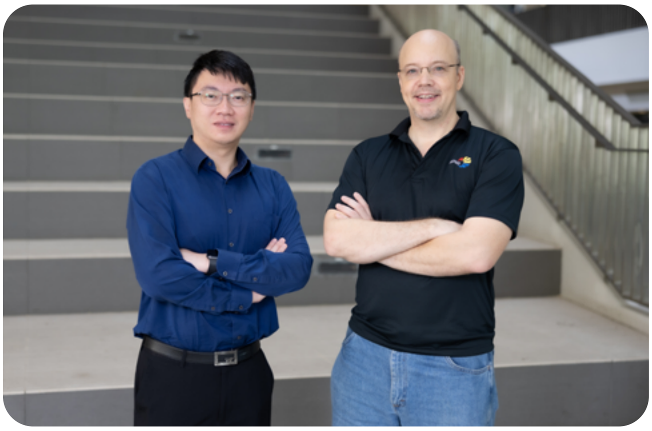
Assoc Prof Karl Erik BIRGERSSON
Dept of Mechanical Engineering (Modelling, optimisation and characterisation of solar cells; Modelling of PV modules)

Assoc Prof Aaron DANNER
Dept of Electrical and Computer Engineering (Application of ultra-thin films to high-efficiency silicon wafer solar cells)

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)

Emerging Solar Technologies Group



This group develops novel mathematical models and simulation tools for thin-film tandem solar cells.

Group Head

- Assoc Prof Karl Erik BIRGERSSON

Team Leader

- Assoc Prof Karl Erik BIRGERSSON (Thin-Film Device Modelling)

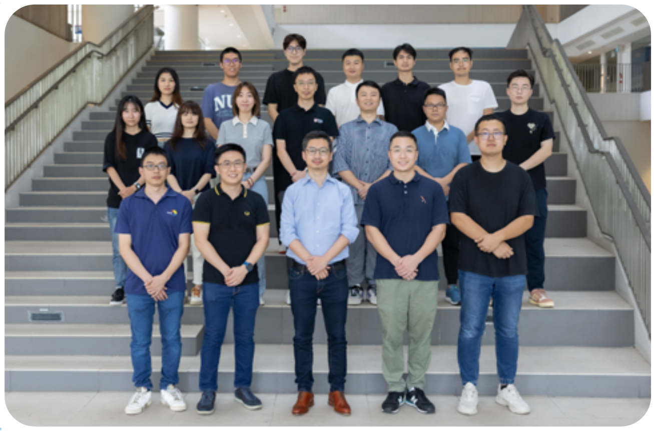
Adjunct Researcher

- Assoc Prof TAN Zhi Kuang

PhD Students

- TAN Hu Quee (until Jun 2023)
- TAY Shao En, Timothy
- ZHAO Xinhai (until Aug 2023)

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
- Dr JIA Xiangkun (until Jun 2023)
- Dr JIA Zhenrong
- Dr Donny LAI Jiancheng
- Dr LI Jia (until Oct 2023)
- Dr LIU Shunchang
- Dr NIU Xiuxiu (since Oct 2023)
- Dr WANG Tao (since Nov 2023)

PhD Students

- Ezra ALVIANTO
- CHEN Jinxi
- DONG Zijing
- GUO Xiao
- LEE Ling Kai
- LIANG Haoming
- SHI Zhuojie
- WANG Xi
- WANG Yuduan
- WEI Zhouyin
- ZHANG Yan (until Aug 2023)
- ZHOU Qilin

PV Devices Characterisation Group

The group focuses on the research & development of innovative characterisation & analysis solutions for solar photovoltaic materials and devices. Its activities involve disciplines of science and engineering, with applications covering the entire PV value chain. The group manages and operates the PV Devices Characterisation Laboratories at SERIS, which are equipped with a raft of measurement, diagnostics and analysis tools. In 2023, the Solar Cell Measurement Laboratory successfully completed the assessment by the Singapore Accreditation Council (SAC) for the ISO 17025:2017 SAC-SINGLAS accreditation, on the scope of measurement of photovoltaic current-voltage characteristics and spectral responsivity. Selected R&D activities in 2023 were:

i. Performing high-quality standard measurements (such as 1-Sun solar cell efficiencies) in accordance to the IEC 60904-1 international standard.
ii. Advanced electrical, optical and electronic characterisations to uncover and understand PV material and device properties.
iii. Analysis into solar cell efficiency limiting factors. This encompasses mainstream (e.g. Si based) and emerging materials (e.g. perovskites), as well as novel concepts in photovoltaics.
iv. Development of novel characterisation and metrology methods, for both research and industrial applications.

Group Head
- Dr CHOI Kwan Bum

Team Leaders
- Dr CHOI Kwan Bum (Solar Cell Testing, Acting)
- Dr WANG Puqun (Advanced Characterisation)

Adjunct Researcher
- Assoc Prof Aaron DANNER

Research Scientists / Engineers
- Elisaveta UNGUR
- YE Jiayi

PhD Students
- Khalid Ibrahim A ABU WARDAH (since Aug 2023)
- Sai Prashanth JOSYULA
- LAN Yuchi
- Laxmi NAKKA

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 deployment of PV technologies in Singapore and abroad, and to support the transformation of the global energy systems towards sustainability, continuous improvements of the efficiency, manufacturing cost, and long-term stability of industrial solar cells and modules are required. This Cluster researches next-generation industrial solar cells and modules that provide superior performance and lower cost than today's technologies. The experimental work in our solar cell laboratories focuses on (i) low-cost high-efficiency devices based on monocrystalline silicon substrates and (ii) upscaling of perovskite-silicon tandem solar cells (SERIS flagship project). The Cluster also hosts, manages and operates the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics established at NUS in 2023. In December 2023, the Cluster had 26 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
(since Oct 2023)

Laboratory Manager

LAM Yiin Fan
(since Mar 2023)

NISCM Cluster

Advanced Solar Cells Group

Corporate Laboratory Group

Organisation chart of the Next-Generation Industrial Solar Cells and Modules Cluster (in Dec 2023)

Group Heads	Team Leaders
Prof Armin ABERLE Advanced Solar Cells	**Dr Nitin NAMPALLI** Heterojunction Solar Cells (until Sep 2023)
Dr Nitin NAMPALLI Corporate Laboratory (since Oct 2023)	**Dr Jeremie WERNER** Large-Area Tandem Cells (until Mar 2023)
Dr Pradeep PADHAMNATH Solar Cell Metallisation (until May 2023)	

Adjunct Researcher, NUS

Prof Armin ABERLE
Dept of Electrical and Computer Engineering (Photovoltaic materials, devices & modules)

Advanced Solar Cells Group

The Advanced Solar Cells Group focuses on the development and commercialisation of low-cost high-efficiency solar cells. 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 large (> 200 cm²) perovskite-silicon tandem solar cells with an efficiency target of > 30% (SERIS flagship project). A modern cleanroom lab (> 1200 m²) 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 & module fabrication, and related equipment R&D.

Group Head

- Prof Armin ABERLE

Team Leaders

- Dr Nitin NAMPALLI, Heterojunction Solar Cells (until Sep 2023)
- Dr Jeremie WERNER, Large-Area Tandem Cells (until Mar 2023)

Laboratory Manager

- LAM Yiin Fan (since Mar 2023)

Research Scientists / Engineers

- Dr Yu Jin JANG
- Dr Romika SHARMA (since Jun 2023)
- John Derek Dumaguin ARCEBAL
- Gabby Alonzo DE LUNA
- Kaylynn SEW (until Feb 2023)
- YAP Qi Jia

Technician

- CHOY Woon Loong (until Sep 2023)

PhD students

- Khalid Ibrahim A ABU WARDAH (since Aug 2023)
- Varsha DAHIYA
- Erik Maurits SPAANS

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 cm²) 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-m² 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 staff also have access to 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 Nitin NAMPALLI (since Oct 2023)

Principal Investigator

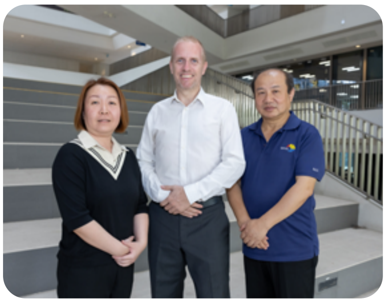
- Prof Armin ABERLE

Research Scientists / Engineers

- Dr Biplab GHOSH (since Apr 2023)
- Dr Yong Ryun KIM (since Jun 2023)
- Dr Krishna SINGH
- Dr Selvaraj VENKATARAJ
- Jammaal Kitz BUATIS
- Mohammed M S FARAJ (since Aug 2023)
- Rosalie Cleofe GUERRA
- Jeffrey Garcia ISON
- Maria Luz Loria MANALO
- Mohd Asri Bin MOHD HAMDAN
- Delio Justiniani PEREZ
- Ashwath Narayan RAVICHANDRAN (since May 2023)
- Louis Nicholas RETNAM (since Apr 2023)
- Ranjani SRIDHARAN
- 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 Mauro PRAVETTONI
Director

Dr LONG Jidong
Lab Manager

Mabel LEOW
Cluster Secretary

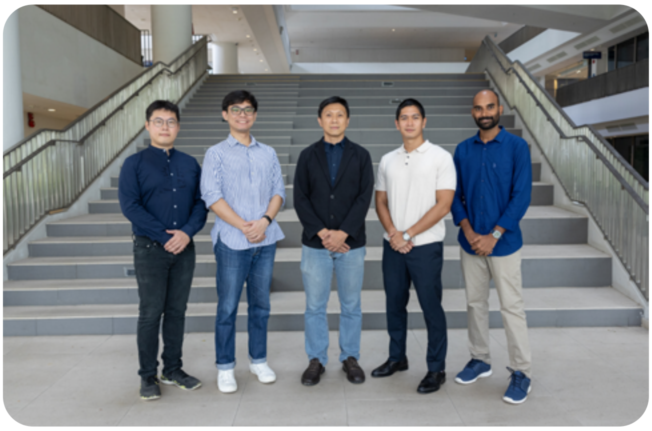
PVM Cluster

- **Building-Integrated PV Group**
- **PV Module Characterisation & Reliability Group**
  - **PV Module Characterisation Team**

Organisation Chart of PV Modules for Urban Solar Cluster (in Dec 2023)

Group Heads	Adjunct Researchers, NUS
Dr LEOW Shin Woei BIPV	**Prof Seeram RAMAKRISHNA** Dept of Mechanical Engineering (PV modules)
Dr Mauro PRAVETTONI PV Module Characterisation and Reliability	**Assoc Prof Karl Erik BIRGERSSON** Dept of Mechanical Engineering (Modelling of PV modules)

Building Integrated Photovoltaic (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 unconventional 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 advancement of visually aesthetic PV modules. The group is also active in PV module recycling research, exploring energy efficient methods to break up and separate constituent materials.

Group Head

- Dr LEOW Shin Woei

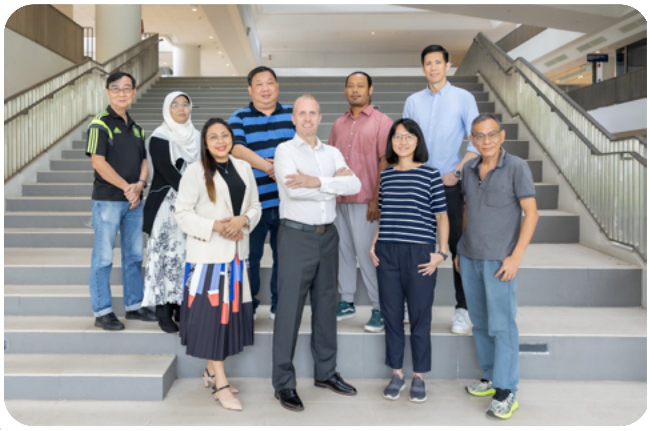
Research Scientists / Engineers

- Ryan ALINSOD (until May 2023)
- Dr CHEN Tianyi (since Jul 2023)
- Dr Carlos Enrico Cobar CLEMENT
- Dr LIANG Tian Shen (until Mar 2023)
- Srinath NALLURI
- Gavin Prasetyo RAHARJO

PhD Students

- Vundrala Sumedha REDDY
- SAW Min Hsian (until Jun 2023)
- Jovan TAN

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 Mauro PRAVETTONI

Research Scientists / Engineers

- Maryknol Estrada DELOS SANTOS (Quality & Safety)
- Henry LIM Kian Meng (Head of Metrology)
- Dr Amit Singh RAJPUT (until Mar 2023)
- Dr SAW Min Hsian (since Jul 2023)
- Jack Garcia VILLANUEVA

R&D Project Executive

- Zuraidah Binte JA'AFAR

Technicians

- CHOY Woon Loong (since Oct 2023)
- 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 and the economics of PV installations.

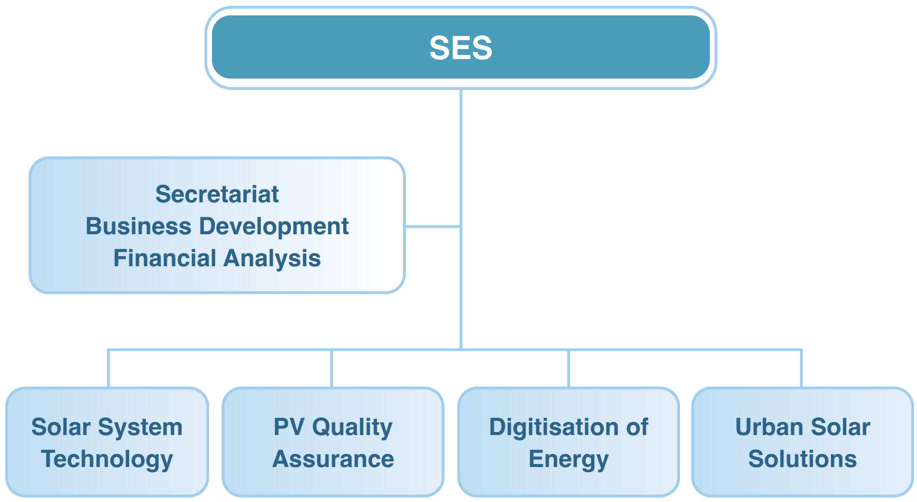
Cluster Director's Office

Dr Thomas REINDL
Cluster Director

Eddy BLOKKEN
Senior Business Development Manager

Dr Xiaoqi XU
Research Fellow

Marinel DUNGCA
Cluster Secretary



Organisation chart of Solar Energy Systems Cluster (in Dec 2023)

Group Heads

Dr Carlos RODRÍGUEZ
Solar System Technology

Rachel TAN Yek Wha
PV Quality Assurance

Dr Thomas REINDL
Digitisation of Energy (acting)

Dr Serena LIN Fen
Urban Solar Solutions

Team Leader

SOE Pyae
PV Monitoring

Adjunct Researchers, NUS:

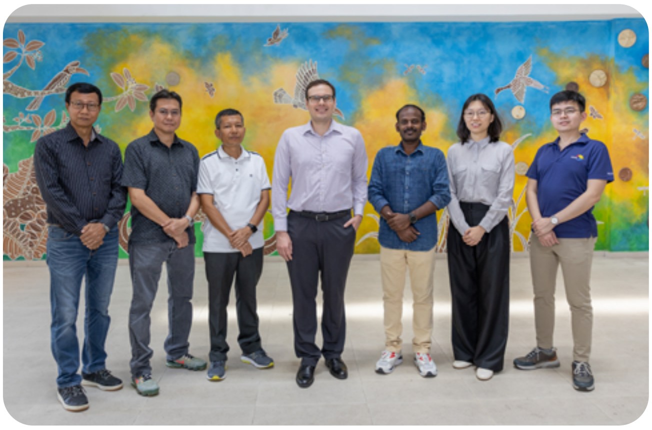
Assoc Prof Ashwin KHAMBADKONE
Dept of Electrical and Computer Engineering (Analysis and solutions for PV grid integration through energy system modelling and advanced power electronics & control for smart grids)

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

Research Scientists / Engineers
- Myint Khaing AUNG
- Dr Oktoviano GANDHI
- Haresh PANDIAN (until Mar 2023)
- TING Shi An (until Jan 2023)
- Lokesh VINAYAGAM
- Dr Jaffar Moideen YACOB ALI
- ZHAO Shengnan

Technicians
- David KHUP
- Jamil Bin ZAINAL

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 and energy yield assessments of PV systems to feasibility studies and comprehensive due diligence evaluations. Other important services are those of the "Owner's Engineer" which include PV installation inspection and evaluation, system performance assessment or energy audit, and testing and commissioning 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

Research Scientists / Engineers
- LOW Yiin Feng (until Aug 2023)
- Stanley PHUA Chee Siang
- Lutfi Irawan Bin RAWAN

Technicians
- Norhisham Bin HABDIN
- Muhammad Fahmie Bin IDRUS
- KOH Jun Yong
- Kendrick LOH Chun Ming
- 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 those 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 (Energy Market Authority). It combines several data streams from ground sensors, satellite imagery and numerical weather prediction models with advanced machine learning blending approaches to generate the best-possible combination of forecasting techniques over time horizons ranging from 5 minutes to 24 hours ahead. 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 allows asset owners to know their PV power generation in real time, which greatly assists trouble shooting and reporting to the authorities (e.g. to the grid operator). Under-performance can quickly be detected, and even predicted, by the group's "smart O&M" software solutions. The group also has in-depth knowledge in solar potential assessment (on building, neighbourhood and city-scale), 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
- Dr HE Yaohua
- KYAW Zin Win
- David LEE Soon Kiat
- Ivan POON Kin Ho
- Sholihin Bin SANI
- Dr SUN Huixuan
- Dr Gokhan Mert YAGLI

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 of existing infrastructures with PV, 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. A self-learning AI algorithm is being developed, in collaborations with the Digitisation of Energy (DoE) Group, for demonstrating an autonomous Agrivoltaics system. Furthermore, the group explores novel approaches for PV systems in the tropics, such as the integration of solar energy generation, cooling, waste heat harnessing and energy storage.

Group Head

- Dr Serena LIN Fen

Research Scientists / Engineers

- LIU Tianyuan, Damien
- Haresh PANDIAN (until Jul 2023)

SERIS
Central Services Units

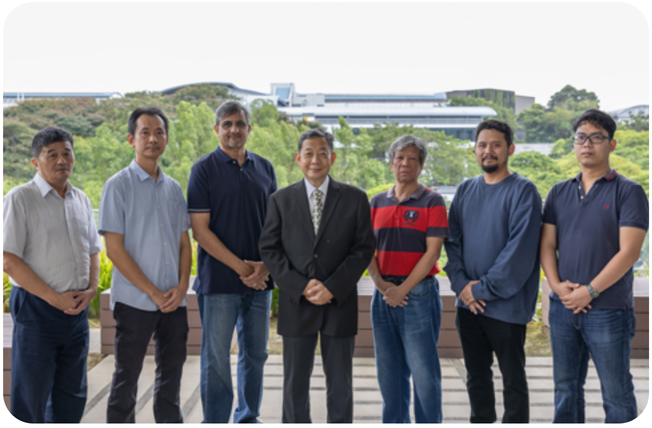
Administration

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

Director
- Shakander Singh CHAHAL

Team
- CHUA Ai Leng
- Sherlyn LOW Si Ning (until Nov 2023)
- Noor A'ishah Bte MOHAMAD
- Mitchell SENG Honghui

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

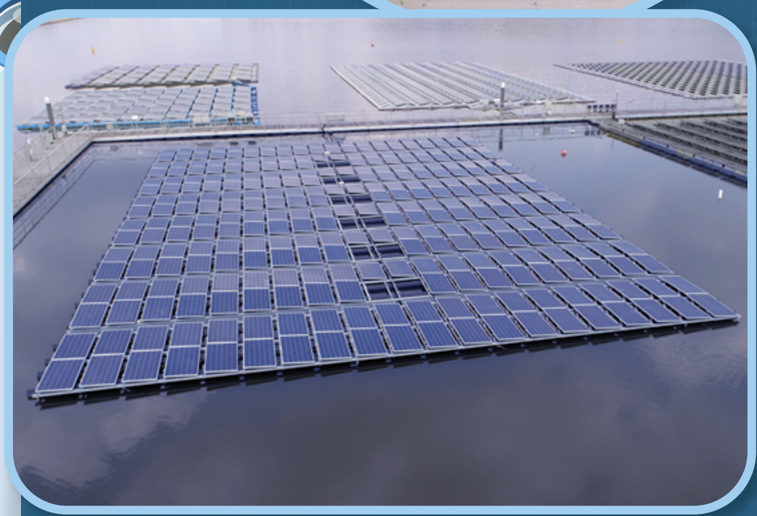
Team Leaders
- Peter LIM Young Leng (QESH)
- LOI Teck Shiun (Technical Infrastructure)

Laboratory Manager
- Dr Firdaus Bin SUHAIMI (Perovskite Solar Cell Lab)

Staff, Technical Infrastructure Team
- CHEANG Kong Heng
- CHEW Siow Choen
- Muhammad Shaheer HARDIP
- Ma Luisa OPENA (until Mar 2023)
- 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 2023, the Cluster's research focused on the development of single-junction perovskite cells, double- and triple-junction perovskite-silicon tandem cells (SERIS Flagship project), as well as the enhancement of our characterisation, modelling, simulation and reliability study capabilities for tandem cells. We are accelerating the development of perovskite-based solar cells by using low-cost coating methods for high-quality wide-bandgap semiconductors, making them an excellent choice for the top sub-cells in tandem applications paired with lower-bandgap bottom sub-cells such as silicon. 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.

1. Major activities / achievements in 2023

Single-junction perovskite solar cells on glass:
In April 2023, the Perovskite-based Multijunction Solar Cells Group demonstrated a new world-record efficiency of 24.35 ± 0.5% for a single-junction perovskite solar cell with an active area of 1 cm^2. This was achieved through passivation strategies and interfacial engineering, to enable both high fill factor and high open-circuit voltage. The certification measurement was performed at China's National PV Industry Measurement and Testing Centre (NPVM), and the 24.35 ± 0.5% result has been included in the Solar Cell Efficiency Tables (version 62, see Fig. 1) of the journal Progress in Photovoltaics which lists the record efficiencies of different types of solar cells with a minimum active area of 1 cm^2.

TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Silicon							
Si (crystalline cell)	26.8 ± 0.4[a]	274.4 (t)	0.7514	41.45[b]	86.1	ISFH (10/22)	LONGi, n-type HJT[4]
Si (DS wafer cell)	24.4 ± 0.3[a]	267.5 (t)	0.7132	41.47[c]	82.5	ISFH (8/20)	Jinko Solar, n-type
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[d,e]	80.3	NREL (4/14)	Solexel (35 µm thick)[5]
Si (thin-film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[d,f]	72.1	FhG-ISE (8/07)	CSG Solar (<2 µm on glass)[6]
III–V cells							
GaAs (thin-film cell)	29.1 ± 0.6	0.998 (ap)	1.1272	29.78[g]	86.7	FhG-ISE (10/18)	Alta Devices[7]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[8]
InP (crystalline cell)	24.2 ± 0.5[h]	1.008 (ap)	0.939	31.15[i]	82.6	NREL (3/13)	NREL[9]
Thin-film chalcogenide							
CIGS (cell) (Cd-free)	23.35 ± 0.5	1.043 (da)	0.734	39.58[j]	80.4	AIST (11/18)	Solar Frontier[10]
CIGSSe (submodule)	**20.3 ± 0.4**	**526.7 (ap)**	**0.6834**	**39.55[d,k]**	**75.1**	**NREL (5/23)**	**Avancis, 100 cells[11]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[c]	79.4	Newport (8/14)	First Solar, on glass[12]
CZTSSe (cell)	**12.1 ± 0.3**	**1.066 (da)**	**0.5379**	**35.29[k]**	**63.6**	**NPVM (4/23)**	**IoP/CAS[13]**
CZTS (cell)	10.0 ± 0.2	1.113 (da)	0.7083	21.77[l]	65.1	NREL (3/17)	UNSW[14]
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[i,h]	1.001 (da)	0.896	16.36[c]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	11.9 ± 0.3[h]	1.044 (da)	0.550	29.72[l]	75.0	AIST (2/17)	AIST[16]
Perovskite							
Perovskite (cell)	**24.35 ± 0.5[m]**	**1.007 (da)**	**1.159**	**25.60[k]**	**82.1**	**NPVM (4/23)**	**NUS/SERIS[17]**
Perovskite (minimodule)	22.4 ± 0.5[m]	26.02 (da)	1.127[d]	25.61[d,k]	77.6	NPVM (7/22)	EPFLSion/NCEPU, 8 cells[18]

Fig. 1: World record efficiency of 24.35% for a SERIS-made 1-cm² single-junction perovskite solar cell on glass.

Two-junction perovskite-silicon tandem solar cells:
In June 2023, the Multijunction Group successfully developed a 31.0% efficient two-junction perovskite-silicon tandem solar cell with very high open-circuit voltage of 2.01 V, using a commercially available Cz-based silicon bottom subcell. This was achieved by depositing a high-quality perovskite cell (1.71 eV) onto the textured silicon bottom cell (see Fig. 2). The cell efficiency was measured in-house at SERIS using a 1.0-cm^2 aperture mask. One of the core challenges in our device research is how to modify the path of the light rays inside the tandem architecture to further improve the short-circuit current density (presently 19.5 mA/cm^2).

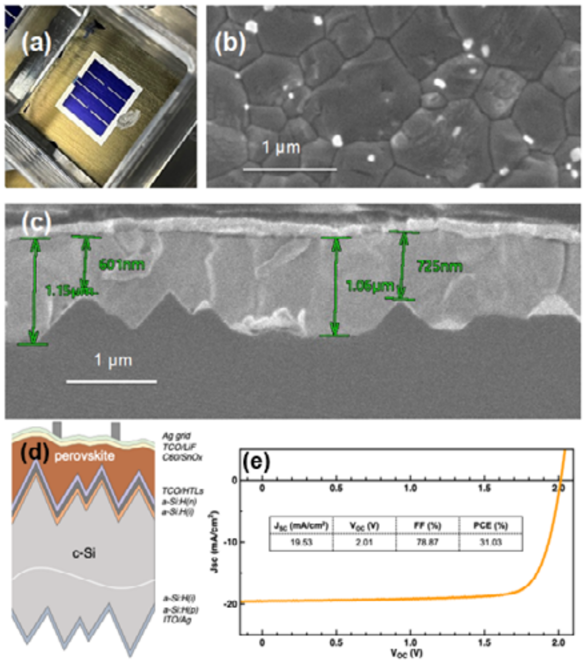


Fig. 2: (a) Photograph of the perovskite-Si tandem solar cell (1.0 cm² aperture area) with in-house measured efficiency of 31.0%; (b) Top-view SEM image of the 1.71-eV perovskite cell; (c) Cross-sectional SEM image of the perovskite-Si tandem solar cell; (d) Cross-sectional schematic of the perovskite-Si tandem solar cell; (e) SERIS-measured J-V curve of the 31.0% perovskite-Si tandem solar cell.

Triple-junction perovskite-perovskite-Si tandem cells

The Multijunction Group also developed efficient triple-junction solar cells in 2023, by combining a 1.55-eV perovskite middle cell with a 1.9-eV wide-bandgap perovskite top cell on a heterojunction Si bottom cell provided by an external collaborator. These solar cells have an aperture area of 1.0 cm^2 and use double-side textured n-type Cz-Si wafers for the bottom cell. Through careful process optimisation works, we achieved the deposition of a high-quality 1.55-eV perovskite middle cell on a textured Si bottom cell, whereby its top surface is smooth. A thin 1.9-eV perovskite top cell was then deposited onto the smooth middle cell surface. As shown in Fig. 3, one of these triple-junction solar cells made by SERIS in 2023 has an efficiency of 27.5%, as certified by the National Renewable Energy Laboratory (NREL) in the USA. This value is a new world record efficiency for perovskite-perovskite-silicon triple-junction solar cells.

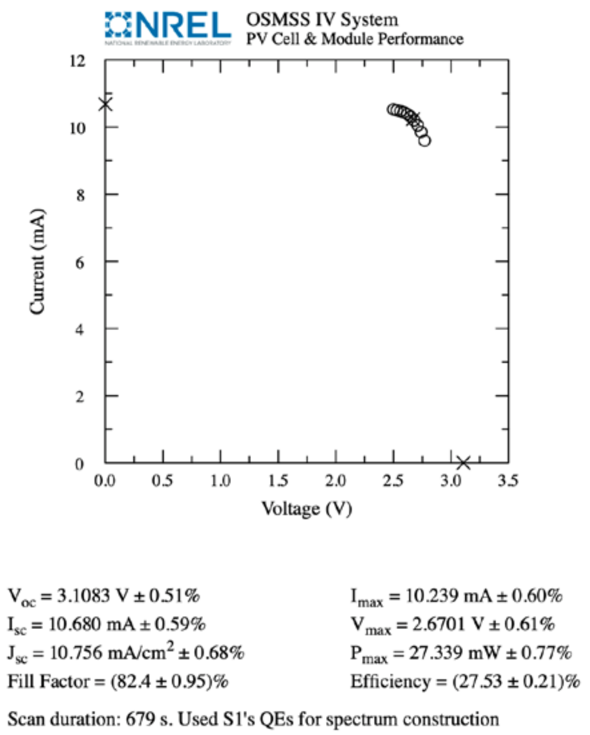


Fig. 3: NREL certified efficiency of 27.53% for a perovskite-perovskite-silicon triple-junction solar cell (1.00 cm^2 aperture area) made in SERIS on a textured Cz silicon bottom cell.

Advanced characterisation of perovskite cells and tandem cells

Being able to understand and measure the properties of thin films and related tandem solar cell materials is important for improving the solar cell device performance and reliability. SERIS is equipped with several advanced characterisation tools and will continue to develop new measurement and analysis techniques to provide deeper insights for device optimisation and process control. In 2023 we commissioned a new tandem solar simulator with A^+AA^+ classification, see Fig. 4. This machine allows fine spectral adjustments that provide a high-quality artificial solar spectrum for tandem cell measurements. The machine is also able to perform an asymptotic P_{max} measurement protocol, which is required for accurate I-V measurements of multi-junction devices featuring one or more perovskite sub-cells.

Fig. 4: Photograph of the new tandem solar cell simulator at SERIS for I-V measurements of tandem solar cells. The high-quality artificial solar spectrum (AM1.5G) and the I-V scanning algorithm enable accurate 1-Sun I-V measurement results for tandem solar cells.

Studying the long-term stability of perovskite solar cells and modules is another important research topic. One concern relates to potential-induced degradation (PID), which can occur in fielded PV modules due to high voltage stress (up to ~1000 Volts) between the module front glass pane and the solar cells. This degradation mechanism has been well investigated for silicon-based PV modules, but studies for perovskite-based devices have so far been very limited. In 2023 we performed a detailed experimental study on PID of glass-encapsulated perovskite solar cells and observed that there is severe PID due to sodium ion migration from the glass pane into the perovskite absorber layer (see Fig. 5). Furthermore, we discovered that adding a thin NiO_x blocking layer onto the transparent front electrode (TCO) of the perovskite solar cell helps to mitigate PID. More details on this PID research can be found in the R&D Chapter of this SERIS Annual Report 2023.

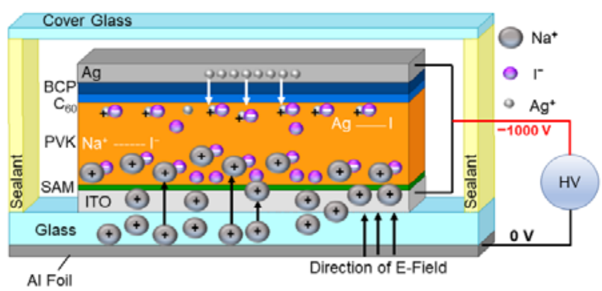


Fig. 5: Schematic of an encapsulated p-i-n perovskite solar cell. The PID experiment was conducted using the foil method where high-voltage stress is applied between the short-circuited perovskite solar cell and the aluminium foil on the front glass pane.

The team has also made good progress in using the Griddler simulation tool for tandem solar cell research. For example, we have studied the effects of different 2D design features on the efficiency of perovskite-biPoly™ silicon tandem cells, see Fig. 6. With further improvements, this approach can soon become very useful for detailed loss analyses of perovskite-Si tandem solar cells. More details on our PV material and device characterisation capabilities can be found in the Sections "Photovoltaic Devices Characterisation Laboratories" and "Characterisation and Testing of PV Materials and Solar Cells" of the SERIS Annual Report 2023.

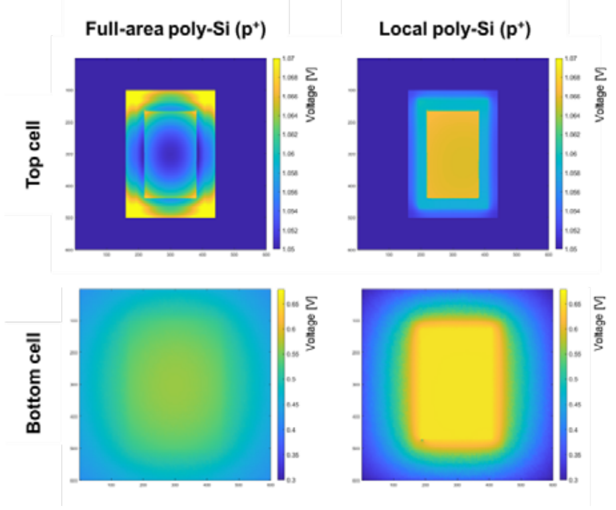


Fig. 6: Simulated diode voltage map of the perovskite top cell and the Si bottom cell of perovskite-biPoly™ tandem devices featuring (left) a full-area deposition of polycrystalline silicon and (right) a local-area deposition of polycrystalline silicon.

Modelling of perovskite-based tandem solar cells

We are developing advanced, calibrated, and experimentally validated mathematical models and simulation tools to support the fabrication and characterisation of tandem solar cells featuring a perovskite top cell on different types of bottom cells. For example, in 2023 we carried out a mixed-integer optimisation of the short-circuit current density of two-terminal perovskite-perovskite tandem solar cells operating under bifacial conditions. We explored a vast parameter space, considering over a million material combinations for the two subcells, varying thicknesses of the thin-film layers in the tandem solar cell, and several albedos. Additionally, we applied constraints to ensure energy-level matching, thereby promoting smooth charge carrier transport. The results of this optimisation are presented in Fig. 7, showcasing the optimised perovskite bandgaps and thicknesses, the top-subcell transmittance, and current matching for the 6 investigated albedo conditions.

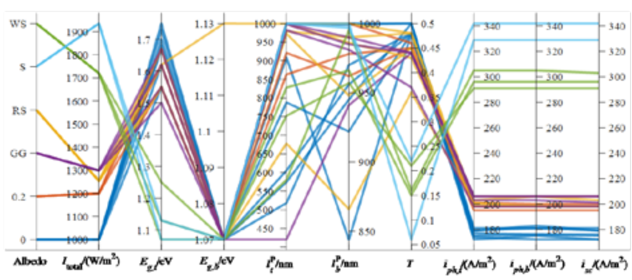


Fig. 7: Total irradiance, perovskite bandgaps and layer thicknesses, top subcell transmittance, photogenerated and short-circuit current densities of mixed-integer optimised two-terminal perovskite-perovskite tandem solar cells for monofacial conditions (albedo = 0), and bifacial conditions at 0.2 albedo, green grass (GG), roof shingle (RS), snow (S), and white sand (WS).

Selected publications:

Nakka, L., Luo, W., Aberle, A.G., Lin, F. Study of potential-induced degradation in glass-encapsulated perovskite solar cells under different stress conditions, Solar RRL 7, 2300100 (2023)

Zhao, X., Tan, H.Q, Birgersson, E., Xue, H. A mixed-integer optimisation for bifacial two-terminal perovskite-on-perovskite tandem solar cells, Solar Energy 262, 111905 (2023)

Chen, Y., Feng, J., Huang, Y. et al. Compact spin-valley-locked perovskite emission, Nature Materials 22, 1065 (2023)

Feng, J., Wang, X., Li, J. et al., Resonant perovskite solar cells with extended band edge, Nature Communications 14, 5392

2. Plans of NPVC Cluster for 2024

- Achieve 32% efficiency for a two-junction 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 that provide superior performance and lower cost than current technologies."

Research Focus / R&D portfolio of NISCM Cluster

In 2023, the cluster's research focus remained on next-generation industrial solar cells and modules that provide better PV efficiency and lower cost ($/W) than today's market leading technologies. The experimental work in our laboratories focused on (i) low-cost high-efficiency devices based on large (~244 cm^2) monocrystalline (Cz) silicon substrates and (ii) upscaling of perovskite-silicon tandem solar cells (SERIS flagship project) to industrial device areas of more than 200 cm^2. In addition, the cluster hosts, manages and operates the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics established at NUS in 2023.

1. Major activities / achievements in 2023

Further development of biPoly™ silicon solar cells ("TOPCon"):
In 2023 the Advanced Solar Cells Group successfully developed an ~23% efficient front selective biPoly™ silicon solar cell with 50% reduced silver (Ag) usage. The cells were fully fabricated in-house using screen-printed metal pastes obtained from our industry partners. A schematic cross-sectional representation of the solar cell is shown in Fig. 1. The group also developed an ultra-fast deposition process for in-situ doped TOPCon layers using the PECVD technology. These layers are being used for developing next-generation biPoly™ solar cells. Furthermore, the group developed "thin" oxygenated TOPCon layers providing > 730 mV implied open-circuit voltage and > 85% implied fill factor for biPoly™ solar cell precursors. These oxygenated layers are a promising candidate for realising high-quality bottom cells for perovskite-silicon tandem solar cells.

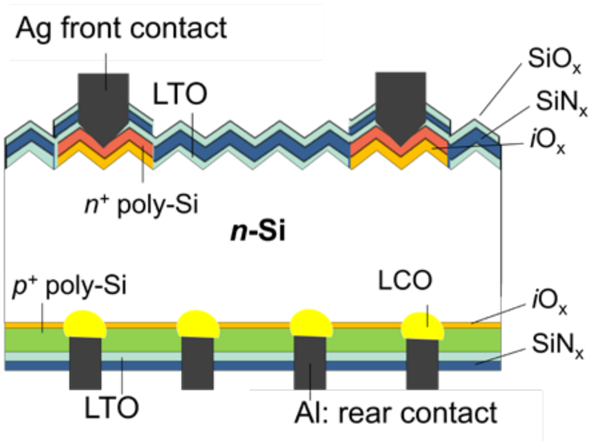


Fig. 1: Schematic representation of a front selective biPoly™ silicon solar cell developed by SERIS

Further development of silicon heterojunction solar cells:
In 2023 the Advanced Solar Cells Group completed the commissioning of a new PECVD equipment for doped silicon layers for silicon heterojunction solar cells. A starting efficiency of ~22% and open-circuit voltage of > 740 mV was achieved on fully in-house made heterojunction solar cells (Fig. 2) using amorphous-silicon passivation, industry-compatible *p*-doped layers using diborane-based boron doping, sputtered transparent conductive oxide (TCO) transport layers deposited using a unique low-sputter damage process and silver paste based screen-printed metallisation. An advanced post-cell annealing process for silicon heterojunction solar cells has also been developed in-house, with an efficiency boost of 0.7 - 0.9 $\%_{abs}$ achieved with a rapid (90 seconds) process. The group has published a roadmap to maximise the short-circuit current density (J_{sc}) of industrial silicon heterojunction solar cells. Furthermore, the group has begun the development of advanced PECVD-based 'window layers' to achieve high-performance silicon heterojunction cells as well as high-performance heterojunction-based bottom cells for perovskite-silicon tandem solar cells.

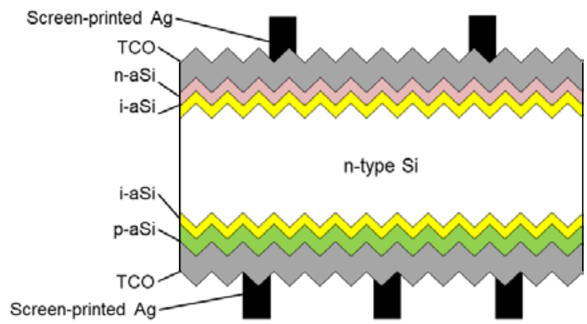


Fig. 2: Schematic representation of a silicon heterojunction solar cell

Upscaling of perovskite-silicon tandem solar cells to M2-size Cz silicon wafers (244 cm^2):
In 2023, within the framework of SERIS' Tandem cell flagship project, the Advanced Solar Cells Group successfully developed fully in-house fabricated large-area (244 cm^2) 2-terminal (2T) perovskite-silicon tandem solar cells with 1.7-eV perovskite top cells integrated with double-side textured silicon heterojunction bottom cells made on M2-size Cz silicon wafer substrates, as shown in Fig. 3. All layers of the perovskite cells were deposited using industrially compatible deposition processes. A low-temperature screen-printed metallisation was utilised on both sides of the 2T tandem solar cells. These tandem cells exhibit 1-Sun efficiencies of more than 17% (measured in-house with a class AAA I-V tester). This makes SERIS the only facility in Singapore, and one of the few laboratories in the world, capable of producing fully in-house fabricated perovskite-silicon 2T tandem solar cells on industrial-size (M2) silicon wafer substrates.

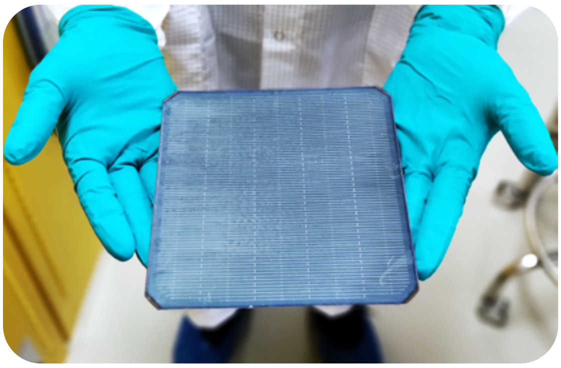


Fig. 3: Photograph of a perovskite-silicon 2T tandem solar cell on a M2-size (244 cm²) Cz silicon substrate with > 17% 1-Sun efficiency (measured in-house). Both the silicon bottom cell and the perovskite top cell were fully fabricated at SERIS.

Upscaling of perovskite-silicon 2T tandem solar cells to G12-size Cz silicon wafers (440 cm²):
Following the official launch of the REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics in June 2023, a new R&D group - the Corporate Laboratory Group - has been formed in the NISCM Cluster. By December 2023, the group's headcount had grown to 13 persons. The group is establishing new deposition tool capabilities at SERIS to enable perovskite-silicon 2T tandem solar cell fabrication on G12-size substrates (area 440 cm²) by 2025, with ambitions to demonstrate > 30% efficiency by 2027 on tandem cells made solely using ultrafast deposition equipment and industry-compatible large-area fabrication methods.

Selected publications:

- Spaans, E., Venkataraj, S., Aberle, A., Nampalli, N. Practical J_{sc} limits for silicon heterojunction (SHJ) devices: Insights from modelling; 13th International Conference on Crystalline Silicon Photovoltaics (SiliconPV) 2023.
- Padhamnath, P., Choi, W.J., De Luna, G., Arcebal, J.D., Rohatgi, A.; 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 256, p. 112351, 2023
- Padhamnath, P., Choi W.J., De Luna, G., Arcebal, J.D., Rohatgi, A.; 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; Solar Energy Materials and Solar Cells (under review)

2. Plans of NISCM Cluster for 2024

- Further development and upscaling of perovskite-silicon 2T tandem solar cells:
  - Demonstration of high-V_{oc} silicon bottom cells
  - Process development for wide-bandgap perovskite top cells on large Si wafers
  - Development of low-temperature metallisation processes suitable for perovskite solar cells
  - Procurement of advanced deposition tools for perovskite-silicon 2T tandem solar cell fabrication on G12-size substrates (area 440 cm²) by 2025 (Corp Lab project)
- Achievement of 26% efficiency for a perovskite-silicon mini-module with active area of at least 150 cm²
- Further enhance the fabrication and characterisation capabilities for perovskite-silicon tandem solar cells and mini-modules
- Conduct reliability studies for perovskite-silicon tandem solar cells and mini-modules
- Demonstration of > 24% efficiency for silicon heterojunction solar cells

PVM **Cluster Director's Foreword**

Dr Mauro PRAVETTONI
Director, PV Modules for Urban Solar Cluster

"Where development, reliability and circularity go hand in hand"

Research Focus / R&D portfolio of the PVM Cluster

In 2023, the Cluster's research focused on two main topics: (i) Reliability of PV modules, (ii) Building Integrated Photovoltaics (BIPV). In addition, the Cluster's research on recycling of PV modules has achieved a major milestone, i.e. the design of a PV Module Recycling Laboratory. With its planned kick-off in early 2024, SERIS will be one of the first solar research institutes worldwide to achieve the target of circularity: from PV 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 runs SERIS' ISO/IEC 17025 accredited laboratory for PV module testing, and the BIPV Group, which focuses on PV module development.

1. Major activities / achievements in 2023

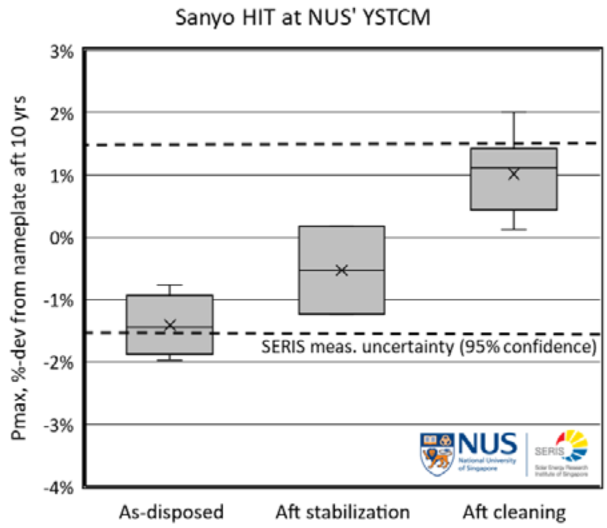
PV Module Characterisation & Reliability Group

The support of the local PV industry remained the focus of the group in 2023. This work has a strong influence on the quality of PV module manufacturing in Singapore and the region, and we are proud that the regional PV industry recognises our group's competence when dealing with quality matters.

The group conducted two major research campaigns in 2023: Pre-normative research towards a qualification programme for PV modules for floating PV systems, and the continuation of the activity of failure mode analysis of PV modules, with a particular focus on PV modules installed in Singapore during the last decade.

Within the framework of a research collaboration with Fred. Olsen Renewables and DNV on Floating PV, a risk matrix with over 100 different causes of PV module failure was developed, followed by a campaign of reliability tests aiming at the identification of some of the critical stresses for Floating PV. Preliminary results are presented in the Section "Update on R&D Projects 2023" of this SERIS Annual Report 2023. The activities have now advanced to the global level at the International Electrotechnical Commission (IEC), aiming at the formation of a New Project Team in the Technical Committee 82 Working Group 2 for the qualification of PV modules for floating applications.

The group has also continued to explore the specific degradation modes in PV modules installed during the last 10-15 years in tropical Singapore. In this period, the global PV manufacturing capacity grew massively from less than 20 GW per year to more than 300 GW in 2023, causing temporary shortages in the availability of several key module components (e.g. backsheets). These shortages forced many PV manufacturers to try new materials, for which we now start observing their actual real-world longevity. In 2023 we analysed PV modules from two different systems: A 15-year-old installation of mono-Si modules at Marina Barrage (showing outstanding performance of their robust Tedlar® backsheets, see the Section "Update on R&D Projects 2023"), and pioneering silicon heterojunction technology (HJT) modules from a 10-year-old installation in the testbed on the roof of the Yong Siew Toh Conservatory of Music (YSTCM) at NUS. The analysis of the field data of the latter is still ongoing and will only be released in 2024, but our preliminary data suggest that the performance degradation of these HJT modules (the former Sanyo HIT product, a real champion of innovative technology of that time) is well within the warranty offered by the manufacturer (< 1%/yr degradation compared with the nameplate power rating of the modules). This is an encouraging result for today's HJT module manufacturers such as REC in Singapore.



Relative deviation of the SERIS-measured 1-Sun P_{max} from the nameplate power for a set of 8 Sanyo HIT modules, after 10 years of operation on the roof of the Yong Siew Toh Conservatory of Music (YSTCM) at NUS. (Left) As-disposed modules; (Middle) After stabilisation of the metastability of HJT modules; (Right) After cleaning of the modules to remove soiling.

Selected publications:

- Pravettoni, M., Rajput, A. S. On the metastability of silicon heterojunction solar photovoltaic modules MRS Bulletin 48, (2023)
- Pravettoni, M., Long, J. Reliability of modules in floating photovoltaics: stresses, severities and tests. Plenary Talk, 50th IEEE Photovoltaic Specialists Conference, San Juan, Puerto Rico (2023)

BIPV Group

The group's activities focus on the development of innovative BIPV products. In 2023, significant efforts went into the concept of "pixel PV". These are small PV modules for a more configurable design, with investigation of new mechanical and electrical connection methods, in order to mitigate the negative effects of complex shading environments that are typical for vertical PV installations in urban environments.

Another important activity has been a collaboration with the Singapore Civil Defence Force (SCDF) on fire testing of BIPV modules. The objective is to help SCDF with test designs on module and system levels. This would provide a better understanding of the actual fire risks and eventually lead to a possible easing of the current regulatory framework. One solution could be to develop light-weight non-combustible (or fire resistant) materials and coatings for BIPV products.

Building on the success of its "Peranakan" PV module, the group continued its research on optimised coloured PV solutions. We explored lower-cost options (e.g. film inserts instead of printing on glass) and options giving lower transmission losses (e.g. interference inks). Furthermore, we worked on improving the "pointillism" technique introduced by us in 2022.

Beyond the product development activities, the group also expanded the work on Building Information Modelling (BIM), which is a collaborative and data-driven process that entails creating and managing digital representations of a building's physical and functional characteristics. Adding BIPV module propertied to BIM is one of the technical milestones of SERIS' BIPV flagship project. It progresses from geometric modelling (3D) to time scheduling (4D), cost estimation (5D), energy simulation for sustainability (6D), and encompassing management and operation aspects (7D). A comprehensive literature review and the development of a framework (including interviews with Singapore government agencies and the development of guidelines based on current local regulations) were the focus of our BIM activities in 2023.

Urban PV solutions also include PV integrated in the infrastructure, among which noise barrier PV has been a research activity of our group for several years. In 2023 this topic was revisited with Singapore's Land Transport Authority (LTA), with the identification of three target areas: (i) a road noise barrier for new sites (or replacement of decommissioned noise barriers instead of retrofitting), with the possibility of modular designs and incorporation of noise absorption features; (ii) noise barrier for train tracks (Singapore MRT), with the proposal of a test site at the MRT depot to minimise disruptions of the normal traffic flow; (iii) a temporary noise barrier for construction sites.

2. Plans of PVM Cluster for 2024

- Pre-normative reliability tests for perovskite modules and perovskite-silicon tandem modules
- Design and installation of an indoor testbed for PV modules for floating PV, including water impact, water immersion and thermal shock tests
- Inauguration and operation of the new PV Module Recycling Laboratory at CleanTech Park
- Development of a BIM BIPV library
- Realisation of a testbed for light-weight PV modules (for retrofitting of buildings) and for plug & play BIPV at CleanTech Park.

SES **Cluster Director's Foreword**

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

"2023 saw a major milestone in the deployment of solar PV in Singapore: The city state has surpassed 1 GW_p of installed capacity, which makes it one of the most solar-dense cities in the world. We are proud having contributed to this achievement through innovations, technical standards, quality assurance, and policies tailored to Singapore's densely built-up urban environment and tropical climate conditions."

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 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 2023

Solar System Technology Group

Floating Solar Systems:
In 2023, the Solar System Technology Group expanded its global leadership in the area of floating PV (FPV). Our research work on near-shore and off-shore Floating Solar - jointly with key industry partner Fred. Olsen Renewables (FOR) - has led to an in-depth understanding of the challenges faced by floating PV installations in maritime conditions. This has helped FOR to become a leading project developer and future operator of large-scale near- and offshore FPV power plants. In addition, novel and possibly game-changing technologies that enable such FPV plants are being developed.

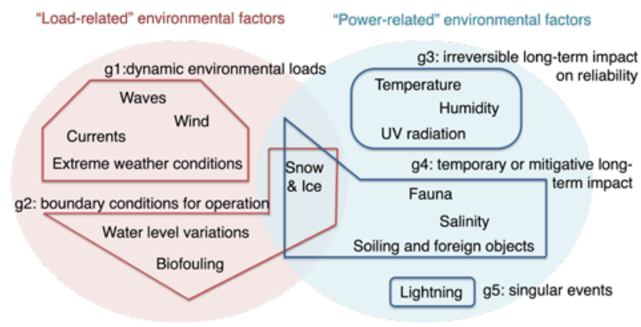
As part of this long-term collaboration, the SERIS team has developed an algorithm with very high time resolution to predict the mismatch losses in FPV modules due to variations in module tilts when experiencing waves under different wave characteristics, FPV parameters and site characteristics. The algorithm is being tested against the real performance data from FOR's near-shore FPV testbeds. Furthermore, a screening of potential failures and their root causes on both sub-system and component level has been conducted. This very detailed failure mode and effects analysis (FMEA) study has identified more than 100 failure modes as well as suitable mitigation measures.

The group also continues to analyse the operation and long-term reliability of the existing FPV testbed in Singapore's Tengeh reservoir, which in turn helps to better understand the economic viability of FPV systems. Potential environmental causes for failures in FPV systems have been identified, and the relationships and inter-dependencies of these causes have also been studied (see figure).

SERIS has also made good progress in the collaboration projects with EDPR (setting up a near-shore floating PV testbed in Singapore in combination with energy storage systems, funded by an EMA-KETEP grant) and Keppel Infrastructure (development of utility-scale floating hybrid renewable energy systems, which are designed to integrate other renewable energy technologies, such as tidal energy turbines or wind turbines).

Internationally, SERIS' in-depth know-how on Floating Solar has been highly valued by financiers and project developers from around the world. For example, in calendar year 2023, SERIS was involved in feasibility studies and system design of FPV systems with a combined capacity of ~1.8 GW_p.

More details on SERIS' Floating Solar flagship project can be found on page 55 of this Annual Report.



Environment-related root causes for failures in FPV systems

Other PV system research areas:
Beyond floating solar, the group also enhanced its capabilities in field testing of PV technologies in real-world conditions. SERIS' well-known Outdoor Module Testing (OMT) centre has been upgraded to also accommodate the new PV modules made from larger wafers which can reach maximum power levels of 700 W_p.

The group also signed a Research Collaboration Agreement with a major regional developer, for which SERIS has designed, planned and implemented a 5 MW_p solar technology testbed featuring various solar cell architectures, module configurations, tracking and storage technologies.

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 Marina Barrage and is operated in close collaboration with Singapore's national water agency PUB. 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 provides feasibility studies, lender's technical due diligence, and testing & commissioning (T&C) services for solar PV projects in Singapore and the region. In 2023, the group worked closely with the Housing and Development Board (HDB) to act as their representative overseeing the construction phase of PV installations on HDB residential buildings, largely related to the SolarNova project, Phases 4 & 6 (SN4, SN6). The group also carries out the T&C work for the other government agency installations (i.e., non-HDB blocks). In addition, the team won Owner's Engineering or T&C contracts for major installations in Singapore from both the public and private sectors.

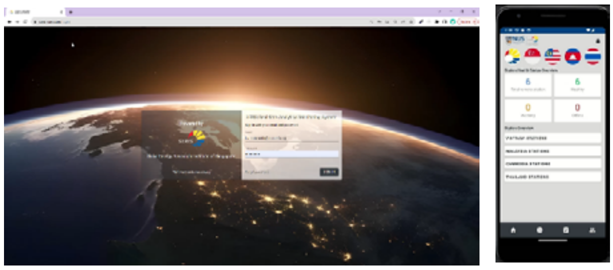
The group is also strongly involved in cross-group activities in the SES Cluster, such as the "smart O&M" project, and acts as the interface to the PV DOCTOR™ spin-off (see figure and also page 12 of this Annual Report).

Cross-group assessment of a C&I rooftop installation in Singapore led by the PVQA Group, implementing a number of on-site testing under the PV DOCTOR™ framework (here: EL analysis identifying microcracks in the installed PV modules).

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 2023, the PV Monitoring Team signed a major contract with NUS University Campus Infrastructure (UCI) to deploy 60 remote monitoring stations to capture the output and performance of the ~10 MW_p of installed solar PV capacity on the main NUS campus (Kent Ridge). Leveraging its in-house developed "live" PV monitoring system and solar asset management platform (see figure), SERIS will also provide the mandatory consolidation and real-time reporting to Singapore's grid operator (EMA, Energy Market Authority of Singapore). Furthermore, the transfer of SERIS' entire monitoring solution to the cloud has been finalised in 2023, and physical servers are now only used as back-up to increase system resilience in case of data transmission failures. Currently, more than 100 remote monitoring stations (with multiple loggers per site) in 12 countries are in operation (both research and commercial projects). The solar forecasting software has also been added to the solar asset management platform, which is designed for scalability and thus ready for future expansion and commercialisation.



Landing page / sign-in page and mobile app of SERIS' in-house developed Solar Asset Management platform.

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 allows EMA to anticipate the solar power output ahead of time and inform the market operator, Energy Market Company (EMC), of the expected solar power generation in the next bidding cycle(s). EMC has issued a circular to inform market participants that such solar forecasts will be provided going forward. 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. 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 team also published a comprehensive review paper on the value of solar forecasting for both grid operators and energy markets. A short version of the paper can be found on page 75 of this Annual Report.

In parallel, the group further evolved its activities in the area of predictive maintenance of solar PV systems ("smart O&M"). Using a number of test cases, the project team developed its own PV system simulation algorithm, which has greater flexibility than commercially available software tools and can be directly linked with on-site measurements (e.g., string I-V curves) for faster assessment of the root causes of system faults or under-performance (e.g., due to partial shading or potential-induced degradation, PID). As a result, a software tool was developed that automates the assessment of string IV curves from field measurements and derives both series and shunt resistance values – which then can be linked to known module failures.

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 performing glare studies for solar developers. As the potential glare from solar installations is becoming increasingly important in Singapore's densely built-up environment, the team has developed its own glare assessment tool, which also takes into account potential objects in the line-of-sight. Those objects (e.g., a building) could be either between the sun and the PV system (during certain times of the day) or between the PV system and the observation points. Commercially available software tools (e.g., those designed for glare studies around airports) typically do not include this feature of partially interrupted line-of-sight. The in-house developed software was presented in September 2023 at the 40th EU PVSEC in Lisbon and has raised interest from both industry and academy for possible collaborations.

Urban Solar Solutions Group

The Urban Solar Solutions (USS) Group has been established in early 2023 and 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. Trying to overcome the space scarcity here, the group's research focuses on the multiple use of existing infrastructures with PV, for example overarching of carparks, roads, flood canals and "busy" rooftops. The project scopes include design, test-bedding, and optimisation of various novel urban PV concepts.

A key achievement of the group in 2023 was the implementation of two testbeds for agrivoltaics (i.e., agriculture & PV) at the Yuhua Agritech Solar (YAS) Living lab, which was officially opened by the Minister for Sustainability and the Environment (MSE), Ms Grace Fu in November 2023. The two testbeds are designed to comparatively test different growing and control technologies leveraging a novel, self-developed rotatable PV louver roof design. For more details, please refer to page 80 of this Annual Report.

Aerial view of the two SERIS testbeds at the Yuhua Agritech Solar (YAS) Living Lab that was inaugurated by the Minister for Sustainability and the Environment (MSE), Ms Grace Fu, in November 2023

Selected publications:

- Zhang, W., Inglin, C., Reindl, T. et al. SEAS-SCDF PV Fire Safety Handbook (Preliminary version) - Best Industry Practices: Part I: Fire Safety Requirements for roof-mounted Photovoltaic (PV) Panel Installations. Published online by the Sustainable Energy Association of Singapore (SEAS) with input from Singapore Civil Defence Force (SCDF), Nov 2023
- Gandhi, O., Zhang, W., Kumar, D.S., Rodríguez-Gallegos, C.D., Yagli. G.M. The value of solar forecasts and the cost of their errors: A review. Renewable and Sustainable Energy Reviews, vol. 189, Part B, 113915 (published online 8 Nov 2023)
- Zhao, S., Low, Y.M., Rodríguez-Gallegos, C.D., Reindl, T. Potential root causes for failures in floating PV systems. Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2023), 11-16 Jun 2023, Australia (in press)

2. Plans of SES Cluster for 2024

- Further expand the activities in the Floating Solar flagship project, especially for near-shore and off-shore areas, also with combined uses such as hybrid renewable energy systems.
- Carry out research activities in the two newly set-up agrivoltaics testbeds at Yuhua Agritech Solar (YAS) Living Lab
- Design and test novel deployment options, e.g., for over-building existing infrastructures.
- Finalise the regional operational solar forecasting model for individual solar farms and start to commercialise the technology.
- Optimise the developed "smart O&M" algorithms for application in a broader range of solar systems.
- 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 2023**

SERIS Flagship Projects

SERIS is working on three flagship research projects to strengthen and deepen its solar capabilities.

1. Thin-film on silicon tandem solar cells
2. Building-integrated photovoltaics (BIPV)
3. Floating solar systems

Selected R&D Projects

1. Refining the substrate surface morphology for achieving efficient inverted perovskite solar cells
2. Study of potential-induced degradation and its mitigation in glass-encapsulated perovskite solar cells
3. 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
4. Photoluminescence imaging on silicon modules using LED floodlights
5. A study of PV module degradation after 15 years of operation at Singapore's Marina Barrage
6. Reliability of modules in floating photovoltaics: environmental conditions, severities and stress tests
7. 3D glare assessment tool for photovoltaic (PV) deployment in high-density urban environments
8. The value of solar forecasts and the cost of their errors
9. Levelised cost of PV integration for distribution networks
10. Agrivoltaics (Agri + PV) – multiple use of space in dense urban settings like Singapore

SERIS **Flagship Project**

Thin-film on silicon tandem solar cells

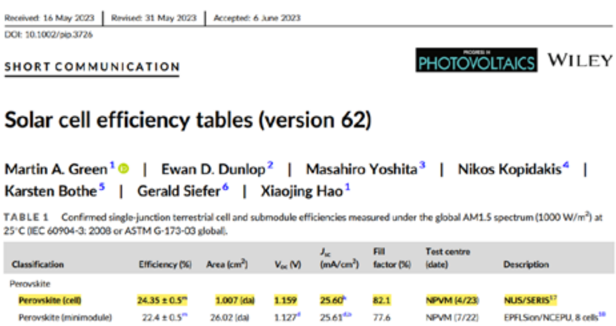
Asst Prof HOU Yi, Dr CHOI Kwan Bum, Assoc Prof Erik BIRGERSSON, Prof Armin ABERLE

Introduction

Singapore's space constraints require 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) and a practical limit of about 27%, stacking a second solar cell with different electronic properties, characterised by a larger electronic bandgap, onto a silicon cell to create a multi-junction (or "tandem") solar cell offers the potential for much higher efficiencies. For a dual-junction Si-based tandem solar cell, the theoretical efficiency limit under the AM1.5G solar spectrum is 42.5%, whereby a practical cell efficiency limit of around 35% seems possible in future mass production (beyond 2030). Given their exceptional efficiency prospects, tandem solar cells are of very high importance to Singapore's solar sector, for both the manufacturing and deployment sectors. This flagship project focuses primarily on exploring low-cost wide-bandgap thin-film materials, in particular inorganic halide perovskites, as the absorber layer of the top cell on a silicon bottom cell. In 2023, our research efforts within the project focused on the development of single-junction perovskite cells, perovskite-Si tandem cells, perovskite-perovskite-Si tandem solar cells, as well as the enhancement of our characterisation, modelling, simulation and reliability study capabilities for tandem cells.

Single-junction perovskite solar cells

The Perovskite-based Multijunction Solar Cells Group is at the forefront of advancing wide-bandgap perovskite PV technology, with a particular focus on enhancing the uniformity of the interface layer and the perovskite layer in single-junction perovskite solar cells. Through meticulous efforts aimed at reducing recombination losses at the interface of the perovskite layer and improving the uniformity of the interface layer, in 2023 the group has achieved a new world record of 24.35 ± 0.5% for the 1-Sun efficiency of single-junction perovskite solar cells with an area of 1.0 cm^2. This result has been certified by China's National PV Industry Measurement and Testing Centre (NPVM), and has been included in the latest edition of the Solar Cell Efficiency Tables (version 62) published in the Journal of Progress in Photovoltaics, see Fig. 1.



Received: 16 May 2023 | Revised: 31 May 2023 | Accepted: 6 June 2023
DOI: 10.1002/pip.3726

SHORT COMMUNICATION

PROGRESS IN PHOTOVOLTAICS WILEY

Solar cell efficiency tables (version 62)

Martin A. Green[1] | Ewan D. Dunlop[2] | Masahiro Yoshita[3] | Nikos Kopidakis[4] | Karsten Bothe[5] | Gerald Siefer[6] | Xiaojing Hao[1]

TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m²) at 25°C (IEC 60904-3: 2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	Fill factor (%)	Test centre (date)	Description
Perovskite							
Perovskite (cell)	24.35 ± 0.5[m]	1.007 (da)	1.159	25.60[s]	82.1	NPVM (4/23)	NUS/SERIS[17]
Perovskite (minimodule)	22.4 ± 0.5[m]	26.02 (da)	1.127[t]	25.61[d,s]	77.6	NPVM (7/22)	EPFLSion/NCEPU, 8 cells[18]

Fig. 1: Certified efficiency of 24.35 ± 0.5% of a SERIS-made single-junction perovskite solar cell (1.0 cm^2) included in the latest Solar Cell Efficiency Tables (version 62) in the journal Progress in Photovoltaics.

Dual-junction perovskite-Si tandem solar cells on textured heterojunction Cz Si bottom cells

Building on the success of its efficient wide-bandgap single-junction perovskite cells, the Perovskite-based Multijunction Solar Cells Group has made excellent progress in 2023 with the development of perovskite-Si tandem solar cells in collaboration with an external partner. These tandem cells have an area of 1.0 cm^2 and use double-side textured heterojunction Si bottom cells made on n-type Cz Si wafers. Through rigorous optimisation of a fully solution-based perovskite processing technique, the group has achieved the deposition of high-quality 1.71-eV perovskite thin films (over 1 micron thick) on textured heterojunction Si bottom cells, as shown in the cross-sectional electron microscope image in Fig. 2(c).

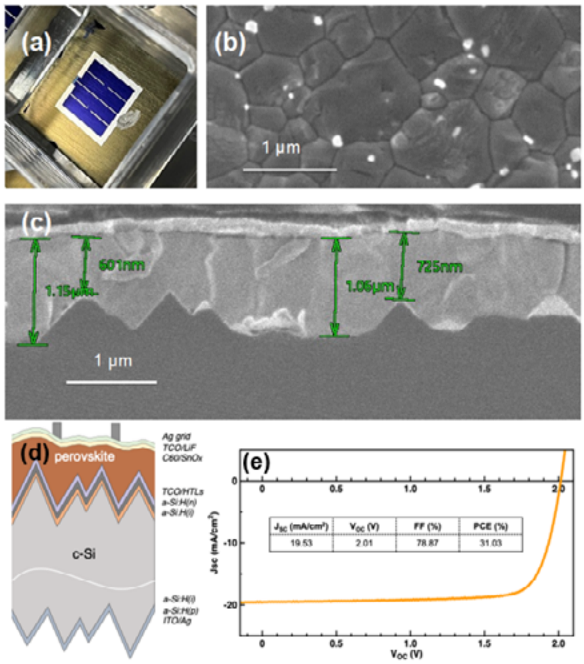
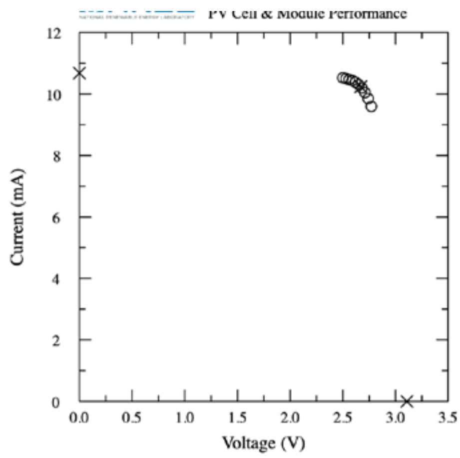


Fig. 2: (a) Photograph of the perovskite-Si tandem solar cell (1.00 cm^2 aperture area) with in-house measured efficiency of 31.0%; (b) Top-view SEM image of the 1.71-eV perovskite cell; (c) Cross-sectional SEM image of the perovskite-Si tandem solar cell; (d) Cross-sectional schematic of the perovskite-Si tandem solar cell; (e) SERIS-measured J-V curve of the 31.0% perovskite-Si tandem solar cell.

The group's research also led to excellent progress with the electrical 1-Sun performance of these 2-terminal (2T) perovskite-Si tandem solar cells. As shown in Fig. 2(e) our best cell has an open-circuit voltage (V_{oc}) of 2.01 Volts, which is the highest voltage ever reported for a highly efficient perovskite-Si tandem solar cell. The power conversion efficiency (PCE) of 31.0% (measured in-house) of this cell is a remarkable result considering the fact that the cell has a heterojunction Si bottom cell made from a low-cost commercial Cz Si wafer with thickness of well below 200µm (note that all reported perovskite-silicon tandem cells with efficiency > 31% were made on expensive float-zone (Fz) silicon wafers with thickness > 200µm). The rapid progress made by the group in 2023 provides a clear pathway towards a perovskite-silicon tandem cell efficiency of 33% on low-cost Cz Si wafers in the near future, by further improving the fill factor (FF) and the short-circuit current density (J_{sc}) of the devices.

Triple-junction perovskite-perovskite-Si tandem cells on textured heterojunction Cz Si bottom cells

The Perovskite-based Multijunction Solar Cells Group has also developed efficient triple-junction solar cells in 2023, by combining a 1.55-eV perovskite middle cell with a 1.9-eV wide-bandgap perovskite top cell on a heterojunction Si bottom cell provided by an external collaborator. These solar cells have an aperture area of 1.00 cm^2 and use double-side textured n-type Cz-Si wafers for the bottom cell. Through careful process optimisation works, the group achieved the deposition of a high-quality 1.55-eV perovskite middle cell on a textured Si bottom cell, whereby its top surface is smooth. A thin 1.9-eV perovskite top cell was then deposited onto the smooth middle cell surface. As shown in Fig. 3, one of these 2T triple-junction solar cells made by SERIS in 2023 has an efficiency of 27.53%, as certified by the National Renewable Energy Laboratory (NREL) in the USA. This value is a new world record efficiency for perovskite-perovskite-silicon triple-junction solar cells.



V_{oc} = 3.1083 V ± 0.51%
I_{sc} = 10.680 mA ± 0.59%
J_{sc} = 10.756 mA/cm^2 ± 0.68%
Fill Factor = (82.4 ± 0.95)%

I_{max} = 10.239 mA ± 0.60%
V_{max} = 2.6701 V ± 0.61%
P_{max} = 27.339 mW ± 0.77%
Efficiency = (27.53 ± 0.21)%

Scan duration: 679 s. Used S1's QEs for spectrum construction

Fig. 3: NREL certified efficiency of 27.53% for a perovskite-perovskite-silicon triple-junction solar cell (1.00 cm^2 aperture area) made in SERIS on a textured Cz silicon bottom cell.

Industrial size perovskite-silicon tandem solar cells on textured silicon heterojunction bottom cells

In 2023, the Advanced Solar Cells Group in SERIS' NISCM Cluster has successfully developed fully in-house fabricated 2T perovskite-silicon tandem solar cells with 1.7-eV perovskite top cells integrated with double-side textured silicon heterojunction bottom cells made on M2-size Cz silicon wafer substrates (area 244 cm^2), as shown in Fig. 4. All layers of the perovskite cells were deposited using industrially compatible deposition processes. A low-temperature screen-printed metallisation was utilised on both sides of the 2T tandem solar cells. These tandem solar cells exhibit 1-Sun efficiencies of more than 17% (measured in-house with a class AAA I-V tester). This makes SERIS the only facility in Singapore, and one of the few laboratories in the world, capable of producing fully in-house fabricated perovskite-silicon 2T tandem solar cells on industrial-size silicon wafer substrates. SERIS has plans to upgrade the existing tool capabilities to enable tandem solar cell fabrication on G12-size substrates (area 440 cm^2) by 2025.

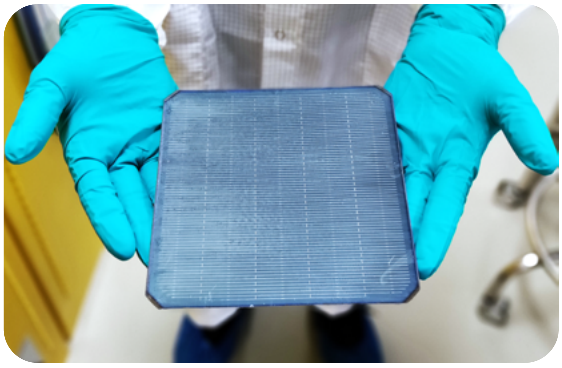


Fig. 4: Photograph of a perovskite-silicon 2T tandem solar cell on a M2-size (244 cm^2) Cz silicon substrate with > 17% 1-Sun efficiency (measured in-house). Both the silicon bottom cell and the perovskite top cell were fully fabricated at SERIS.

Advanced characterisation of perovskite cells and tandem cells

Being able to understand and measure the properties of thin films and related tandem solar cell materials is important for improving the solar cell device performance and reliability. SERIS is equipped with several advanced characterisation tools and will continue to develop new measurement and analysis techniques to provide deeper insights for device optimisation and process control. In 2023 we commissioned a new tandem solar simulator with A^+AA^+ classification. The excellent artificial solar spectrum provided by this machine enables accurate 1-Sun I-V measurements of tandem solar cells. Furthermore, through adjustment of its optics, it is possible to perform some changes on the spectrum that are necessary for accurate tandem cell measurements, and in conjunction with the asymptotic P_{max} measurement protocol necessary for I-V measurements of perovskite solar cells.

Fig. 5: Photograph of the new tandem solar cell simulator at SERIS for I-V measurements of tandem solar cells. The high-quality artificial solar spectrum (AM1.5G) and the I-V scanning algorithm enable accurate 1-Sun I-V measurement results for tandem solar cells.

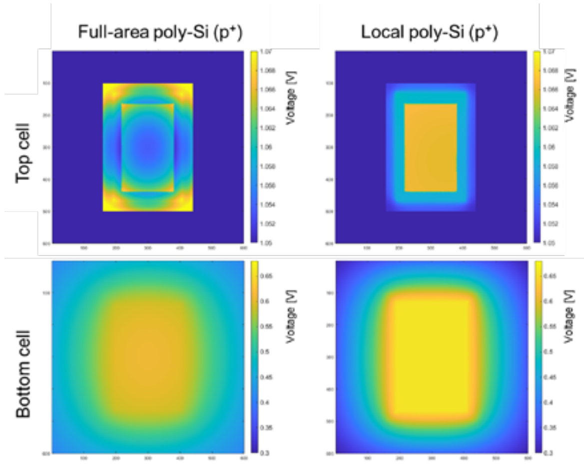


Fig. 6: Simulated diode voltage map of the perovskite top cell and the Si bottom cell of perovskite-biPoly™ tandem devices featuring (left) a full-area deposition of polycrystalline silicon and (right) a local-area deposition of polycrystalline silicon.
(Image source: Fig. 6 in Puqun Wang, Tianyuan Liu, 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)

The team has also made good progress in using the Griddler simulation tool for tandem solar cell research. For example, we have studied the effects of different 2D design features on the efficiency of perovskite-biPoly™ silicon tandem cells, see Fig. 6. With further improvements, this approach can soon become very useful for detailed loss analyses of perovskite-Si tandem solar cells. More details on our PV material and device characterisation capabilities can be found in the Sections "Photovoltaic Devices Characterisation Laboratories" and "Characterisation and Testing of PV Materials and Solar Cells" of the SERIS Annual Report 2023.

SERIS **Flagship Project**

Building-integrated Photovoltaics (BIPV)

Dr LEOW Shin Woei, Dr Carlos CLEMENT, Dr SAW Min Hsian, Dr CHEN Tianyi, Gavin Prasetyo RAHARJO, Srinath NALLURI

Introduction

Solar deployment in Singapore has grown exponentially, with approximately 800 MW$_p$ (Megawatt-peak) of photovoltaic (PV) panels installed within the last five years. At the current rate, the nation is projected to achieve 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.

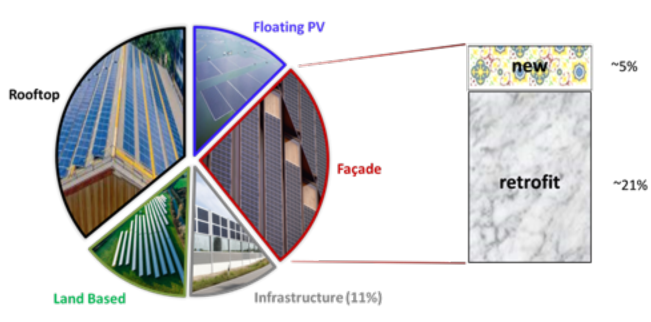


Fig. 1: Distribution of PV installation capacity in Singapore

The majority of existing installed PV systems have been on rooftops. While significant roof space remains unexploited, several challenges could hinder its growth. Competition by building utilities, use of roof space as green areas and the increasingly fractured landscape of rooftops in residential buildings presents hurdles to PV deployment. Two significant areas that remain untapped are Building-integrated PV and Infrastructure-integrated PV (collectively termed BIIPV). BIIPV represents a significant resource in Singapore with an estimated 13.98 km^2 of deployable area (~38% of total PV potential). Challenges such as higher costs and integration complexity remain an issue to the penetration of PV products in these sectors.

Visually appealing PV modules

Improving the visual appeal of PV modules remains an important factor in promoting wider adoption of BIPV especially in areas with high visual impact such as facades, glass railings and sloped roofs. In 2023, we continued to build upon the Peranakan PV concept to expand the design complexities achievable, while retaining the same hot-spot free property. We produced designs consisting of 3 distinct patterns and 5 colour compositions that adhere to the same design principles. The patterns are repeated throughout the panel to create a visually striking tapestry. The number of designs and arrangements that can be implemented are not limited to 3 and in principle could accommodate greater variety.

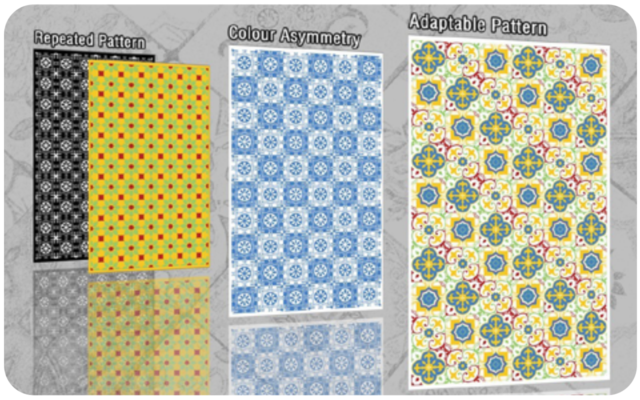


Fig. 2: Peranakan PV modules

An algorithm utilising the pointillism concept was developed to translate non-repeated images, such as the Samsui Women portrait below, into BIPV modules, to add further design flexibility. Through our understanding of the light transmission properties of the inks, and through proper design of the colour pixels, uniform light transmission throughout the entire PV module is maintained and consequently the modules are hot-spot free.

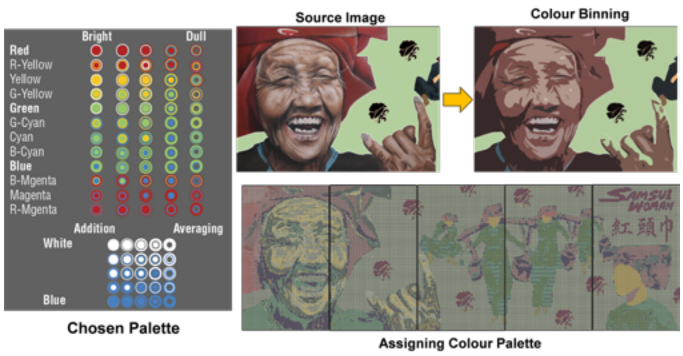


Fig. 3: Pointillism PV image translation workflow

Integrated PV module development

BIIPV possesses its own unique challenges. Viewed as both an electrical product and a building material, BIIPV modules are often subjected to additional regulatory requirements and multiple industry operational practices. To that end, we investigate solutions that help make PV products viable in these market segments. BIIPV modules are typically deployed in areas such as facades, windows, low-rise canopies, railings and fences, and each use case will have their own functional and material requirements.

The shading environment is often much more complex compared to typical rooftop or PV farms, with dynamic shadows and lighting conditions throughout the day. This is especially so in dense urban environments such as Singapore where buildings are densely packed and foliage abundant. The impact to power generation and consequently the viability of BIIPV systems is significant, and hence there is interest internationally to explore the resilience of such systems to changing shade conditions and mitigating solutions that can be adopted.

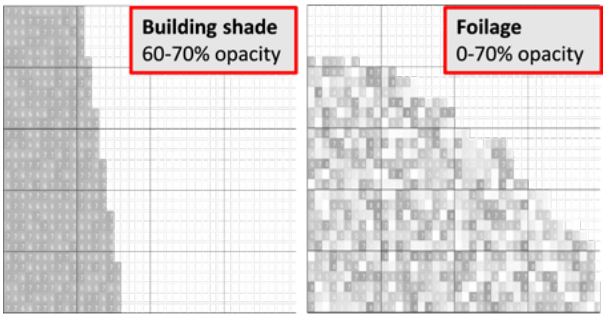


Fig. 4: Examples of shade conditions experienced by BIPV

Figure 4 shows an example of the preliminary modelling work that has been carried out in shade analysis of BIIPV. Shading could range from hard shadows cast by building elements or a patchwork such as those produced by foliage. As the shade environment is time dependent, it is important to understand the temporal power performance of the module and system under several representative use cases. In particular, we are also interested in investigating intentional shading caused by the printing of patterns and images in aesthetic PV panels. The goal would be to develop performance / economic assessment metrics for field reference, and a guide on suggested system stringing configurations and when optimisation tools need to be applied.

Other areas of BIIPV research include re-designing modules to align with infrastructure installation requirements such as fire safety, module handling, electrical connection, and routing. This includes functional requirements such as environmental sealing and noise reductions such as in PV noise barriers. We have been in close collaboration with the fire department, building code regulators and material manufacturers and continue to advance this area of research. We are also in early discussions with the Land Transport Authority to explore new and retro-fit sound barriers in areas such as MRT tracks, highways and at construction sites.

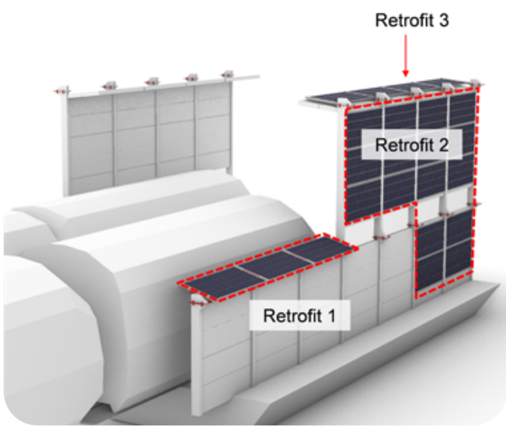


Fig. 5: Proposed modular PV noise barriers for railway tracks

In 2023 we embarked on re-designing our BIPV testbed that is to be constructed on the roof of the Clean Tech One building. This design will incorporate multiple attachment points and a swappable façade system to facilitate the testing of various types of BIPV solutions. A unique feature is the planned integration of a PV testing dome to perform outdoor module characterisation, which has been filed for international patent protection (application WO 2023/191718 A3, “Apparatus for characterisation of photovoltaic modules”).

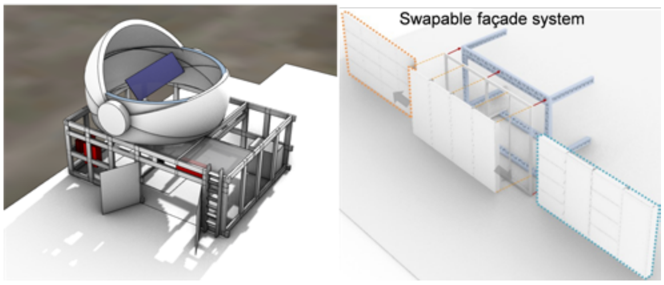


Fig. 6: BIPV testbed with PV testing dome concept design

BIPV Digitalisation

To promote BIIPV’s uses in the construction industry, integrating PV products into the design and production management systems will help to facilitate their use and deployment. The Building Information Management (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. There is currently a lack of BIM models for BIPV products and a lack of consensus on how to implement such models. This has resulted in BIIPV being largely passed over as material for consideration at the design and development stage of a new construction project. The result are lost opportunities to solarise our urban infrastructure, or higher added costs when exploring after-thought or retrofit options.

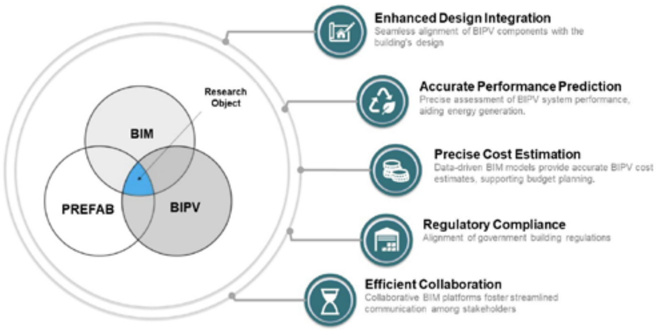


Fig. 7: BIM for BIPV model development objectives

Figure 7 illustrates the properties of the ideal BIPV BIM model and our development objective. We have completed preliminary work in analysing the current literature for BIPV BIM to identify issues or shortfalls in current BIM models. Present work includes developing suitable proposals that align with Singapore’s building and construction workflow, and getting the buy-in from relevant stakeholders.

SERIS **Flagship Project**

Floating Solar Systems

Dr Oktoviano GANDHI, Dr Carlos RODRÍGUEZ, 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. Despite the COVID-19 pandemic, FPV installations have continued to rise, mainly in Asia and Europe. At the end of 2022, the cumulative installed global FPV capacity had reached around 6 GW_p (see Fig. 1).

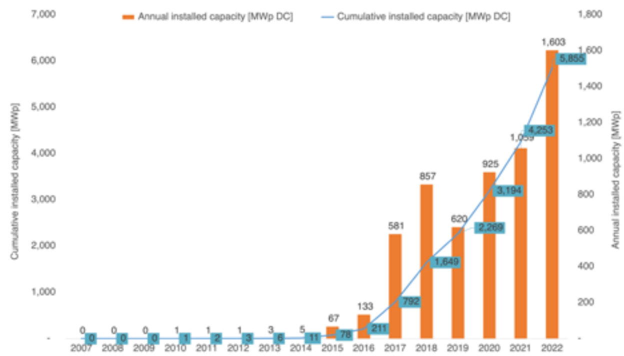


Fig. 1: Globally installed FPV capacity (Source: SERIS database)

In order to better understand the global potential of reservoir-based FPV, SERIS compiled a database of all in-land water bodies worldwide (over 250,000) and overlaid them with the available solar resource data (see Fig. 2). The results showed that covering merely 10% of the world's reservoir surface areas with FPV systems gives an installed capacity of ~23 TW_p and a potential energy yield of around 25,000 TWh/year – which is equivalent to the total global electricity demand in a year (2022 data). This demonstrates the immense potential of reservoir-based floating PV in the future.

The potential for marine FPV is even larger. A SERIS assessment showed that after limiting the ocean regions to those with favourable wind speeds (≤ 30 m/s), wave heights (≤ 10 m), water depths (≤ 100 m), distances from shore (≤ 200 km), and after removing any areas that may experience ice formation or belong to protected areas, the resulting ocean area spans ~10.6 million km^2. By covering just 10% of this area with FPV, the electricity generation would be 6 times as much as today's world electricity consumption.

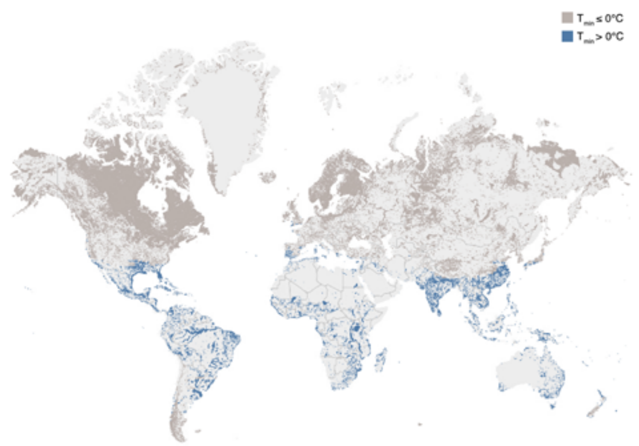


Fig. 2: Global potential of reservoir-based FPV systems

SERIS has been leading the Floating Solar research in Singapore and worldwide since 2016, leveraging the technical expertise gained from the 1-MW_p FPV testbed at Singapore's Tengeh water reservoir that had been inaugurated in the same year. SERIS – in close collaboration with Singapore's national water agency PUB and the Singapore Economic Development Board (EDB) – had managed the design, construction, testing & commissioning (T&C), operation & maintenance (O&M) of the Tengeh FPV testbed, and is also leading the scientific-technical evaluations. This includes data analysis as well as testing of innovative approaches for O&M. To share its knowledge, SERIS had published the "*Where Sun meets Water*" report series, together with the World Bank Group. In 2023, downloads of these reports from the World Bank sharing website (ESMAP) have surpassed 130,000. 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. 3 and further explained in detail in the following sections.

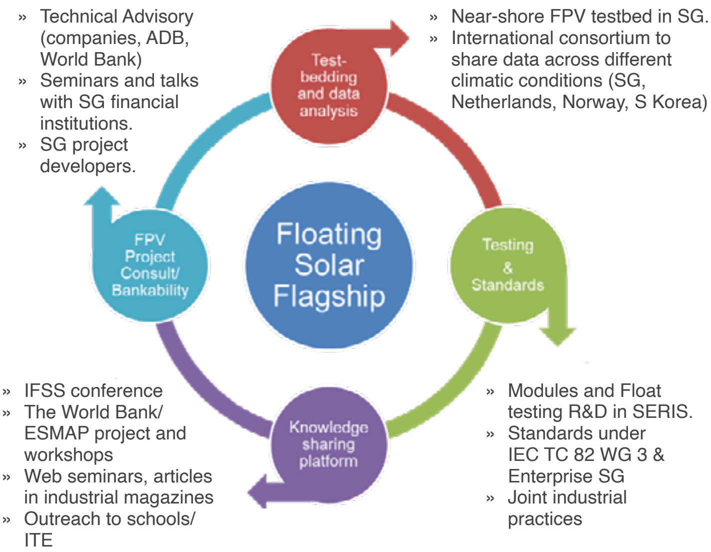


Fig. 3: Key thrusts of the Floating Solar flagship project

1. 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 and Suriname to transfer its knowledge to their real-world projects, be it as part of feasibility studies or the engineering design work. For example, in calendar year 2023 SERIS was involved in the feasibility studies and design of ~1.8 GW_p of FPV systems.

2. 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 design, 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 bio-fouling 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 leadership role in marine floating solar, leading projects related to near-shore floating PV systems. At the national level, SERIS is involved in a consortium with leading solar developer EDPR to develop a system that combines FPV with a floating energy storage system (ESS). A testbed located in deep-water sea conditions in Singapore is under preparation. At the international level, SERIS has expanded the collaboration with its trusted key partner, Fred. Olsen Renewables (a leading Norwegian shipping and renewable energy company) to develop a set of unique competencies for near- and off-shore FPV systems.

As part of this long-term collaboration, the team has developed an algorithm with very high time resolution to predict the mismatch losses in FPV modules due to variation in module tilts when experiencing waves for different wave characteristics, FPV parameters, and site characteristics. The algorithm is being tested against the real performance data from the near-shore FPV testbeds of Fred. Olsen Renewables.

SERIS also continues to analyse the operation and long-term reliability of the existing FPV testbeds in 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. 4), 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 near-shore FPV systems. This very detailed failure mode and effects analysis (FMEA) study has identified more than 100 failure modes as well as suitable mitigation measures.

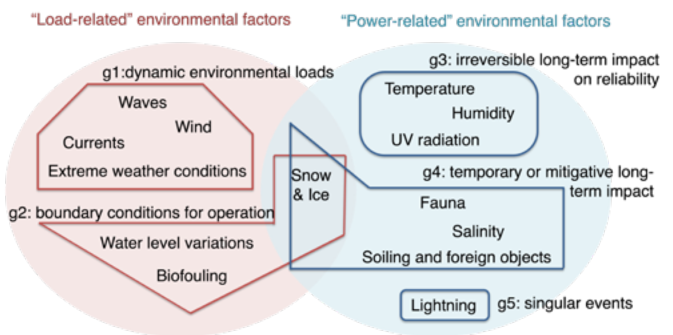


Fig. 4: Environment-related root causes for failures in FPV systems

3. FPV standards formation

SERIS has led the 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. In addition, the institute is also leading the efforts for FPV standards on international level as part of Singapore's active membership in IEC TC82 WG3.

4. Knowledge sharing platform

As one of the leading research institutes in floating solar, SERIS' knowledge and expertise are highly sought after. Throughout 2023, SERIS has been invited to major international PV conferences – in Australia, China, Indonesia, Singapore, South Korea and the US – to share the latest trends on Floating Solar, as well as the results of its research on FPV potential, reliability, and operation, among others.

SERIS shared its experiences not only with academia and industry, but also with the wider community by giving a training course on FPV at the Sustainable Energy Association of Singapore (SEAS) and by actively participating in the Singapore Food Agency (SFA)-NUS Science Day 2023.

Selected R&D **Project**

Refining the substrate surface morphology for achieving efficient inverted perovskite solar cells

Dr GUO Renjun, WANG Xi, Dr JIA Xiangkun, GUO Xiao, Dr LI Jia, Asst Prof HOU Yi

1. Background

With their high absorption coefficient, tunable bandgap, long carrier diffusion lengths, and defect tolerance, perovskite solar cells (PSCs) exhibit remarkable performances in both single-junction and tandem cells [1-4]. Additionally, their cost-effectiveness and large chemical space position them as a promising contender for advancing photovoltaic technology. However, despite continuous efforts by the scientific community to enhance power conversion efficiencies, perovskite solar cells still face limitations in their open-circuit voltage (V_{OC}) and fill factor (FF). These key parameters currently limit their efficiencies due to non-radiative recombination processes within the PSCs. To approach the theoretical efficiency limit of PSCs, it is important to develop advanced device architectures and interface contact designs, and to improve the electronic quality of the absorber layer.

2. Scope of project & objectives

To overcome the aforementioned challenges of inverted PSCs, many studies have applied PEDOT:PSS to improve their device performance. Several self-assembled monolayer (SAM) materials, such as 2PACz and Me-4PACz, have demonstrated their ability to suppress non-radiative recombination and enhance the charge collection at the hole-transporting contact. However, achieving a high-quality coating with very thin (a few nm) SAMs at the interface between the perovskite absorber and the transparent conducting oxides remains challenging. This is due to issues related to low conductivity, fabrication compatibility, uniformity, and wettability. Balancing perovskite quality, passivation, and carrier transport presents a challenge in simultaneously maximising both V_{OC} and FF of PSCs. This trade-off also complicates the upscaling of the fabrication process, particularly when utilising a solution-based approach. SAMs establish a conformal, single-layer coating on ITO substrates, with phosphate groups binding to the ITO.

3. Significance & impact of project

In this study we present a comprehensive investigation into the influence of substrate morphologies on the growth modes of hole-transporting layers (HTLs) and their impact on PSCs. By utilising the grazing-incidence small-angle X-ray scattering (GISAXS) technique to analyse the domain distributions of HTLs, we identify distinct growth modes influenced by the substrates and their associated morphologies. By carefully regulating the substrate morphology, we achieve a maximum power conversion efficiency (PCE) of 24.5% for a p-i-n PSC. The quasi-steady-state J-V scan gives a PCE of 23.5%. Furthermore, our substrate morphology modifications demonstrate excellent operational stability, as evidenced by a stable maximum power point tracking efficiency during 400 hours.

4. Methodology & Results

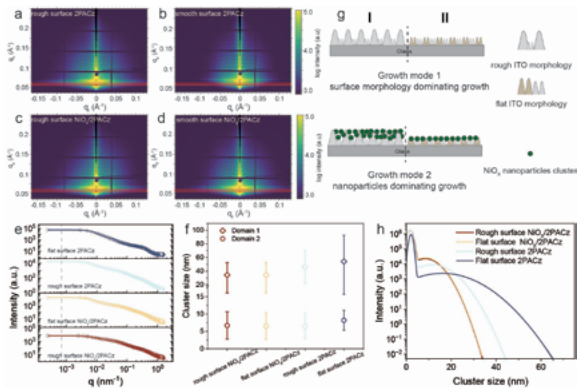


Fig. 1: a-d) 2D GISAXS data of SAMs, SAMs/NiO_x on rough and smooth ITO substrates. a) 2PACz on rough surface ITO substrates, b) 2PACz on smooth surface ITO substrates, c) NiO_x/2PACz on rough surface ITO substrates, d) NiO_x/2PACz on smooth surface ITO substrates. e) double-logarithmic plots of the horizontal line cuts of the 2D GISAXS data at the critical angles (highlighted by red frames in Figs. 1a-1d. The text explains that solid lines are fitted with the one-dimensional paracrystal model to determine the significant in-plane length scale. For clarity, the curves are shifted along the intensity axis. The vertical dashed lines mark the resolution limit towards large-scale structures. The bottom two curves are NiO_x/2PACz, which grows on rough surfaces, and the top two on smooth surfaces. f) Most prominent domain sizes of 2PACz that grow on different morphology. Information on the two different domain sizes, R_1 and R_2 (form factors), is plotted from the fit of the horizontal line cuts from 2D GISAXS data. g) Schematic diagram of electron-blocking materials growth mode dominated by different morphology. h) Domain size distributions of NiO_x/2PACz, 2PACz on rough and smooth ITO substrates for different form factors extracted from the model.

Current state-of-the-art architectures of p-i-n perovskite cells for the HTLs are NiO_x nanoparticles with SAMs and a single layer of SAM. Thus, we deposit NiO_x/2PACz and 2PACz on the rough ITO substrate (UVO treatment) and the smooth substrates (plasma treatment) for the following study. To probe the distribution of HTLs on the different morphology ITO substrates, we use GISAXS which features excellent statistics over a macroscopic area about the object geometry, size distribution, and spatial correlation down to nm scale without special sample preparation (Figs. 1a-1e). We measure the HTL stack of NiO_x/2PACz and 2PACz atop the smooth and rough ITO substrates (Figs. 1a-1d). Due to the multi-layer architecture, we execute horizontal line cuts at the critical angle of respective HTLs to analyse data quantitatively, highlighted by a red frame in the 2D GISAXS data.

In Fig. 1, we summarise two different growth modes of SAMs: growth mode 1 (surface morphology-dominated growth) and growth mode 2 (nanoparticle-dominated growth). To visualise the distribution of the SAMs clearly, we further present the SAM domain size distributions without normalising the form factor of different domains. The broader distributions of a single layer of SAM on the smooth ITO substrates confirm the conformal growth dominated by growth mode 1-II (Fig. 1g). In comparison, the ITO substrate morphology cannot affect the SAMs domain growth, which is the existence of NiO_x nanoparticles (growth mode 2).

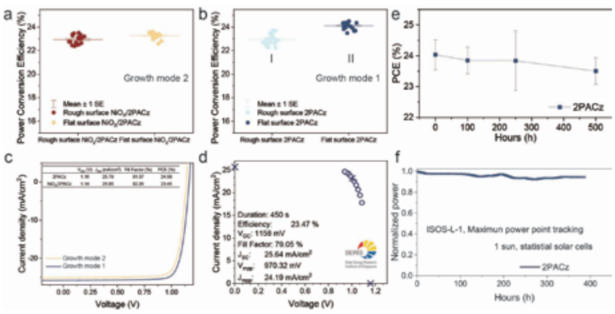


Fig. 2: a) Statistical distribution of power conversion efficiency of PSCs using NiO_x /2PACz that grow on the rough and smooth ITO surfaces (growth mode 2). b) Statistical distribution of power conversion efficiency of perovskite solar cells using 2PACz that grow on the rough and smooth ITO surface (growth mode 1). c) J-V scans (0.1 V s^{-1} with voltage step of 0.02 V) under simulated AM 1.5G illumination calibrated to 100 mW cm^{-2} for devices utilising NiO_x /2PACz (growth mode 2, Fig. 1g), 2PACz (growth mode 1-II, Fig 1g) as HTLs that grow on the smooth ITO surface. d) The quasi-steady-state J-V measurement of the champion device using 2PACz on a smooth ITO substrate measured at SERIS (aperture area = 0.05 cm^2). e) Moisture stability test under ISOS-D-2 protocol for PSCs using 2PACz that grow on the smooth ITO surface (growth mode 1-II). f) Long-term MPP tracking using an LED illumination of an encapsulated solar cell with 2PACz (growth mode 1-II) in air at a controlled device temperature of 55 °C and a relative humidity of 60 to 80% under the ISOS-L-1 protocol.

We test a series of PSCs with NiO_x /2PACz and 2PACz on rough and smooth ITO substrates (Figs. 2a and 2b) to evaluate the relationship of the growth modes with the device performance. With the improved light management due to the removal of the NiO_x layer with the feature of absorbing visible sunlight and defect passivation for 2PACz on rough ITO substrates (growth mode 1-I), we achieve an average PCE of 22.7% (Fig. 2b). For growth mode 1-II, due to the improved conformal distribution of NiO_x /2PACz on the smooth ITO substrates, the average PCE is boosted to 24.1%. Finally, we achieved a champion PCE of 24.5% (aperture area = 0.05 cm^2) with the architecture of 2PACz on top of smooth ITO substrates by substrate morphology modification (Fig. 2c). These devices show a quasi-steady-state PCE of 23.5% (Fig. 2d). We also evaluate PSCs' moisture and operational stability with our substrate morphology modification strategies. We encapsulate solar cells with growth mode 1-II and store them in ambient air with a relative humidity of about 60 % (ISOS-D-1). PSCs with growth mode 1-II maintain PCEs higher than 97 % of the initial PCEs and present excellent moisture stability by our surface morphology strategy (Fig. 2e). After 400 h of maximum power point tracking, PSCs with growth mode 1-I maintained about 95% of their initial efficiency. In comparison, PSCs with growth mode 2 retained only 92 % (Fig. 2f).

5. Conclusions

The growth mode of SAMs depends on the substrate surface morphology or attached nanoparticles. Nanoparticles dominating the growth mode have been a popular fabrication method due to their high compatibility with different substrate morphologies. However, we propose to mitigate the non-radiative recombination at the HTL/perovskite interface by proper substrate surface morphology modification. The flatter ITO surface morphology can facilitate a conformal growth of the SAMs to passivate interface states and prevent the formation of trap states induced by the HTL/perovskite contact. As a result, we achieve an efficiency of 24.5 % for p-i-n PSCs due to the improvement of V_{OC}, J_{SC} and FF, indicating a significant reduction in non-radiative recombination losses. Moving forward, the advancement of inverted PSCs necessitates the utilisation of charge-selective materials with improved transport properties, particularly for the HTLs.

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Selected R&D **Project**

Study of potential-induced degradation and its mitigation in glass-encapsulated perovskite solar cells

Laxmi NAKKA, Prof Armin G. ABERLE, Dr Fen LIN

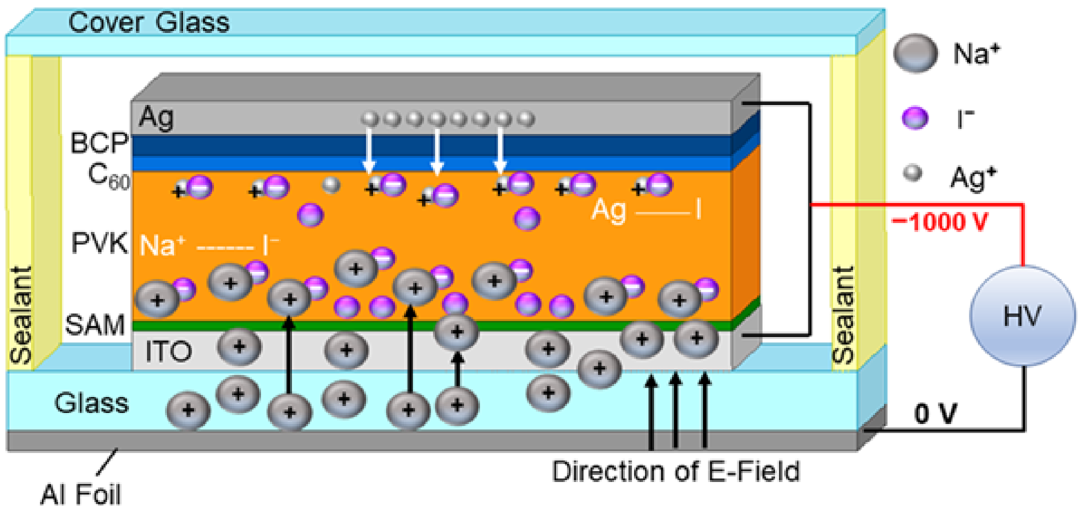

Fig. 1: Schematic of an encapsulated p-i-n perovskite solar cell. The PID experiment is conducted using the foil method where -1000 V high-voltage stress is applied between the short-circuited perovskite solar cell and the aluminium foil on the front glass. Also shown is the mechanism of degradation in the investigated PSCs under negatively biased PID.

1. Background

The efficiency of organic-inorganic metal halide perovskite solar cells has remarkably improved from 3.1% in 2009 to 26.1% in 2023 [1]. However, long-term reliability, durability and scalability are the technological barriers in the commercialisation of perovskite solar cells (PSCs) [2]. One of the serious concerns affecting the reliability of photovoltaic cells in PV systems is potential induced degradation (PID). This is a degradation mechanism that occurs due to high voltage stress between the cells and the grounded frame of the PV modules [3]. PID has been widely investigated in crystalline silicon PV modules, but this mechanism is not yet fully explored and there is very limited research on PID of PSCs [4-7]. Initially, Carolus et al. applied high voltage stress of 1000 V along with a thermal stress of 60°C and relative humidity (RH) of < 60% for 18 h and observed that the PV efficiency dropped by 95% [4,5]. The degradation was shown to be predominantly due to the oversaturation of the perovskite layer with Na^+ ions from the glass. In terms of PID mitigation in PSCs, application of a reverse bias is the only existing strategy to recover the efficiency of PID affected PSCs, whereby it has two important limitations. First, the recovery varies with reverse bias exposure time and depends on the device configuration. Second, the reverse bias strategy is only applicable on devices already subjected to PID and it is uncertain that these devices can fully recover from PID even after prolonged hours of exposure to reverse polarity. Therefore, it is of utmost importance to understand the PID mechanism in PSCs and investigate suitable techniques for PID mitigation.

2. Scope of project & objectives

In this work, we conducted comprehensive studies on the PID mechanism in p-i-n configured PSCs, including elevated stress conditions. Furthermore, we also address the PID mitigation in PSCs to bridge the current research gaps. With the existing limited research on PID of PSCs, it is evident that there is still a big research gap in this field to understand its underlying degradation mechanism. The existing works on perovskite related PID studies have reported external Na^+ ion migration towards the perovskite as the source of degradation under external high voltage stress. PID arising due to the external potential difference could technically be addressed at the cell level by introducing a suitable barrier that blocks the external Na^+ ion migration into the perovskite layer.

3. Significance & impact of project

This work reports the first detailed investigation of the effects of PID in glass-encapsulated perovskite solar cells under both room condition (RC) as well as elevated stress condition (ESC). In addition, with a comprehensive understanding of the PID mechanism in PSCs, we demonstrate for the first time the successful PID mitigation in glass-encapsulated perovskite solar cells with a novel and facile strategy. As degradation rates in PV modules affect their corresponding LCOE, addressing the PID bottleneck of PSCs will contribute to the acceleration of the journey towards successful commercialisation and deployment of PSCs.

4. Methodology & Results

In this research work, single-junction single-cell glass-encapsulated perovskite mini-modules with an active area of 1.2 cm^2 are fabricated to study the effect of potential-induced degradation and its mitigation. We have fabricated and encapsulated the devices in a controlled nitrogen environment with a cover glass and epoxy resin as edge sealant. The device structure along with the detailed PID mechanism is shown in Fig. 1. All the PID experiments in this work are performed using the standard foil method as described in IEC 62804-1.

The fabricated devices are divided into two groups, i.e., devices tested under room condition (RC) and devices tested under elevated stress conditions (ESC). Initially, the devices in each group were tested without application of any high voltage stress, to elucidate the effects of RC and ESC on the performance of the devices. These devices are termed RC and ESC, respectively. For RC the climate chamber is maintained at 25°C and 20% RH, while for ESC it is maintained at 60°C and 60% RH. To clearly understand the effect of PID under both stress conditions, these two groups of devices are subjected to high voltage stress. They are termed as nPID_RC and nPID_ESC, respectively. The performances of all the devices are compared with that of the reference device (ref) which is stored in a N_2 environment without either environmental or voltage effects. The normalised box plots of the power conversion efficiency (PCE) are shown in Fig. 2. The reference devices demonstrated a normalised PCE of 96% and the differences between the normalised efficiencies of the devices under RC and ESC are only 4%. However, after application of high voltage stress, the devices under room condition retain 37% of the initial efficiency, whereas the devices under elevated stress conditions retain only 9% of the initial PCE. Hence, while both types of devices suffer significant degradation under high voltage stress, the devices under elevated stress conditions exhibit more severe degradation compared to the devices under room conditions. The underlying mechanism is further identified through advanced characterisations [8] and presented in Fig. 1.

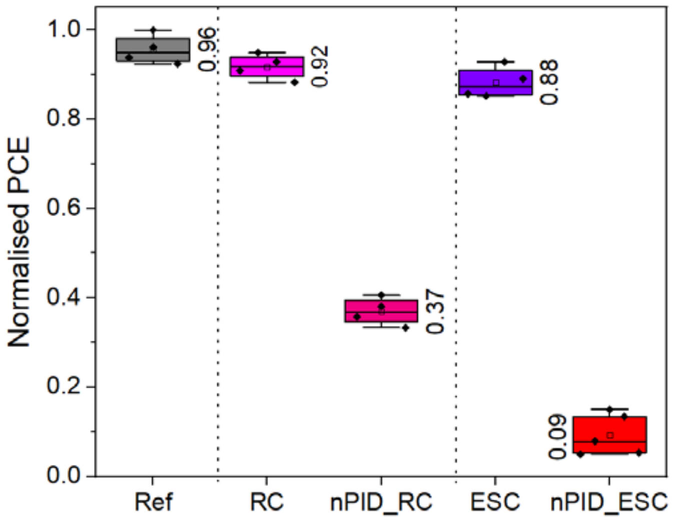

Fig. 2: Normalised PCE of control and modified devices tested under room condition (RC), elevated stress condition (ESC) and negatively biased PID (nPID_RC, nPID_ESC).

As can be seen in Fig. 1, the electric field due to the applied potential difference will force the Na^+ ions in the glass to drift into the ITO layer. As a result of the increasing Na^+ concentration in the ITO, some of these ions then diffuse through the SAM layer into the perovskite layer. The diffused Na^+ ions interact with the negatively charged iodine (I) ions in the perovskite layer which may lead to the formation of a weak $Na^+ I^-$ bond as depicted in Fig. 1. The rate of transport of Na^+ ions is further enhanced when the perovskite solar cell is operated under the elevated stress condition, resulting in catastrophic failure.

With the understating of the PID mechanism in PSCs, we proposed a path towards PID mitigation in PSCs at the device level. We fabricated modified devices introducing a NiO_x layer in-between the ITO and SAM. In this experiment, both the control and modified devices are exposed to negatively biased high voltage stress for 96 hours. As shown in Fig. 3, the normalised

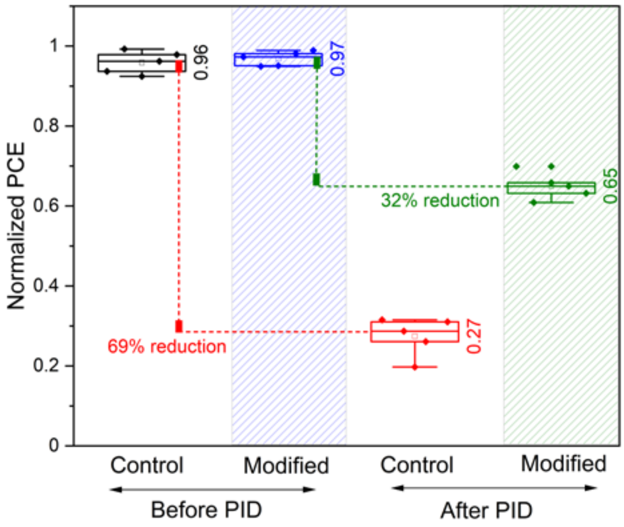

Fig. 3: Normalised PCE of control and modified devices before and after PID.

PCE of the control and modified devices is similar before the application of high voltage stress. The control device suffered an overall reduction in the efficiency by 69% after PID, whereas the modified devices have shown better resilience to high voltage stress with only 32% reduction in the efficiency. Therefore, the modified devices demonstrate superior performance compared to the control devices after PID. The NiO_x layer in the modified devices is responsible for the suppression of ion migration, and NiO_x is also an interlayer that can act as an excellent barrier to external ions and provides a better SAM-perovskite interface and preserves the quality of the perovskite film.

The EDX spectrum (top right) in Fig. 4 confirms that the control device has a high concentration of Na^+ ions which have migrated from the front glass pane during the PID stress test, whereas this concentration is strongly reduced in the modified devices (see the EDX spectrum at the bottom right of Fig. 4) [9]

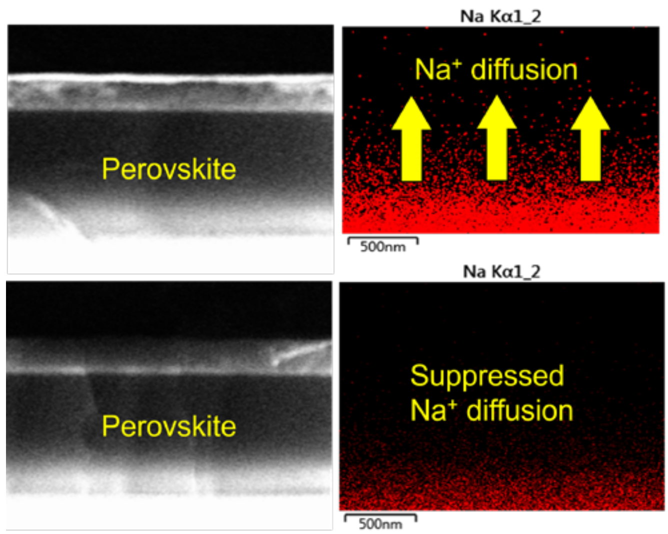

Fig. 4: SEM images of the EDX characterisation showing Na^+ diffusion in control devices and suppressed Na^+ ion diffusion in the modified devices.

5. Conclusions

This work reports the first detailed investigation of the effects of PID and its mechanism in glass encapsulated perovskite solar cells at room conditions and elevated stress conditions. We observed that the devices subjected to high voltage stress under elevated stress conditions are more prone to PID compared to devices under room conditions. Further, the PID mitigation in glass-encapsulated perovskite solar cells is reported for the first time in the literature. We introduced a barrier NiO_x layer between the ITO layer and the SAM layer in the modified devices. After 96 hours of stress testing, the modified devices show better resilience to PID compared to the control devices. Our characterisation results clearly indicate that the movement of Na^+ ions is blocked at the SAM-NiO_x interface, and that the modified devices are highly resistive to PID stress. We show that introducing a barrier layer between the ITO and HTL could be a potential solution to PID of perovskite solar cells. Although this is not yet a complete mitigation, the underlying degradation mechanisms revealed in this work will assist the future works on full mitigation of PID and the successful commercialisation and deployment of perovskite solar cells.

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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

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

1. Background

The industrial acceptance and growth of the monoPoly™ solar cell technology platform developed by SERIS has been impressive [1-2]. According to the predictions in the ITRPV report published in March 2023, solar cells with passivated contacts ("TOPCon") are expected to become the globally leading technology in production within next five years. Passivated contact solar cells, such as monoPoly™, use a combination of doped polysilicon and an ultra-thin dielectric layer on only one side of the cell (usually the rear) to isolate the metal contacts from the crystalline silicon absorber [3-4]. While the monoPoly™ technology featuring passivated contacts on the rear side has gained massive industrial acceptance, in this work we present SERIS' biPoly™ technology platform on large-area (M2-size) mono-crystalline wafers featuring poly-Si/SiO_x based passivated contacts on both the front and the rear side. On the front, the poly-Si/SiO_x is present only beneath the metallised regions, which we refer to as 'poly-Si fingers'. Excellent passivation on the front and rear surfaces is achieved, resulting in implied open-circuit voltages of 720 - 730 mV on unmetallised solar cells. The industrially scalable solar cells achieve 22% efficiency under 1-Sun illumination. With further optimisation and improvements, efficiencies exceeding 25% seem possible.

2. Scope of project & objectives

In this work, we present large-area (244.4 cm^2) rear-junction bifacial solar cells featuring poly-Si based passivated contacts on both sides (biPoly™). On the front side, the poly-Si is present only under the metal contacts (selective poly-Si fingers), while on the rear side it covers the entire surface. The poly-Si fingers on the front are fabricated using an industrially scalable inkjet masking process followed by wet-chemical processing. The metal contacts are screen-printed using metal pastes that etch through the dielectric layer and contact the doped poly-Si layer when annealed at high temperature. Such pastes are known as fire-through pastes and, along with screen-printing, remain the dominant technology used in the PV industry. We describe the development, design, and performances of double-side passivated contact solar cells having full-area and selective poly-Si on the front side. The large-area solar cells fabricated using industrial processes achieved 21% and 22% efficiency for full-area poly-Si and selective poly-Si, respectively. We analyse the various loss mechanisms in the solar cells and develop a computational model for double-side passivated contact solar cells with full-area and selective poly-Si on the front. With the help of a loss analysis and computational modelling, we identify the pathway towards achieving biPoly*™* solar cells with efficiencies exceeding 25%.

3. Significance & impact of project

Solar cells featuring poly-Si based passivated contacts ("TOPCon") have already gained industrial acceptance and will soon become the leading technology in the PV industry. The doped polysilicon layer provides excellent passivation quality, however, due to the associated parasitic absorption, it is currently limited to the rear side of the solar cell [5-6]. Our work provides a way to integrate the poly-Si layer on both sides of the cell. The innovative approach presented in this work of using poly-Si fingers only below the metal contacts retains the advantages of the poly-Si based passivating contacts while the disadvantages are minimised. Having doped poly-Si fingers beneath the metal contacts on the front side prevents the metal contacting the absorber layer, resulting in improved open-circuit voltages. Additionally, limiting the fingers to only below the metal contacts minimises the parasitic absorption on the front side, hence the short-circuit current of the solar cell is not significantly affected. Furthermore, having the metal contact on a highly doped layer improves the fill factor of the solar cell. This leads to an overall improved efficiency of the solar cell with double-side passivating contacts. The developed biPoly™ solar cells are also suited for applications in two-terminal tandem solar cells.

4. Methodology & Results

Processing details:

Large-area (244.4 cm^2) phosphorus-doped (n-type, 180 *µ*m, 1.2 Ω-cm) Cz-Si wafers were used for fabricating the solar cells. The wafers were first cleaned using a standard wet chemical process prior to thermally growing a thin interfacial oxide (iOx) and depositing an intrinsic polysilicon (i-poly-Si) in a horizontal tube low-pressure chemical vapour deposition (LPCVD) furnace. The ex-situ doping of the poly-Si layers was accomplished in a horizontal tube diffusion furnace. After ex-situ diffusion, a PECVD SiN_x mask (~50 nm) was deposited on one side (rear) of the samples using an inline plasma-enhanced chemical vapour deposition (PECVD) tool. The unmasked side was processed using wet chemistry to achieve a textured front surface. iOx was grown and i-poly-Si was deposited using LPCVD and doped ex-situ with P in a diffusion furnace, then followed by another PECVD SiN_x masking of the front side of the samples.

An acid resistant hot melt ink was used to form a mask for subsequent etching steps using an industrial inkjet printer. The SiN_x is then removed using HF at room temperature, and the hot melt ink mask is then removed in an alkaline solution. After this process the SiN_x mask remains below the regions protected under the ink, while on unprotected regions the n^+ poly-Si is exposed. Next, the poly-Si is etched using a proprietary process developed at SERIS using an ultra-slow silicon etch (patent applied). This etching process only etches away the poly-Si layer without causing significant damage to the underlying textured c-Si layer. Finally, the SiN_x masks on the n^+ poly-Si fingers and rear side p^+ poly-Si are removed using HF. Solar cells with poly-Si covering the entire front surface were also fabricated as a reference.

The portion of the front surface not covered with n^+ poly-Si is referred to as the field region. A low-temperature oxide (LTO) layer is grown on the samples in a thermal tube furnace to passivate the field region (c-Si). The front and rear PECVD passivation and anti-reflection stacks are deposited using PECVD, and the solar cells are metallised using an industrial screen-printer. Cross-sectional schematics of both the full-area and selective n^+ front poly-Si rear-junction biPoly™ cells are shown in Fig. 1.

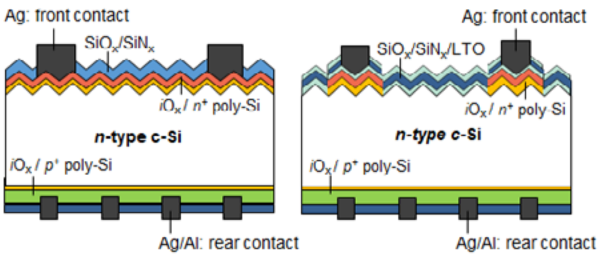

Fig. 1: Schematic of biPoly™ solar cell with full-area poly-Si on the front (left) and with selective poly-Si under the front metal contacts (right).

1-Sun solar cell measurements:

Figure 2 presents the measured 1-Sun parameters of a batch of 20 biPoly™ solar cells. It can be seen that the cells with selective poly-Si on the front present only under the metal contacts have significantly improved V_{oc} and J_{sc}. The J_{sc} improved by 0.3-1 mA/cm² absolute as compared to the J_{sc} of full-area biPoly™ solar cells. This is attributed to the reduction in parasitic absorption at the front surface due to the absence of poly-Si in the unmetallised regions. The FF data of the selective biPoly™ cells also exhibits a slight improvement. As a result, the selective biPoly™ solar cells gained 0.75-1% absolute in efficiency (Eff). The parameters of the champion solar cell of each type are shown in Table 1.

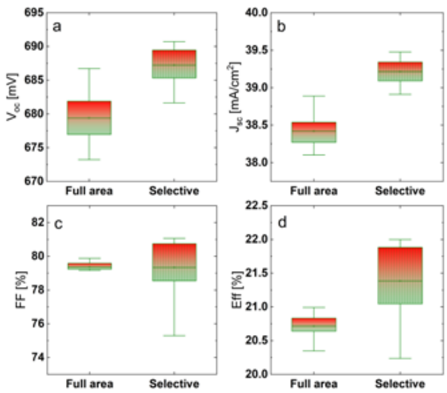

Fig. 2: Measured 1-Sun parameters of a batch of 20 biPoly™ solar cells. Full area refers to full area poly-Si on the front side, while selective refers to poly-Si only under the metal contacts on the front side. a) V_{oc}; b) J_{sc}; c) FF; d) Eff.

Table 1: J-V data of the champion biPoly™ solar cell from the two different types of solar cell fabricated in this work.

Solar cell type	V_{oc} [mV]	J_{sc} [mA/cm²]	FF [%]	Eff [%]
full-area biPoly™	681.9	38.9	79.2	21.0
selective biPoly™	690.7	39.3	80.9	22.0

Voltage loss analysis:

To understand the sources of difference in the solar cell voltage between the two different types of biPoly™ solar cells, detailed characterisation with respect to the passivation properties were carried out. It was found that the deterioration in the passivation properties was mainly limited to the front surface after high-temperature firing.

Current (J_{sc}) loss analysis:

As shown in Fig. 2, the biPoly™ solar cells with selective poly-Si on the front surface gained ≈ 1-1.5 mA/cm² in J_{sc} on average as compared to their counterparts with full-area poly-Si on the front. This is attributed to the absorption in the poly-Si layer on the front side of the solar cell, which also appears as the loss in the blue region of the solar spectrum in the J_{sc} loss analysis breakdown shown in Fig. 3. All other contributing factors to the total J_{sc} loss are similar, except for the blue loss.

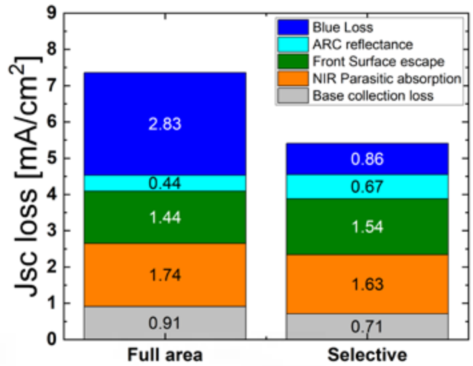

Fig. 3: Different factors contributing to the total loss in J_{sc} for biPoly™ solar cells with full-area and selective poly-Si on the front.

Fill Factor loss analysis:

The FF factor is mainly determined by the series (R_s) and shunt (R_{sh}) resistances of a solar cell. An additional component contributing to the FF loss could be the non-ideal recombination. The fill factor loss arising from R_s and R_{sh} is similar for both types of solar cell (the R_s of both types of solar cell was ≈ 0.55 ± 0.1 Ω-cm²), the non-ideal recombination is slightly lower for biPoly™ cells with selective poly-Si on the front. This could be attributed to the lower edge and peripheral recombination due to the additional etching process which removes poly-Si closer to the edges of the wafer.

Development of simulation model for biPoly™ solar cells with full area and selective poly-Si layers on the front:

3D optical and 2D electrical device simulations were performed to improve the fundamental understanding of the fabricated biPoly™ solar cells with full area and selective poly-Si layers on the front side. The parasitic light absorption in poly-Si layers on both sides of the cell and other loss components contributing to the photon current loss is quantified using a ray tracing software. Using all the experimentally measured device parameters and the simulated generation current, a free energy loss analysis (FELA) showed the optical and electrical advantages from the structural transition to the selective biPoly™ solar cell structure. The optical simulation estimated that 35 nm of full-area and 90 nm of selective-area (11.5% area fraction) front iOx/n^+ poly-Si layer parasitically absorb 1.70 mA/cm² and 0.37 mA/cm², respectively. Thus, a selective biPoly™ solar cell is projected to generate 1.27 mA/cm² higher photocurrent density in the absorber than the full-area biPoly™ solar cell. This simulation result is consistent with the J_{sc} difference between the fabricated full area and selective area biPoly™ solar cells, see Fig. 2.

Using the constructed simulation models for full-area and selective biPoly™ solar cells, a free energy loss analysis (FELA) was conducted to investigate the source of performance loss in the said solar cell operation. As presented in Fig. 4, FELA concluded that the biggest cell performance improvement of selective biPoly™ solar cell was enabled by the significant reduction of parasitic light absorption in the front n^+ poly-Si. Based on the loss breakdown for both full-area and selective biPoly™ solar cells, recombination loss is the dominating power loss mechanism for both cell structures, making it the best candidate for further optimisation to achieve efficiencies beyond 25%.

5. Conclusions

A solar cell efficiency of 22% was achieved for a rear-junction biPoly™ cell with selective n^+ poly-Si on the front. Patterning the front n^+ poly-Si was key to improving the current by 1-1.5 mA/cm^2 on average. The patterned poly-Si fingers effectively passivate the front contacts, resulting in a high voltage without adversely affecting the Fill Factor. However, detailed modelling shows further scope in improvement of the passivation (by employing advanced processes) and absorption (by further modifying the poly-Si layer). With these optimisations, efficiencies exceeding 25% seem possible for large-area solar cells.

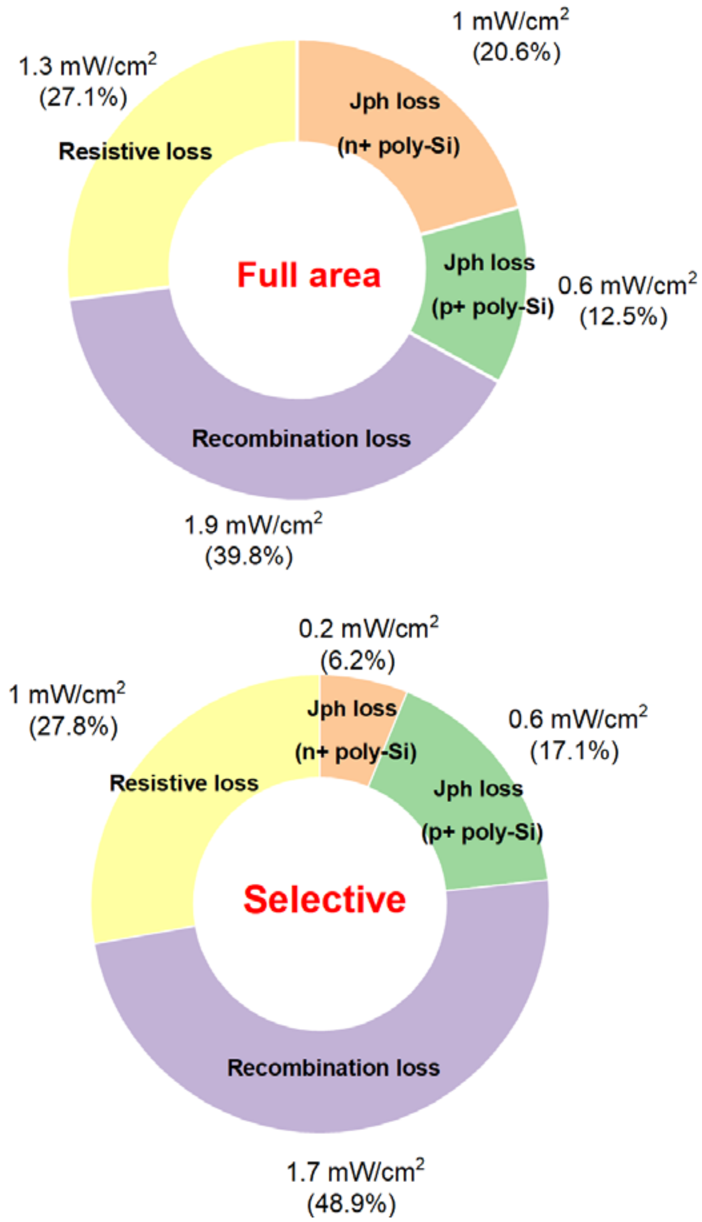

Fig. 4: Detailed power loss breakdown at MPP of biPoly™ solar cells with full area and selective poly-Si on the front.

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This article is an extract of a more comprehensive work published in Solar Energy Materials and Solar Cells, Volume 256, 1 July 2023, 112351, Padhamnath et alia, "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". Copyright (2023), reproduced with permission from the publisher Elsevier Ltd.

Selected R&D **Project**

Photoluminescence imaging of silicon PV modules using LED floodlights*

Anna CYNTHIA, Dr SAW Min Hsian, Dr Mauro PRAVETTONI

1. Background

In both electroluminescence (EL) and photo-luminescence (PL) imaging of PV modules, images are created by capturing photons emitted by radiative recombination of charge carriers upon excitation. While EL generates this optical signal by current injection into the solar cells, PL uses optical excitation to achieve the signal. PL emission is highest in open-circuit (OC) condition and lowest when the measurement is made in short-circuit (SC) condition [1]. The difference in luminous intensity can be used to indicate the intensity of the emission due to PL.

PL imaging, like EL, is a well-established inspection and characterisation technique used for inline quality control in the production of solar cells, as an example. However, unlike EL imaging, PL is contactless. This allows PL to be applied on a wider range of samples such as silicon bricks, as-cut wafers and partially processed wafers [2], where EL cannot be used due to the lack of electrical contacts on the partially processed samples. Because of this advantage, PL has also been trialled as an outdoor characterisation method for modules for defect detection and allows modules to be characterised in the field [3].

2. Scope of project & objectives

Despite the prevalence of PL imaging as a characterisation technique, there are only a few studies of conducting PL imaging on PV modules, and there is currently no standard yet for PL imaging. This study aims to determine the types of defects identified by PL and EL respectively, as well as to establish a method of conducting PL for full-sized modules in a lab environment. The validity of PL imaging as a characterisation method for silicon modules will be validated with current standard testing methodology, primarily with EL.

Images can be obtained with an infrared camera for modules under EL or PL. Assuming reflected light is not present or has been accounted for, PL can identify several types of defects as listed in Table 1 [3]. Comparing observations from both EL and PL images can also identify potential causes of defects, as shown in Table 2.

3. Methodology & Results

Four commercial blue LED floodlights from Aeon Lighting Technology (series Lodestar-F02, 145 W) were used as the excitation source. The set up is placed in SERIS' darkroom (Fig. 1). The uniformity of the LED system is Class C (better than ±10% over the 2×2 m^2 target area), with peak intensity on target of approximately 30 W/m^2.

Table 1: Visibility of different defect types with different imaging techniques

EL at I_{sc}	EL at 10% × I_{sc}	PL
Severe PID Cracks Inactive areas (caused by broken contacts) Bypass diode SC-failures Snail trails (for EVA modules) Interconnection failures	PID Cracks Inactive areas (caused by broken contacts) Bypass diode SC-failures Severe interconnection failures	Cracks Snail trails Inactive areas (caused by defective cells) EVA degradation Soiling

Table 2: Potential causes for brightness of cells under EL and PL

EL at I_{sc}	EL at 10% × I_{sc}	PL	Potential Cause
Dark cell	-	Dark cell	Poor quality of semicon-ductor material [2] Increase of non-radiative recombination [2]
Dark cell	-	Bright cell	Interconnection failures [2, 4] Increased series resistance [2, 4]
-	Dark cell	-	Corrosion from potential-induced degradation (PID-c)
-	Dark cell	Dark cell	Shunting from PID (PID-s) [2]
-	Dark cell	?	Polarisation from PID (PID-p)

As the LED lamp emits only in the blue with a sharp peak spectrum, and the PL emission from silicon is in the near-infrared (IR), the emission and the reflected light can be easily filtered out. A Nikon D600 camera is used to take the IR picture; image subtraction is done to remove the impact of reflection on the PL image. The measurement protocol is as follows:

1. The IR image of the modules is taken in OC (Fig. 1a);
2. The IR image of the same modules is then taken in SC condition (both images are taken with the same exposure time and at the same position, Fig 1b);
3. The PL image is obtained by image subtraction, to filter out reflectance from the light source from PL emission (Fig. 1c);
4. The brightness of the image is further amplified by 100% throughout the image to increase the contrasts between bright and dark areas and ease the process of visually identifying defects (Fig. 1d).

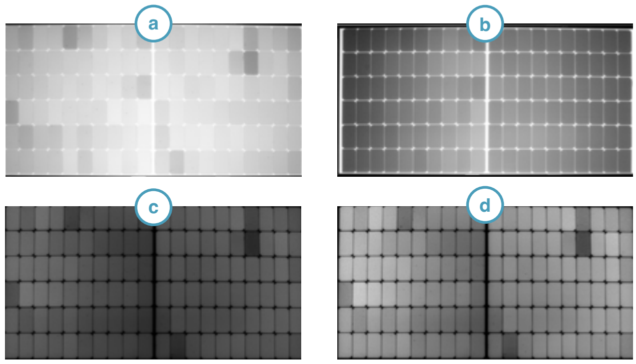

Fig. 1: PL measurement protocol at SERIS for PV modules: (a) PL in OC condition; (b) Reflection in SC condition; (c) PL image after subtraction; (d) PL image after amplification.

* *An extended version of this article has been presented to the 34th International Photovoltaic Science and Engineering Conference, held in Shenzhen, China, 6-10 November 2023 and submitted for publication in the conference proceedings.*

The PL images obtained from various commercial modules of different sizes and technologies were compared with images obtained from EL at 10% and at 100% of the short-circuit current (I_{sc}). We report here the results for an interdigitated back-contact (IBC) module (Fig. 2) and for a silicon heterojunction (HJT) module (Fig. 3).

The cracks at the bottom left corner of the IBC module are clearly visible in Fig. 2a (EL at 100% I_{sc}), while the cells in those positions are dark in the EL image at 10% of I_{sc} and in the PL image (Figs. 2b and 2c). The equivalence between the latter two is possibly due to the lower excitation energy in both cases.

In the HJT sample, the PL of Fig 3c highlights areas of poor IR emission in the two central bottom cells, which are not identified in the EL images at 100%×I_{sc} and only poorly visible in the EL at 10% of I_{sc}. This can arise from poor quality or contamination of the starting wafers.

In general, the darker cells seen in EL coincide with the relatively darker regions in PL, indicating increased non-radiative recombination and thus poorer cell quality in most of the cases.

The comparison between EL and PL can in principle be beneficial to identify defects produced by corrosion of the metallisation, which are detectable by EL – usually at low excitation, i.e. 10% of I_{sc} , but may not be detectable by PL. A remarkable example is Potential-Induced Degradation due to corrosion (PID-c), which is expected to be detectable in EL imaging, but should be hardly detectable in PL imaging.

4. Conclusions

PL imaging is a complement to EL, by verifying the presence of defects and providing more information on cell performance losses than what can be done with EL alone. Cracks are visible in both EL at 100% of I_{sc} and PL, although they appear fainter in PL. As PL is a contactless imaging technique and does not involve current circulation, poorly connected or electrically isolated regions can be easily differentiated from degraded areas with lower carrier lifetime. Furthermore, PL may identify other areas that may contain defects. As our study demonstrated, there are potential defects identified in PL images that do not match or are not found in EL images alone. Understanding what defects are visible with PL imaging and identifying how it can complement EL imaging is beneficial for detection of module failures or power losses.

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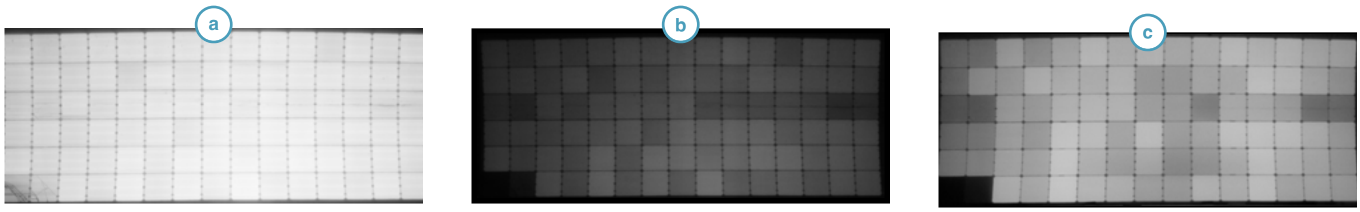

Fig. 2: Test results for a n-type silicon IBC module: (a) EL at I_{sc}; (b) EL at 10% of I_{sc}; (c) PL.

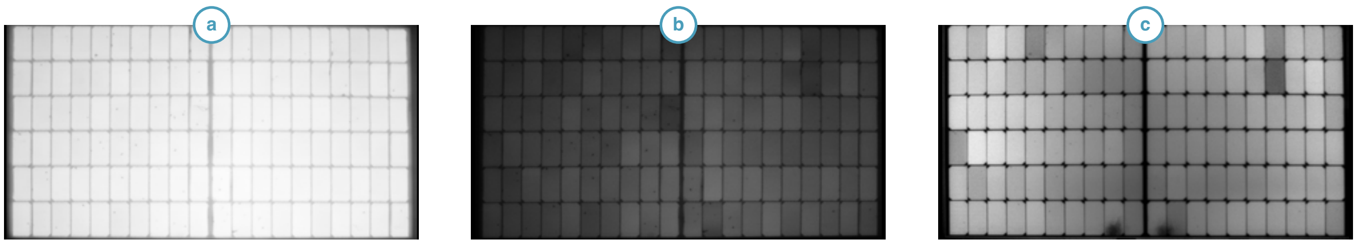

Fig. 3: Test results for a silicon HJT module: (a) EL at I_{sc}; (b) EL at 10% of I_{sc}; (c) PL.

Selected R&D **Project**

A study of PV module degradation after 15 years of operation at Singapore's Marina Barrage†

Rammdarshan S/O RAMESH, Dr Mauro PRAVETTONI

1. Background

Interest in solar photovoltaic (PV) electricity is growing quickly in Singapore and South-East Asia. All countries in the region are planning further adoption of PV in the coming decades, in a variety of deployments. This ranges from conventional solar farms in the country side and floating PV systems to building-integrated PV (BIPV). With increased interest in long-term installations, and decades-long performance warranties [1], much effort must be put into PV module qualification and understanding of degradation mechanisms. However, few field studies are available for tropical climates as compared to temperate ones. This work presents a reliability study of a sampling of PV modules after 15 years of operation in Marina Barrage, a coastal area of Singapore. Various degradation modes are identified, and their occurrence is correlated to the power degradation measured at SERIS' ISO/IEC 17025 accredited testing laboratory.

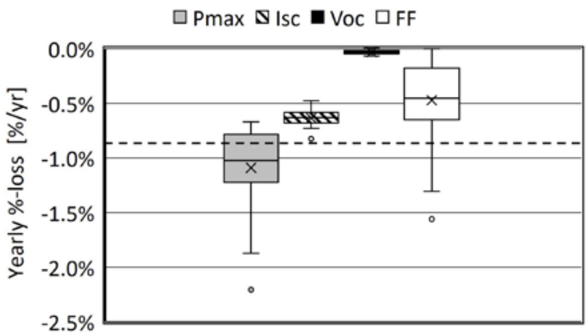

Fig. 1: Yearly relative degradation of the electrical parameters with respect to the nameplate after 15 years of operation in the tropical climate of Singapore, in a coastal area (linear degradation is assumed). The dashed line corresponds to the –0.85% max. yearly degradation as per manufacturer's datasheet [6].

2. Scope of project & objectives

30 PV modules were sampled from the original 405 modules installed on the Marina Barrage Solar Farm (total system capacity: 70 kW_p; module type: SolarWorld SW175 mono; cell technology: monocrystalline silicon; year of installation: 2008). These modules are of particular interest due to their proximity to sea water, and thus the possible augmented risks of corrosion and increase in severity of potential-induced degradation (PID) due to salt mist. These modules used polyvinyl fluoride (Tedlar®) as backsheet, which other studies showed to provide better long-term performance than other backsheet materials [2-3]. The pioneering use of monocrystalline type modules (which was not the mainstream in the early 2000s, but is indeed now) enhances the significance of this study to newer PV installations.

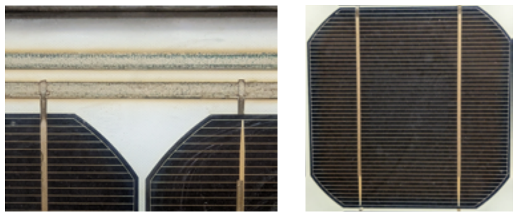

Fig. 2: Visual inspection of oxidation evident on the cross-connectors (left) but poorly visible along the busbars or grid fingers (right), on a typical module with high series resistance.

3. Methodology & Results

Electrical characterisation:

Figure 1 shows the performance degradation of all 30 modules from the original nameplate values [4]:

- Maximum power (P_{max}): 175 W
- Open Circuit Voltage (V_{OC}): 44.4 V
- Short Circuit Current (I_{SC}): 5.4 A
- Fill Factor (*FF*): 73.0%
- Number of cells: 72 (all cells in series)

The guaranteed performance of the modules after 15 years of operation is 87.2% (max. degradation loss: –12.8% from nameplate) of the nameplate value, according to the manufacturer's datasheet. This is equivalent to a linear average degradation of 0.85%/yr. The median observed P_{max} loss from the nameplate value is 1.0%/yr, which, although remarkably low for the region compared to previous studies [5], exceeds the threshold set by the manufacturer [6]: only 27% of the sampled modules show a performance degradation within the guaranteed threshold.

The most significant causes of P_{max} losses are attributed to corrosion (*FF* losses), PID (V_{OC} and *FF* losses) and soiling (I_{SC} losses). Cell cracks may also have played a role in the observed average deviation from nameplate: however, it is not easy to identify the causes of cracks, whether or not these came from transportation and handling during installation or disposal of the modules.

Corrosion:

The observed power degradation showed a strong correlation with the measured series resistance of the tested modules. Series resistance is directly affected by corrosion of the metal contacts and fingers. The R-value of a logarithmic curve-fitting is 0.95, indicating a strong correlation between corrosion and P_{max} loss. Visual inspection (a typical example is shown in Fig. 2) and electroluminescence analysis (EL: example for the worst case in Fig. 3) confirmed that widespread oxidation occurred on the cross-connectors and delamination or poor contact resistivity between the metal grid fingers and the cells.

†*An extended version of this article has been presented at the 1st Middle East and North Africa Solar Conference (MENA-SC), held in Dubai, UAE, 15-17 November 2023 and submitted for publication in the conference proceedings.*

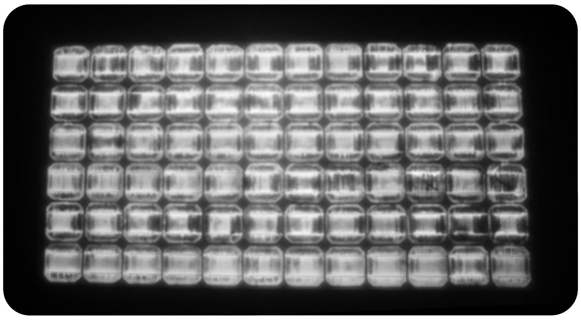

Fig. 3: EL imaging of the module with highest series resistance, showing evidence of delaminated grid fingers.

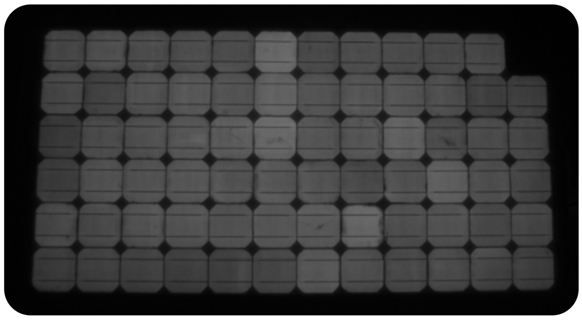

Fig. 5. EL at current injection equal to 10% of I_{sc}. PID affected the cell in the top-right corner (all cells look brighter when EL is observed at current injection equal to 100% of I_{sc}).

Oxidation and the resultant corrosion of the connectors may indicate oxygen and moisture ingress, either through the backsheet or through the edge sealant. Close analysis of the Tedlar® backsheet showed excellent conditions, with no visible signs of bubbles or delamination in any of the modules sampled. The backsheet colouration was consistent throughout with no localised stains or yellowing.

Soiling & Etching:

A further study was conducted to understand the effect of soiling and cemented soiling on P_{max} and I_{SC}. The modules had clearly visible cemented soiling along the edges of the modules, as can be seen in Fig. 4a.

Fig. 4: (a) Presence of cemented soiling, and (b) glass etching.

A sub sample of 10 modules were selected for soiling analysis: 5 modules that were considered the 'dirtiest' (based on visual inspection and I_{SC} measurements) and 5 modules that were considered the 'cleanest': the dirtiest modules were those that had the largest I_{SC} losses with minimal other defects such as PID or cracks. The cleanest modules were those that had the smallest I_{SC} losses from nameplate.

These modules were exposed to tropical storms to be cleaned naturally and then were manually cleaned. Minimal change was observed, indicating that rain and manual cleaning do not help soiling removal, which is usually evidence of soiling cementation.

The presence of salt mist in the coastal area, combined with soiling, may have contributed to significant signs of glass etching found on all modules (see for example Fig. 4b).

Potential Induced Degradation:

Potential Induced Degradation (PID) was investigated through EL imaging. At current injection equal to 10% of I_{SC}, the cells affected by PID would be dimmed or completely dark, depending on the severity of PID.

More than 20% of the tested modules exhibited some form of PID, with either dark cells at the edges at 10% I_{SC} current injection or a large decrease in intensity of these cells. Figure 5 shows an example of a PID-affected module.

4. Conclusions

This study analyses the degradation mechanisms of 30 mono-Si PV modules that were operated for 15 years in a coastal area of tropical Singapore, and the effects that these mechanisms have on their performance. Notwithstanding the harshness of the coastal tropical environment, nearly half of the modules showed good performance, with less than 1%/yr power degradation after 15 years of operation: however, only 27% of the modules sampled showed degradation within the limits stated by the manufacturer.

Corrosion and oxidation were analysed, particularly on the cross-connectors and the metal grid fingers. Visual inspection of the backsheet was conducted to identify any ingress routes of moisture and air, which may have caused the observed oxidation: however, the high quality of the backsheet (Tedlar) seems not to have caused of moisture ingress. Soiling analysis and the effect that cemented soiling has on the performance of the modules was assessed via natural cleaning by tropical storms and manual indoor cleaning. PID was characterised via EL imaging and the difference between imaging at a current injection equal to I_{SC} and to 10% of I_{SC}, respectively.

Overall, understanding the root causes of the observed degradation mechanisms in the high-salinity maritime and tropical environment and their correlation to performance losses is key to future PV installations in the region and in other regions with similar environmental conditions.

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Selected R&D **Project**

Reliability of modules in floating photovoltaics: environmental conditions, severities and stress tests†

Dr Mauro PRAVETTONI

1. Background

The recent evidence of the need for a further boost in solar photovoltaic (PV) deployment has triggered actions from policymakers. These are leading to a change of paradigm in the PV community, from established PV applications (mainly rooftop and utility-scale for commercial PV modules, but also PV on spacecraft, indoor PV and gadgets) towards the exploitation of new “integrated” applications. Since 2022 our institute has co-organised the International Integrated-PV Workshop, bringing together worldwide experts of building-integrated PV (BIPV), vehicle-integrated PV (VIPV), agro PV, floating PV, and PV integrated into urban infrastructures (noise-barrier PV, PV fences, road-integrated PV, PV shields, PV carports, etc.).

Among the integrated PV solutions, floating PV has recently seen a significant growth in the global market. According to Wood Mackenzie [1], the annual global floating PV installations are expected to grow from 0.8 GW_{DC} in 2020 to 4.1 GW_{DC} in 2026, with a market size that is expected to hit USD 10 billion by 2030 [2]. The floating PV demand is currently located mostly in Asia, with about 80% of global share (mainly China, India and Korea, but with a growing interest in Malaysia, Thailand, Indonesia and Vietnam). Outside of Asia, Netherlands and more recently USA are exploring more and more floating PV solutions.

Modules designed for applications in floating PV systems require a re-evaluation of the test procedures for their qualification, and new advanced stress tests will be needed to ensure that the modules will withstand the new operational environments.

2. Scope of project & objectives

Floating PV plays an important role in the Singapore Green Plan 2030 [3], a remarkable example being the large (~45 football fields) floating solar park at Tengeh Reservoir. The plan is to continue maximising solar panel deployment in Singapore, including exploring off-shore floating PV. However, the path towards further deployment of floating PV comes with new reliability challenges. This article lists the environmental features (and associated stresses with severities) that need to be assessed soon to ensure the reliability of PV modules in floating PV applications. Examples are: (i) Rapid change in temperature (thermal shock caused by water impact/immersion), with risk of mechanical failures, cracking, seal damage and insulation leakage; (ii) Acceleration, vibrations and mechanical drops/shocks, with risk of mechanical failures.

A dedicated testbed has been designed to evaluate the mechanical impact of vibrations, impact of water and; thermal shock. New test protocols are to be designed, including: Potential induced degradation (PID) in salt mist [4]; vibration test; drop test and water drop test; partial immersion test; combined tests. Preliminary results are shown below for commercial PV modules.

3. Methodology & Results

Classification of floating PV systems and risk assessment: The new reliability challenges for PV modules in floating PV systems are ultimately caused by two new factors: (i) the installation is in close proximity to water (either fresh or salty); and (ii) the moving environment. Thereafter it is useful, in view of an appropriate risk assessment, to classify floating PV installations as described in Table 1. Broadly speaking, PV modules in floating installations can be:

1. *Physically separated from water*, so that the modules cannot be in contact with water underneath. This can occur because:
   a. Modules are far enough from water;
   b. Modules are separated from water by a physical medium (typically a membrane)
2. *Not physically separated from water*, in which case the contact with water is possible. In this case, the modules can be installed on:
   a. Rigidly joined buoys, so that the distance between modules does not vary;
   b. Non-rigidly joined buoys, so that the modules have the largest possible freedom of movement.

Engineering complexity is expected to be higher when modules are kept far from water (case 1a above), but it is also expected that the reliability challenges are mitigated in this case; on the other hand, floating systems on non-rigidly joined buoys (case 2b, by far the most common solution nowadays), where modules are in close proximity to water, present the higher risk in terms of potential causes of module failures.

A risk matrix with over 100 different causes of module failure was prepared. The causes have been rated on a scale from 1 to 9, in which less likely and less severe causes of degradation (e.g. soiling due to the presence of snow or ice) are distinguished from mid likely and mid severe causes (e.g. PID in the maritime environment or event based structural collapse) and from very likely and very severe causes (e.g. module breakage due to torsion or failure of mechanical structure).

Table 1: Proposed classification of floating PV systems

Physically separated from water		Not physically separated from water	
By physical distance	By physical medium	Rigidly joined buoys	Non-rigidly joined buoys

Higher complexity ← Lower complexity

Lower risk → Higer risk

†*The content of this article was presented in a plenary talk at the 50th IEEE Photovoltaic Specialists Conference (IEEE PVSC) held during 11 - 16 June 2023 in San Juan, Puerto Rico.*

Table 2: Environmental conditions, severities and stress tests for PV modules to be deployed in floating systems.

Conditions & classes (IEC 60721)		Description	Severity	Possible effects & failures	Stress tests (IEC 60068)	Are currently applied to PV?
Climatic conditions: 6K4, 6K5, 6K6 (tropical damp)	Cold & heat	Thermal cycling caused by daily and seasonal temperature variations	Air: -40/+70°C Water: ~0/+35°C	Electrical failure; mechanical failure; increased mechanical stress; increased wear due to contraction/expansion; sealant failure	Thermal cycling Damp heat	Yes
		Thermal shock caused by water impact	Air/water: +40/+5°C Surface: +70/+5°C	Electrical failure; mechanical failure; cracking; sealant failure; leaks	Thermal shock	No
	Humidity	*High:* moisture absorption and adsorption *Low:* desiccation; embrittlement	RH: 10/95%	Loss of mechanical strength; chemical reactions; corrosion; mechanical failures; insulation failures; increase in series resistance	Humidity freeze Damp heat	Yes
	Solar radiation	Photochemical and photophysical reactions caused by exposure to the solar radiation	100-1120 W/m² Accelerated (UV)	Insulation failures; optical failures; light induced degradation (LID); surface deterioration; embrittlement; discolouration	Stabilization Exposure UV	Yes
	Wind	Force application to the centre of the module, with induced vibration and particle deposit	50 m/s 60 m/s (typhoon)	Structural collapse; mechanical failure	DMLT	Yes
	Rain, hail, snow, wetness	Mechanical impact/loading, water absorption, and thermal shock caused by weather conditions	Same as conventional	Insulation failures; electrical failure; cracking; leaks; cracking; surface deterioration/damage; structural collapse	Wet leakage MLT Hail test	Yes
	Other water	Water splash caused by the impact of waves	10 m/s	Insulation failures; electrical failure; cracking; leaks; cracking; surface deterioration/damage; structural collapse	Water impact Water immersion	No
Biological cond.: 6B2	Flora & fauna	Presence of mould, fungus, etc. and of rodents and other animals potentially harmful to modules and components	Ammonia: 3.0 mg/m³ 4.2 cm³/m³	Increased wear; mechanical failure; electrical Failure; corrosion	Ammonia test List of fungus resistant materials	Partially (ammonia)
Chemical subst.: 6CX	Chemically active substances	Extremely corrosive effect of salt (in the assumption of no other industrial pollutants); presence of ions (mainly Na⁺ and Cl⁻)	Salt in water: 30 kg/m³ Ammonia: as above	Increased wear; mechanical failure; electrical failure; corrosion; potential induced degradation (PID)	Salt mist corrosion test Ammonia test PID+salt mist	Partially (salt mist, ammonia)
Mechanical subst.: 6S2-6S3	Mechanically active substances	Deposition of sand and dust transported by wind; deposition of salt by water	Sand: 10 g/m³ Dust: 3.0 mg/(m² h) Salt: Not available	Increased wear; electrical failure; mechanical failure; overheating (hot spot); abrasion	Sand abrasion Hot spot PID+soiling	Partially (abrasion, hot spot)
Mechanical conditions: 6M1, 6M2*	Stationary vibrations (sinusoidal)*	Dynamic stress to the module caused by waves	Displacement: 1.5 mm* Acceleration: 10 m/s² Frequency: 2-13 Hz	Mechanical failure; electrical failure; increased wear; structural collapse; cracking	Vibration tests (sinusoidal)	No
	Vibrations (others)	Dynamic shock caused by the impact of waves	Type I (peak): 50 m/s² Type II (peak): 100 m/s²	Mechanical failure; electrical failure; increased wear; structural collapse; cracking	Vibration test Shock test	Partially (transport)
	Angular motion	Rotation and twist of the module caused by the wave motion	Roll (X): 22.5 deg / 0.14 Hz Pitch (Y): 10 deg / 0.2 Hz Yaw (Z): 4 deg / 0.05 Hz	Mechanical failure; electrical failure; increased wear; structural collapse; cracking	Torsion test Combined tests	No

Environmental conditions and stresses:
The international standard series IEC 60721-6 classifies the environmental conditions and severities that electrical appliances are expected to encounter in maritime operation, ranked in terms of their severity. Table 2 lists the relevant conditions that can be inferred from IEC 60721-6 specifically for PV modules in the floating environment (on fresh or salty water), together with related stress tests from IEC 60068. Some of these tests (e.g. thermal cycling and damp heat) are already common stress tests for the qualification of PV modules; some others (e.g. thermal shock, torsion test) are not (or only partially) addressed in dedicated PV standards. In the next sections, some of the stress tests that are not currently applied to PV modules are described.

PID in a salt-mist environment:
Potential induced degradation (PID) is a known degradation mechanism that can affect PV modules in the field, and has been shown to be particularly aggressive in high humidity and high temperature conditions [5].

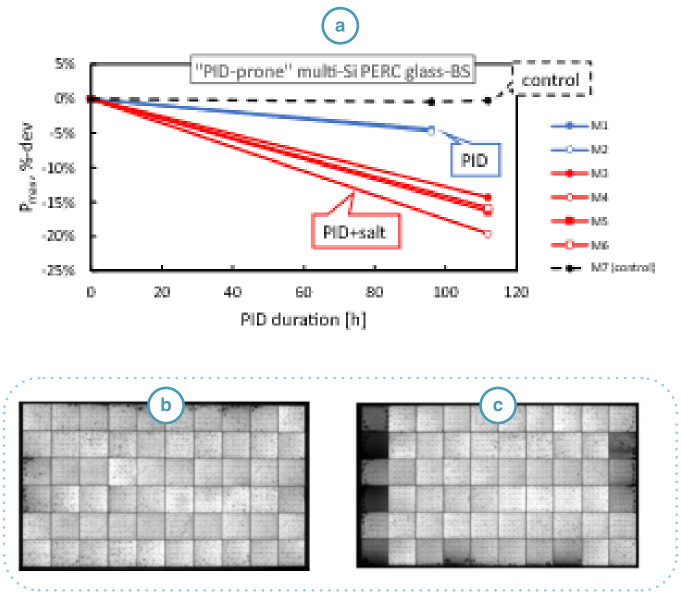

Fig. 1: PID test in a salt mist chamber: (a) Percentage degradation of P_{max} after ~100 hours of standard PID testing (blue lines) and PID in a salt mist chamber (red lines; control module in black); (b) EL of a PID tested module using standard conditions (60°C, 85% relative humidity); (c) EL of a PID tested module in the same conditions but with the addition of salt mist [4].

It is suspected that salt mist accelerates the detrimental effects of PID, hence a combined PID and salt mist test can be considered to assess the robustness of PV modules against PID in floating environments. Figure 1 shows the results of a previous measurement campaign [4] where six PID-prone commercial multi-Si PV modules confirmed the accelerating factor of salt mist to PID.

Mechanical stresses: vibration and torsion:
The moving floating environment may force the PV modules to undergo torsions and vibrations which are normally not considered for modules in conventional (static) installations. In a recent measurement campaign held at SERIS, the mechanical stress caused by the dynamic mechanical load test (DMLT, a standard module qualification test: 1000 cycles of ±1000 Pa of pressure at the centre of the module, with ~0.05 Hz frequency) was used as a benchmark for judging the robustness of commercial-size PV modules against torsion (1000 cycles of ±400 Pa of pressure at the opposite edges of the module, and at the same frequency as DMLT) and vibration (8 hours of sinusoidal vibration at 3 Hz angular motion, a medium-low frequency for stationary vibrations cause by waves – see Table 2).

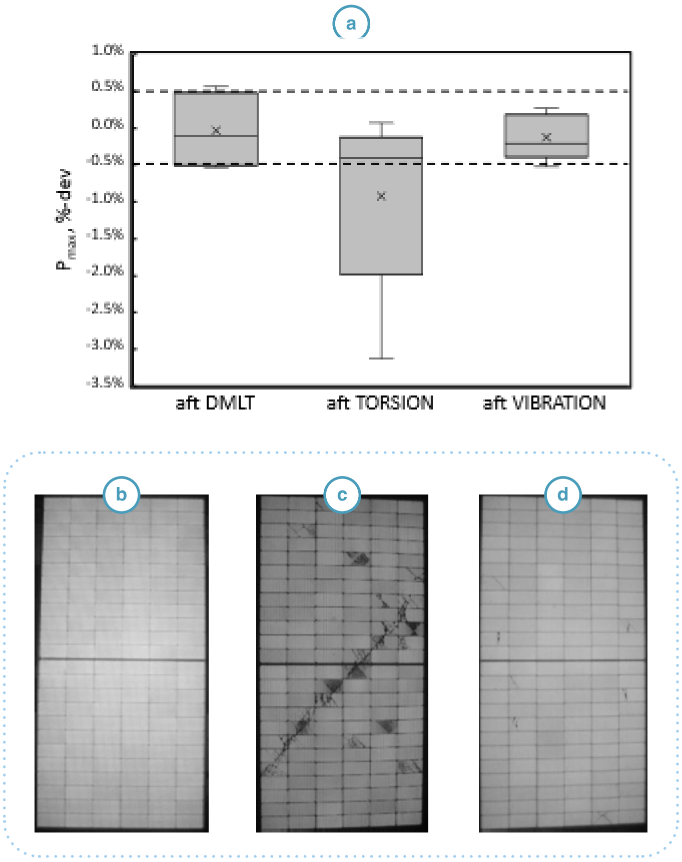

Fig. 2. Mechanical stress tests: Comparison of torsion and vibration tests with the standard DMLT. (a) Distributions of the observed PV power degradation after mechanical stresses for a set of 5 modules from Tier-1 manufacturers (the dashed lines indicate the power deviation tolerance in intermediate precision conditions of measurements). Bottom row: Electroluminescence image of the worst-affected module after DMLT (b), torsion test (c), and vibration test (d).

A set of 5 batches of 4 modules each (1 control module plus 3 modules for DMLT, torsion and vibration tests), all mono-Si PERC from 5 Tier-1 module manufacturers (both glass-glass and glass-backsheet, all framed) were investigated. All manufacturers declare enhanced tolerance to mechanical loading, although no manufacturer usually tests modules for torsion or vibrations. Figure 2a shows the distributions of the measured degradations in maximum power (P_{max}) at standard test conditions after DMLT, torsion and vibration tests. The dashed line indicates our laboratory's tolerance of P_{max} deviations in intermediate precision conditions of measurements (i.e. replicated measurements of the same sample, with the same measurement system, procedure and location, after an extended period of time; variations within the two dashed lines are not significant and may not indicate module degradation. The test of torsion was observed to be significantly more stressful to the modules than the test of vibration and the standard DMLT (the numerous cell cracks generated by the torsion stress are clearly visible in the electroluminescence image of the worst-affected module, see Fig. 2c). This result suggests that a torsion test should be considered for PV modules to be deployed in floating PV systems.

4. Conclusions

Floating PV is receiving ever growing attention worldwide, with more than 4 GW_{DC} of new installations projected in 2026, and > USD 10 billion market size by 2030. SERIS is a pioneer of the research on floating PV systems and is now addressing the challenges for PV module reliability, particularly for off-shore floating systems. Over a hundred new risks of PV module failure have been identified so far for FPV systems, ranked on a scale from 1 to 9 in terms of criticality. Among the most critical aspects – as confirmed by field data – are PID and the mechanical stresses. Experimental results confirmed that the saline maritime environment accelerates and increases the risk of PID. Among the mechanical stresses, torsion seems to be more severe than the standard DMLT and the vibration test. These and other tests are now under evaluation at IEC level for an international agreement of dedicated stress tests for modules to be deployed in floating PV systems.

Acknowledgements

This work was supported by SERIS and by Fred. Olsen Renewables. The author also acknowledges the support of SERIS' Reliability Laboratory staff and of NUS students Mike Mahesh S/O Sundar Das and Rammdarshan S/O Ramesh, without whom the measurement results of this article would not have been possible.

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Selected R&D **Project**

3D glare assessment for PV deployment in high-density urban environments

Dr Huixuan SUN, Dr Thomas REINDL

1. Background

Singapore, a city state near the equator with only ~720 km^2 of land, aims to deploy 1.5 GW$_p$ of solar PV by 2025 and beyond 2 GW$_p$ by 2030. With very limited land available for ground-mounted PV and only some water bodies for Floating PV, the vast majority of PV system will be deployed on (rooftops) or at (BAPV, BIPV) buildings.

To further enhance the solarisation of cities, smart planning is required to optimise PV deployment especially in high-density urban environments. With increasing PV deployment around the world, concerns about glare have also risen, particularly for PV installations at and near airports where glare effects onto the flights paths and the control tower must be avoided (e.g. using the methodology required by the U.S. Federal Aviation Administration (FAA) [1] and the U.S. Department of Defense [2]). In the densely built-up urban context, glare hazard from PV installations to traffic participants and to neighbouring buildings is a concern that has become increasingly important for city planners and residents.

Typical glare assessment tools assume a direct line-of-sight between the Sun and the PV modules and/or the PV modules and the observer. However, in cities this is rarely the case, as there are many obstructions perceivable, be it other buildings or infrastructures. Therefore, a comprehensive glare assessment tool for the complex analysis of PV deployment is needed for densely built-up urban areas.

2. Scope of project & objectives

In this work, we have developed and tested a glare assessment tool using 3D ray-tracing techniques, which can:

a. estimate the total glare occurrences for any viewpoints (360 degree) during any time of the year (in 1-hour resolution);
b. visualise areas around the PV deployment that may experience glare;
c. classify the severity of glare to further identify the glare hazard (e.g. glint);
d. quantify the effect of mitigation plans in reducing the occurrences of harmful glare.

The developed 3D tool is highly flexible, compared with commercially available tools, and includes features such as automatic PV layout generation with precise setting of tilt angle and orientation for PV panels, computation of shadings projected onto the PV system from surrounding buildings, and the modelling of obstructions that may interrupt the line-of-sights and block glare reflections.

3. Significance & impact of project

By providing comprehensive 3D visualisation results, the developed method can be applied as a smart planning tool for PV deployment to better balance renewable energy generation and visual impact and contribute to the optimisation of PV deployment in high-density urban environments.

4. Methodology & Results

An integrated workflow was developed on the Rhinoceros + Grasshopper software platform, using Ladybug and Honeybee component groups for daylight, ray-tracing and radiation modelling (Fig. 1).

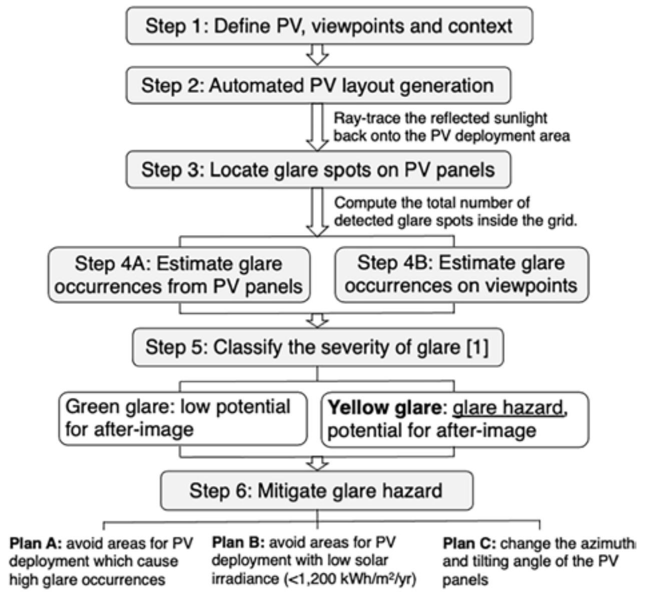

Fig. 1: Workflow for the 3D glare assessment tool

The workflow has been tested in a case study of a densely-built public housing precinct in Singapore. Starting from a hypothetical PV system deployed on the rooftop of a 4-storey carpark, the year-round glare analysis was conducted on hourly intervals for viewpoints that are evenly distributed on surrounding building facades with three different orientations (i.e. south, north, east) and two sets of building heights (e.g. 15-27 m, 36-72 m). Boundary condition settings are summarised in Table 1 and Figure 2.

Table 1: Boundary condition settings of the case study

Hypothetical PV deployment	
PV layout	50 m x 45 m at an elevation of 12 m
PV panels	Dimension: 1 m x 2 m Azimuth: 180°, tilting angle: 15°
Hypothetical viewpoints: evenly distributed by the grid size of 6 m x 6 m	
Height	Orientation
15 - 27 m	North; South; East
36 - 72 m	North

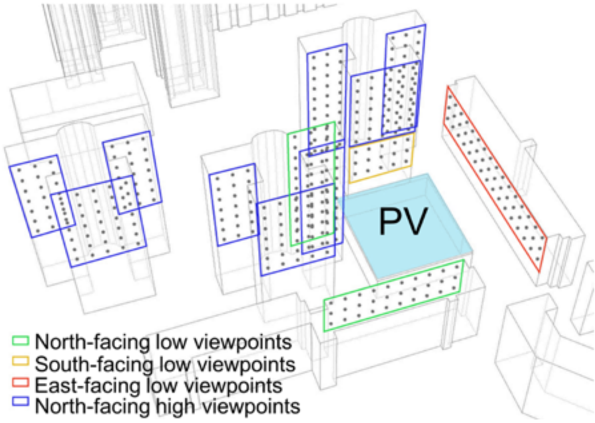

Fig. 2: Location of viewpoints

The glare occurrence is counted when the reflected ray of sunlight reaches the viewpoints, and then mapped for all viewpoint planes and PV deployment areas. The glare severity is classified into two types, namely, green glare (low potential for after-image) and yellow glare (potential for after-image); the very severe red glare (potential for permanent eye damage) is rarely observed in urban contexts. Furthermore, the study also evaluates the results of different mitigation measures: a) Plan A: avoiding PV installation with top 10% annual glare occurrences; b) Plan B: avoiding PV installation with low solar irradiance (<1,200 kWh/m^2/yr). c) Plan C: changing the azimuth and tilt angles of the PV panels.

In this glare assessment tool, the glare occurrences of the viewpoints and PV deployment are visualised (Fig. 3). Using Tableau, interactive dashboards are computed to indicate the time of yellow glare occurrences for different viewpoints (Fig. 4) and quantify the effect of mitigation plans in reducing glare hazard (Fig. 5).

The case study has the following main findings: a) The time of glare occurrences varies with different locations and orientations of the viewpoints. In this case, yellow glare happens before 10 a.m. for the east-facing viewpoints, but only after 12 p.m. for the viewpoints towards north and south; b) PV panels with the top 10% glare occurrences mostly have an annual solar irradiance lower than 1,200 kWh/m^2; c) For this specific PV deployment, mitigation plan A and B reduce 78.1% yellow glare occurrences for north-facing and south-facing viewpoints, yet only 27.5% yellow glare occurrences for east-facing viewpoints.

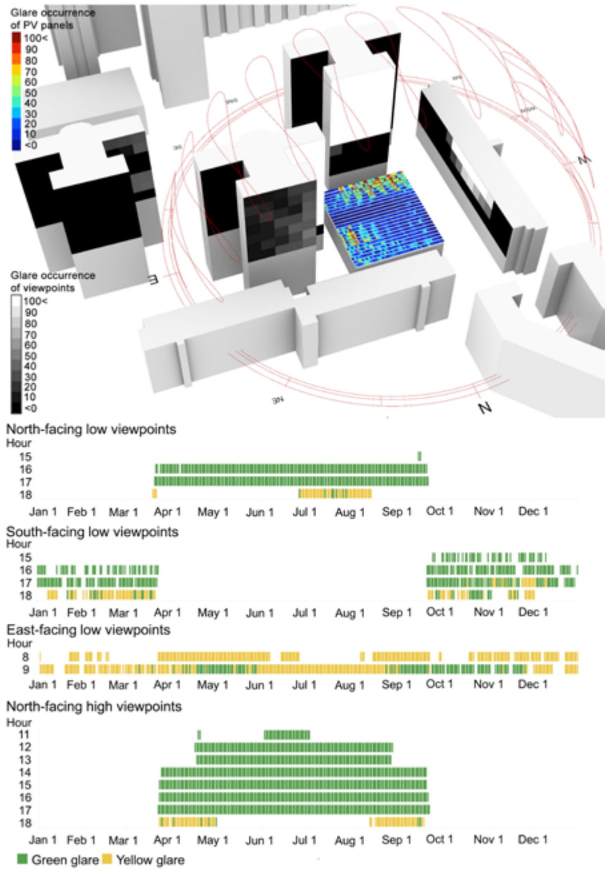

Fig. 3: Visualisations of the time and annual occurrences of the glare at hourly intervals on viewpoint planes and PV deployment areas

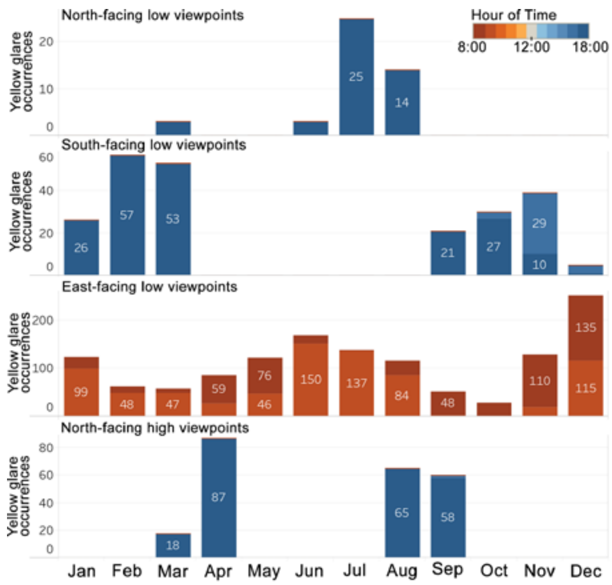

Fig. 4: Distribution of yellow glare occurrences for different viewpoints

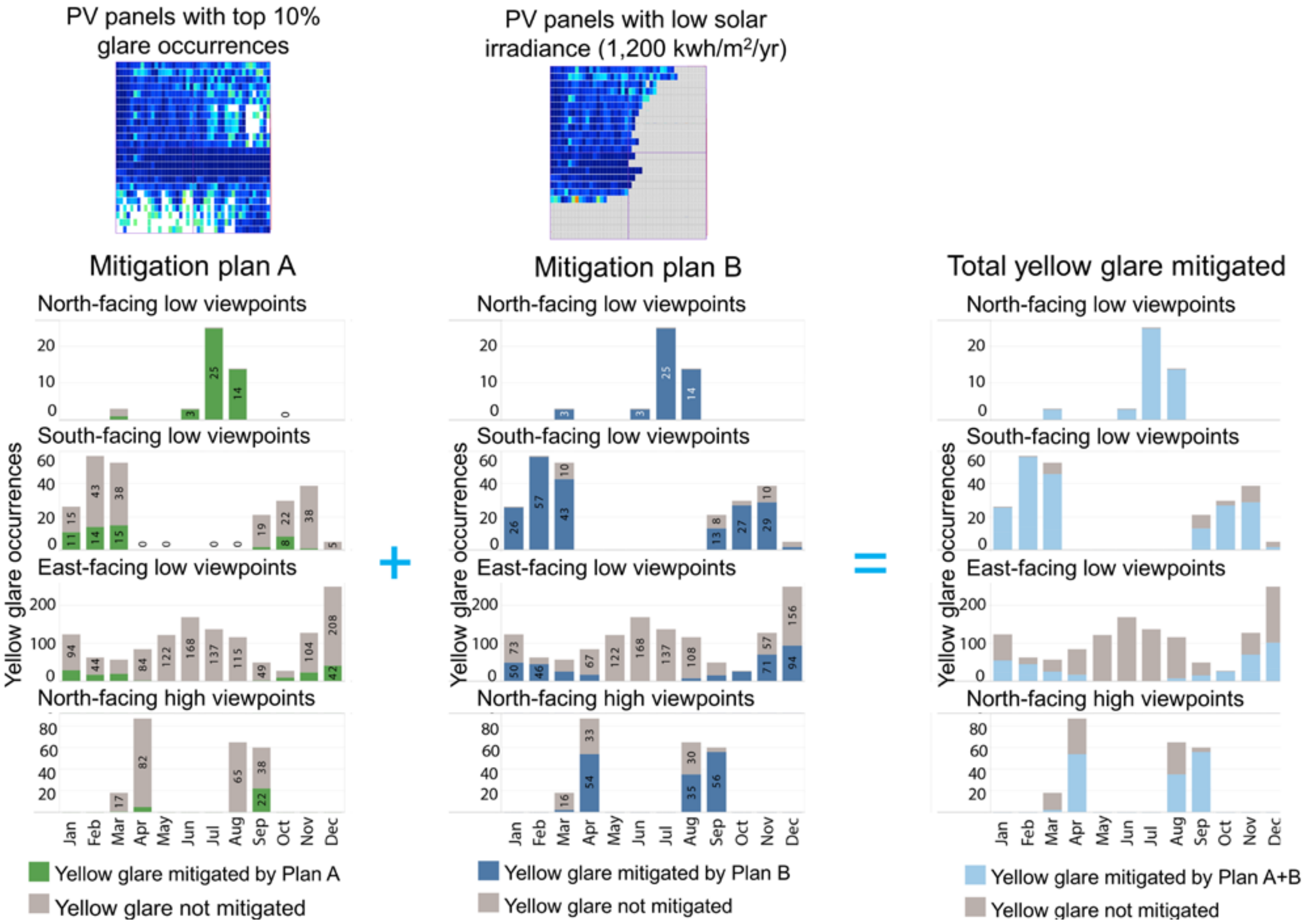

Fig. 5: Yellow glare occurrences reduced by the mitigation strategies

5. Conclusions

A novel 3D glare analysis tool was developed to estimate glare occurrences caused by the target PV installation and received by the surrounding viewpoints for high-density urban areas. This tool can visualise and quantify the results of glare assessment for different PV layouts and compare different mitigation strategies. In the future, this workflow will be developed to automatically generate optimal PV deployment plans that have the least glare hazard and optimise energy yield based on the context setting.

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The value of solar forecasts and the cost of their errors

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1. Background

Solar irradiance, and therefore photovoltaic (PV) power, is inherently uncertain. To manage this uncertainty, solar forecasting has frequently been used to make predictions on the future values of solar irradiance and PV power. Despite the advances in solar forecasting methods and their ever-increasing accuracy, little is known about their value for real applications, e.g., bidding in the electricity market, power system operations, and household electricity bill reduction. There is a need to put these different findings into context and give a holistic view on the economic implications of solar forecasting. Understanding the value of forecast and the cost of the forecast errors, as well as how to mitigate them, will help in advancing PV penetration and decarbonisation efforts.

This research was supported by the Energy Market Authority of Singapore (EMA) through a grant on “Advanced Solar Power Forecasting for Safe and Reliable PV Grid Integration in Singapore” (Award No. NRF2017EWT-EP002-004).

2. Scope of project & objectives

This work comprehensively reviews and quantifies the value of solar forecasts and the cost of their errors across the different applications available in the literature, namely: electricity market, transmission system, distribution system, microgrid, and household, as illustrated in Fig. 1 (left).

3. Significance & impact of project

By knowing the value of solar forecasts and the cost of their errors for different applications, researchers in the field of solar forecasting can put their work into context and possibly direct their efforts into areas that have not been well researched or quantified. PV owners and system operators can use the findings in this work to determine the value of solar forecasts for their specific applications, as well as which metrics to measure their value. Regulators can take some of the findings discussed in this work to design rules, frameworks, and incentives that can reduce grid operational cost, mitigate the cost of forecast errors, and advance the integration of renewable energy. Some of the ways to manage the uncertainty of solar energy that were documented in the literature are outlined in Fig. 1 (right).

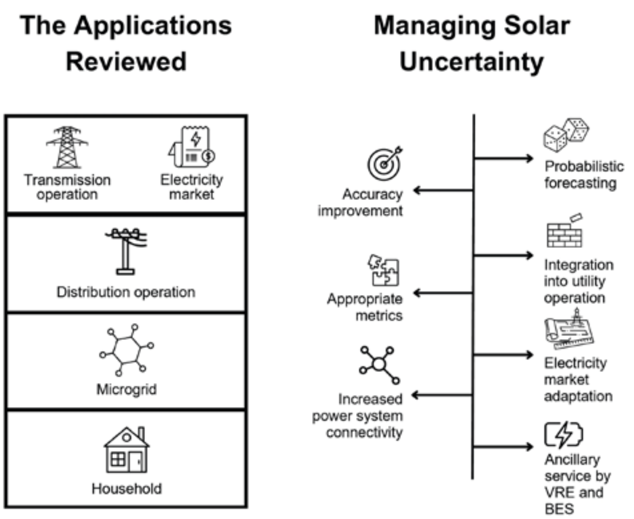

Fig. 1: The applications where the solar forecasts value of cost of their errors are available in the literature (left), and the ways to manage solar uncertainty (right)

4. Methodology & Results

The cost [USD] of forecast errors was obtained by subtracting the system operation cost with perfect forecast from the operation cost of using imperfect forecast. Likewise, the forecast improvement value [USD] was calculated by subtracting the operation cost when using a specific forecast method from the cost of using a reference forecast – usually persistence-based forecast. Next, these quantities [in USD] were divided by the PV yield [MWh] over the same operational period to obtain a [USD/MWh] quantity. When the PV yield was not available directly from the source publications, it was calculated using specific PV output [kWh/kWp] from the Global Solar Atlas at the location mentioned in the publications, multiplied by the PV capacity [MWp].

If not mentioned in the source articles, the normalised root mean squared error (nRMSE) [%] was obtained by dividing the absolute RMSE by 1,000 W/m^2 for irradiance and by installed PV capacity [MWp] for PV power. The skill score [%] was calculated from the nRMSE of a specific forecast method to that of the persistence-based forecast. When the forecast methods were not compared against persistence, the forecast with the highest nRMSE was used as the reference.

The value of solar forecasts for the different applications documented in the literature are listed in Table 1. The savings from employing solar forecasts (compared with no forecast) range from 0.33 USD/MWh to 252 USD/MWh, as shown in Fig. 2. Most works analysed the value of solar forecasts at the transmission level, either from the electricity market perspective or the system operations perspective. This is a given since forecast of utility-scale PV can be used to inform more decisions at the transmission level: the system operator can use solar forecast to conduct unit commitment and economic dispatch (UCED) and determine reserve requirement, while the electricity market participants can use solar forecast to bid in the market and calculate their profits. At lower levels, there are fewer decisions where solar forecast can be employed. The stake with transmission-level PV forecast is also higher since it helps to maintain the stability of the whole power system.

Table 1: The value of solar forecasts documented in the literature for different applications

Transmission operation	Electricity market	Distribution operation	Microgrid	Household (with energy storage)
• Reduce generator cycling • Reduce reserve requirement • Increase dispatch efficiency • Reduce PV curtailment • Reduce/remove the need for energy storage	• Reduce electricity price volatility • Reduce imbalance settlement • Reduce/remove penalty • Increase trading profits	• Reduce imbalance settlement	• Reduce demand charge • Increase energy arbitrage profitability • Reduce fuel consumption	• Reduce demand charge • Increase energy arbitrage profitability • Prevent energy storage failure

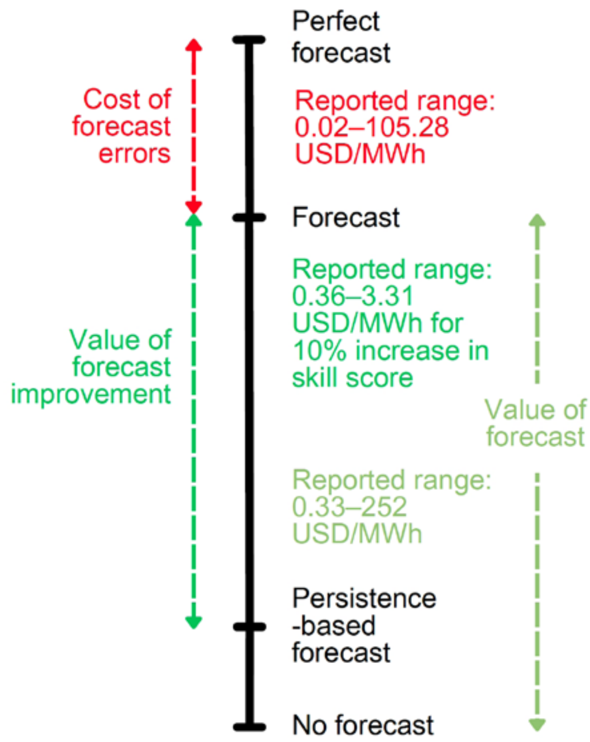

Fig. 2: Range of values of forecast improvement and costs of forecast errors reported in the literature

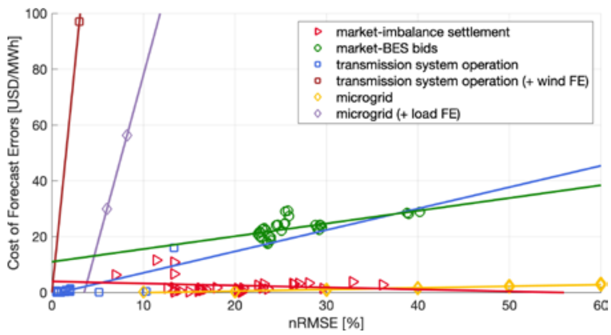

Fig. 3: Cost of solar forecast errors and its corresponding nRMSE reported in the reviewed studies. Least squares regression lines are plotted for each of the category. FE stands for forecast errors.

At the private end-user level, solar forecast only has economic value in households with energy storage and/or shiftable loads; without them, there is no decision-making process that can incorporate solar forecast.

In Fig. 3, the cost of solar forecast errors from a total of 13 publications for different applications and nRMSE are plotted. Linear least squares regression lines for the different applications are drawn to indicate how the cost varies with nRMSE.

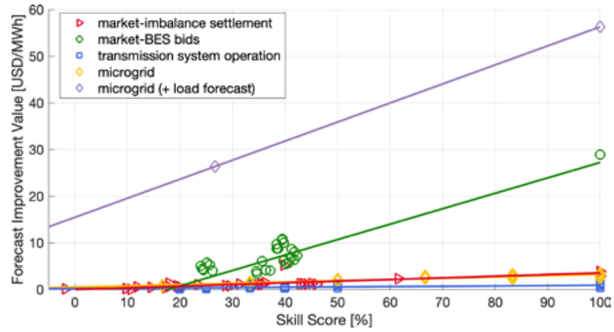

Fig. 4: Value of forecast improvement and its corresponding skill score reported in the reviewed studies. Least squares regression lines are plotted for each of the category.

Counterintuitively, for imbalance settlement, the regression line suggests that at higher nRMSE, the cost of solar forecast error is lower. This is because different publications have different parameters and system characteristics, which renders some of the results not directly comparable. There are some outliers in Fig. 3, which probably arise because wind and load forecast errors were also considered in calculating the cost of forecast errors.

The median cost of PV forecast errors for the four applications shown in Fig. 3 (imbalance settlement, bidding with BES, transmission system operation, and microgrid, without wind or load forecast errors) are 1.43, 22.94, 0.36, and 1.26 USD/MWh respectively. The minimum and maximum cost forecast errors, meanwhile, range from 0.02 USD/MWh all the way to 105.28 USD/MWh, as illustrated in Fig. 2. Putting these costs of forecast errors into perspectives, the levelised cost of electricity (LCOE) of PV systems across Europe and North America range from 40 to 140 USD/MWh.

Figure 4 then shows the value of solar forecast improvement – from a total of 11 publications – for the different applications and skill score. Unlike the trend of forecast error cost and nRMSE plotted in Fig. 3, the linear regression lines clearly suggest that higher skill score likely translates to higher forecast value for all applications. Different applications have different slopes; starting from the steepest, bidding with BES, imbalance settlement, microgrid, and transmission system operation experience a 3.31, 0.36, 0.27, 0.07 USD/MWh increase in forecast value for every 10% increase in skill score.

Additionally, based on the works reviewed, there are a few salient observations:

- The value of solar forecast in electricity markets is largely determined by the imbalance settlement schemes and prices. Depending on system conditions, inaccurate forecast can have higher value than more accurate forecast.
- Updating day-ahead solar forecast with more accurate intra-day forecast can yield benefits through lower imbalance settlement, lower penalty, and energy arbitrage.
- Although the value of probabilistic forecast has not been as widely reported, those that are available suggest that using probabilistic forecasting brings additional value to both system operators and market participants.
- There is diminishing return in improving the accuracy of solar forecast because even if all solar uncertainty is removed, there is still uncertainty from load forecasting, which power systems have been designed for.
- In the absence of clear incentives for higher accuracy, solar forecast that maximises the interest of the PV operators do not necessarily maximise the interest of the power system or consumers.

5. Conclusions

The cost of forecast errors reported in the literature range from as low as 0.02 USD/MWh all the way to 105.28 USD/MWh, with the value of forecast improvement ranging from 0.36 to 3.31 USD/MWh for every 10% increase in skill score, as summarised in Fig. 2. The upper range of these values is not insignificant when compared with LCOE of typical PV systems across Europe and North America: 40–140 USD/MWh. The value of forecast and forecast error cost will still evolve, with improvements in the forecasting methods as well as with changing rules on PV and storage participation in the electricity and ancillary services markets.

Nevertheless, even if PV generation can be perfectly forecasted, it will remove the uncertainty but not the variability. The cost of PV variability, or non-dispatchability, is still much higher than the cost of solar forecast errors at high PV penetration. Therefore, although solar forecasting is necessary and will definitely help smoothen PV integration into power systems, solar forecasting alone is not enough. To decrease the costs of PV variability, the concept of firm PV – making PV dispatchable through oversizing PV systems, adding BES, and proactive PV curtailment – can be implemented gradually as the cost for both PV and BES continues to fall.

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Levelised cost of PV integration for distribution networks

Dr Oktoviano GANDHI, Dr Carlos D. RODRÍGUEZ-GALLEGOS, Asst Prof Wenjie ZHANG, Dr Thomas REINDL, Prof Dipti SRINIVASAN

1. Background

The increasing penetration of variable solar photovoltaic (PV) generation in distribution networks introduces potential power system problems. One of the most important, and often the first to arise, are overvoltages. Although many measures have been proposed and implemented to solve the problem, a standardised metric to assess their economic viability is lacking.

The various PV integration measures do not come for free though; many of them require capital expenditure (CAPEX) and operational expenditure (OPEX). These costs typically increase at higher PV penetration. Yet, most works in the literature have not provided levelised cost in $/kWh, so it is difficult to evaluate whether the cost of integration is justified. Additional factors to consider are: the change in energy losses, system reactive power charge, and PV reactive power cost. Moreover, few works have compared the economics of battery energy storage (BES), even though many have proposed methods to utilise BES for overvoltage mitigation.

This research was supported by the Energy Market Authority of Singapore (EMA) through a grant on "Advanced Solar Power Forecasting for Safe and Reliable PV Grid Integration in Singapore" (Award No. NRF2017EWT-EP002-004).

2. Scope of project & objectives

This work seeks to provide a techno-economic analysis of various PV integration measures observed in the literature, using a newly proposed levelised cost of integration (LCI). Similar to levelised cost of electricity (LCOE), LCI incorporates all the costs associated with PV integration measures over the PV system lifetime and divides them by the energy generated throughout the lifetime. The costs include CAPEX (i.e., inverter oversizing and BES installation) as well OPEX, consisting of change in grid reactive power charge, change in line losses, curtailed PV power, PV reactive power cost, BES maintenance cost, BES roundtrip efficiency losses, and BES energy arbitrage.

Among the evaluated measures, not all of them are able to entirely remove the overvoltage problems. Only the results of those that do are shown, namely:

- Active power curtailment (APC)
- Reactive power control (RPC)
- Active-reactive power control (ARPC)
- Distributed BES with local control (DBES-L)
- Distributed BES with coordinated control (DBES-C)
- Semi-distributed BES with coordinated control (SBES-C)

3. Significance & impact of project

The LCI metric formulated here makes it possible to measure the cost of PV integration measures and compare them with the PV LCOE to evaluate their economic viability. The LCI values and evaluation of the PV integration measures presented in this study can be used by policy makers, regulators, and researchers to determine the measures' suitability based on their priorities and parameters. Although the LCI values depend on certain assumptions, the order of magnitude and trend should apply across different markets and distribution networks. The LCI framework can also be used to evaluate other renewable energy integration policies, methods, and algorithms.

4. Methodology & Results

The measures listed above were simulated on 69-bus and 119-bus distribution networks with real weather and electricity price data over a week. Residential load data are employed as it is the most prone to overvoltage due to low-load conditions during high PV generation around noon. For each distribution network, PV penetration is increased from 0 in steps of 10% up to 300% of peak load – roughly 100% PV penetration by electricity consumption. Overvoltage violation starts to occur at 160% and 90% for the 69-bus and 119-bus networks, respectively. Hence, the voltage mitigation measures are simulated for those penetration levels up until 300%. Only results for the 69-bus network are shown here for brevity.

Among the pertinent results from this work are:

1. ARPC is the most cost-effective voltage mitigation measure, followed closely by RPC and APC,
2. BES cost needs to decrease by more than 80% for BES to be economically viable for overvoltage mitigation, and
3. Change in reactive power charge, line losses, and BES roundtrip efficiency losses are all important components of LCI and need to be considered in assessing PV integration measures.

The results are illustrated in Figs. 1 and 2. From Fig. 1 it is clear that ARPC is the most economical way to mitigate overvoltage arising from high PV penetration levels in the distribution network studied. RPC, although more costly than APC at lower PV penetration, becomes more cost-competitive at higher PV penetration levels. ARPC and RPC LCI all remain below 1.5 SGD cent/kWh at 300% PV penetration, at 8-12% of the assumed PV LCOE in this work (11.4 SGD cents/kWh). This suggests that these measures are economically reasonable to be implemented. Compared with APC, ARPC can yield lower PV curtailment, while reducing the need to oversize the inverter compared with RPC.

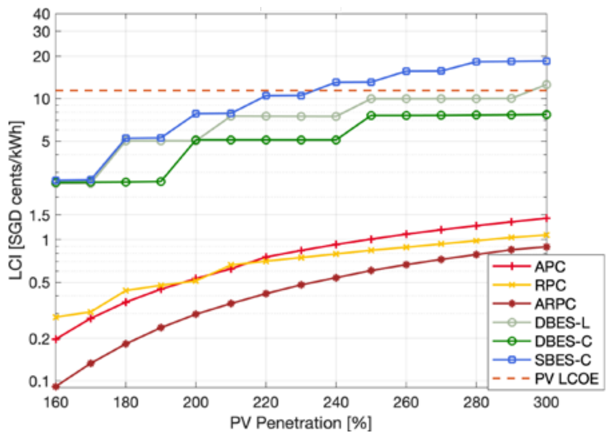

Fig. 1: Levelised cost of integration (LCI) for the different voltage integration measures across PV penetration levels in the 69-bus network. PV LCOE has been added for comparison.

On the other hand, the LCI of the BES measures are one order of magnitude higher than the non-BES measures and become higher than the PV LCOE at 240% for SBES-C. This is because of the large CAPEX required for the BES measures. Hence, installing BES for the sole purpose of overvoltage mitigation is not economically favourable at this point. Among the BES measures, DBES-C is the most economical, followed by DBES-L and SBES-C. This is largely due to DBES-C being able to solve the overvoltage problems with lower total BES capacities than DBES-L and SBES-C.

It is calculated that the BES price has to be 15–93 SGD/kWh (83–98% lower than its current price), for it to be economically competitive with APC. The BES operations and maintenance (O&M) cost also has to be reduced by the same proportion, otherwise BES cannot be competitive. Therefore, methods that can minimise the installed BES capacity can greatly reduce the LCI of the BES measures.

However, economic competitiveness may not be the only priority in implementing PV integration measures. For example, ARPC, the most economically viable PV integration measure for the distribution networks analysed, reduces electricity fulfilment by PV through curtailment. Since there is an urgent need to keep increasing the renewable share in electricity generation and consumption, ARPC's attractiveness is reduced. APC also shares the advantages and disadvantages of ARPC, though APC has higher LCI values. But APC has another advantage of lowering the line losses in the system, albeit at the expense of greater PV curtailment.

BES measures are the only ones among the measures analysed that can reduce line losses and allow more PV energy consumption at the same time. That being said, the roundtrip efficiency of BES also introduces energy losses that are not negligible. Having BES at each PV system is much more beneficial technically and economically in removing overvoltage problems than only at the substation. Although BES are still not economically competitive to be implemented solely for overvoltage mitigation, when their other functions (e.g. storing PV generation for times with low or no irradiance) are considered, BES may make more economical sense.

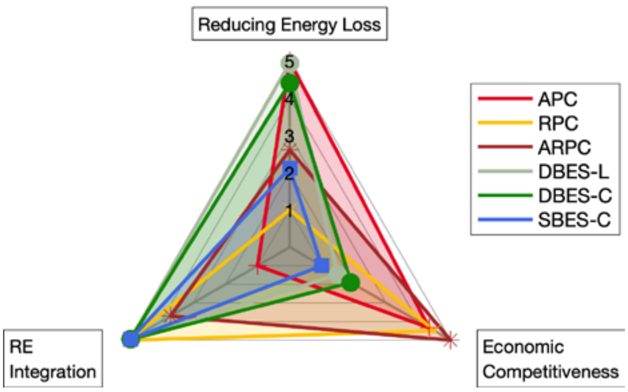

Fig. 2: Characteristics of different PV integration measures for the 69-bus network

Hence, the performance of each measure can be plotted along three different important aspects, namely Reducing Energy Loss, Renewable Energy (RE) integration, and Economic Competitiveness, as visualised in Fig. 2. The measure with the highest performance is given a score of 5 while the lowest is given a score of 1. 'Economic Competitiveness' uses a logarithmic scale while the other aspects use linear scale. When there are further analyses conducted, e.g. the impacts of these integration measures on voltage unbalance, harmonics, etc., more axes can be added to Fig. 2 to illustrate the integration measures' performance on each aspect.

5. Conclusions

Levelised cost of integration (LCI) for PV has been formulated to measure the economics of various PV integration measures. ARPC was found to yield the lowest LCI across PV penetration levels for the analysed distribution networks, followed by RPC and APC. The BES measures can be economically competitive if the BES price and O&M costs drop by more than 80% from their current price. This study also found that changes in reactive power charge, line losses, and BES roundtrip efficiency losses are important components of the LCI and need to be considered in assessing PV integration measures. In fact, BES roundtrip efficiency losses can even be greater than the PV power curtailed in ARPC.

Regulators and policy makers can use the results and framework presented to determine which measures are more suitable for their networks and regions. Moreover, the proposed LCI framework can be used to analyse the cost effectiveness of other measures, control algorithms (e.g. battery power management), as well as the impacts of policy (e.g. lower PV export price, peak demand charge) on the economics of PV and other RE integration. By identifying suitable policy and measures, a roadmap to outline the path to 100% renewables can be crafted. The roadmap, along with incentives and regulations to encourage the private sector to invest accordingly, will help to smooth the transition.

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Agrivoltaics (Agri + PV) – multiple use of space in dense urban settings like Singapore

Dr Serena LIN Fen, LIU Tianyuan, Dr Thomas REINDL

1. Background

As a densely built-up city-state, Singapore is largely dependent on food imports from other countries. In order to increase the resilience of its food supplies, Singapore has started the ambitious "30 by 30" initiative, which pledges to sustainably produce 30% of the nutritional needs locally by 2030. This initiative is also part of the SG Green Plan 2030 [1]. In parallel, the SG Green Plan also sets the goal to deploy at least 2 GWp of solar photovoltaic (PV) systems by 2030, with solar PV being one of the four pillars to decarbonise the energy sector. However, both agriculture and solar PV deployment require large areas of space, and given the land scarcity in Singapore, it is paramount to optimise space utilisation wherever possible. Using the same area for both crop growth and renewable energy generation is therefore one of the novel approaches that has enormous potential in Singapore.

The combination of agriculture and PV, also known as "Agrivoltaics", is a growing trend around the world, which comes in different forms and configurations, depending on the local climate, irradiance, types of crops (and/or livestock) as well as available land spaces. Fig. 1 shows a variety of agrivoltaic configurations, whereby the most relevant type for Singapore's context is Greenhouse Solar, which also enables better pest control. Recently, the Singapore Food Agency (SFA) has also unveiled the plans for the future development of Lim Chu Kang into an agri-food production hub. The options include a "stacked farm approach" to intensify the land use and the use of solar panels on the roof of greenhouses to harness renewable energy [2].

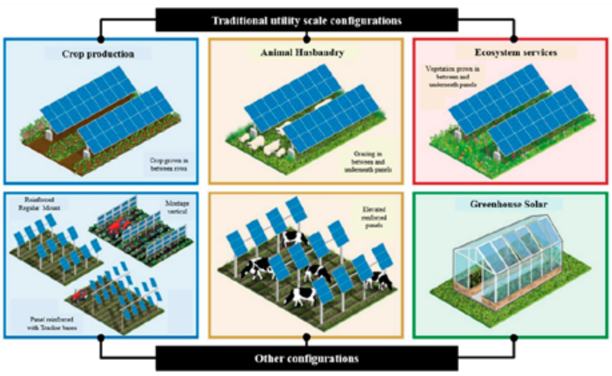

Fig. 1: Types of agrivoltaic system configuration [3]

2. Scope of project & objectives

In 2023, SERIS has set up two agrivoltaic testbeds, each 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 (see Fig. 2).

Fig. 2: 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.

The scientific objective of the two testbeds is to study the balance among crop yield, clean energy generation and energy consumption. The five key thrusts are: 1) maximise crop yield per unit area, 2) maximise solar energy harvesting per allocated slot, 3) integrate novel technologies for farming management, 4) aim for near-zero waste generation, and 5) generate sustainable supply chains and business models. For both testbeds, rotatable PV modules are used to track the sun during the day for maximised power generation. A large number of sensors are deployed, with the aim of developing a self-learning AI algorithm for a future automated control.

3. Significance & impact of project

The 3-year research project allows us to test, and further evolve, 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

The two testbeds both feature rotatable PV modules to track the sun during the day for maximised power generation. Other than sun tracking, the rotation of these PV modules will also be utilised for rainwater protection and collection (for irrigation) and the micro-climate control within the individual greenhouses. Two types of PV module stripes are used with either 10 cells or 12 cells in each stripe, providing different amounts of shading on the plants.

A large number of sensors, including irradiance, photosynthetically active radiation (PAR), temperature, humidity, electric conductivity (for water nutritional level) and pH value, are deployed at various locations and heights in the plots to perform real-time monitoring. In combination with SERIS' proprietary live PV monitoring system, we aim to develop a self-learning AI algorithm for a future automated control of the PV powered set-up.

For the first testbed, vertical growing towers from V-Plus Agritech are employed to optimise crop yield per unit area. As shown in Fig. 3, 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. As the research progresses, the fish will be fed with insects nurtured by the crop waste resulting from the greens harvested from the growing towers. This approach will effectively close the nutrient recycling loop, creating a fully circular agriculture system. A pest-control netting will also be installed.

Fig. 3: SERIS' testbed 1 in Yuhua Agritech Solar (YAS) Living Lab with an aquaponics system consisting of vertical growing towers

Fig. 4: SERIS' testbed 2 in Yuhua Agritech Solar (YAS) Living Lab with a hydroponics system consisting of horizontally layered growing beds

For the second testbed, horizontally layered growth beds from Arianetech are used for maximising the crop yield per unit area. LED stripes are available to provide additional lighting for lower-level growth beds that receive less natural sunlight compared to the upper levels. The amount of additional LED lighting required will be explored through experiments by considering the trade-off between energy consumption and crop yield. Life3 Biotech will be looking into the utilisation of the fresh produce for plant-based meats. At a later stage, this testbed will also feature transparent solar PV panels from ClearVue as greenhouse walls, which can generate electricity from the UV and infrared parts of the sunlight while allowing the visible light to reach the plants inside the greenhouse (Fig. 5). Micro-climate control will later be realised through an automated control system, including the rotation of rooftop PV modules.

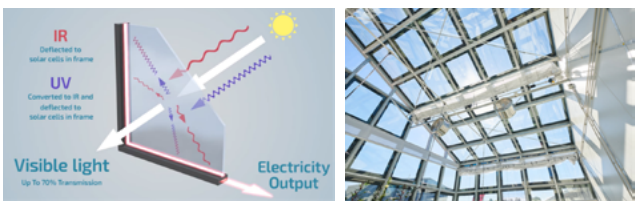

Fig. 5: Transparent glass wall PV panels to be used for SERIS' Agrivoltaic testbed 2. The transparent panels from ClearVue PV transmit visible light while converting the IR and UV lights into electricity (maximised solar power generation).

During the initial experiments, it was found that the coral lettuces that were planted at the same time grew at visibly different rates in the vertical towers depending on the number of cells in the PV module stripes above them (in Fig. 6, the left side receives slightly more sunlight than the right side). However, the different types of vegetables that we experimented with, such as coral lettuce, local lettuce, black rose lettuce, xiao bai chye, chye sim and mizuna, react in different ways when they are under the two types of PV modules, given their different demand for light and other growth parameters.

Fig. 6: Coral lettuce growing at different rates under rotatable PV module stripes consisting of 10 cells (left) and 12 cells (right)

With the same rotatable PV modules installed on both SERIS testbeds, scientific comparisons can be made between different plant growing methods (vertical vs. horizontal), aquaponics vs. hydroponics, transparent PV wall vs. pest-control netting. Different solar PV cell technologies will also be evaluated in the 3-year project.

5. Conclusions

The newly established SERIS agrivoltaic testbeds in Yuhua Agritech Solar (YAS) Living Lab provide an excellent platform to innovate and testbed suitable combinations of crop growth and solar PV generation, which is concurrently supporting two goals of the SG Green Plan 2030: sustainably locally grown food and green electricity generation on the same plot of land. We aim to optimise the balance among crop yield, clean energy generation and energy consumption. Self-learning AI algorithm will be developed for a future automated control of the PV powered greenhouse. Through the 3-year research, we aim to develop feasible and sustainable rooftop agrivoltaic configurations that can be commercialised on other rooftops in Singapore and the region.

References

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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.

Perovskite Thermal Evaporation System (Technol)

This twin-chambered perovskite thermal evaporator is used for the deposition of perovskite-based, metallic, organic and other functional thin films ($MAPbI_2$, Ag, C60, LiF, etc) onto various substrates (glass sheets, silicon wafers) of a wide range of sizes up to 166 mm x 166 mm (M6 wafers). The depositions are carried out either via thermal resistive sources or thermal furnace sources, depending on the material's evaporation or sublimation properties. 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 two-stage pump system that utilises a dry pump (roughing stage, $< 10^{-2}$ Torr) and a turbo pump (high vacuum stage, $< 10^{-6}$ Torr). The interconnected twin-chamber configuration enables sequential deposition of several layers from multiple sources while maintaining the high-vacuum environment, which reduces the chances of contamination between processes. Furthermore, the vacuum chamber has a rotating substrate holder to enable laterally uniform film thickness across large-area substrates. 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). The hardware is supported with a user-friendly software programme, capable of running automated (PID-controlled) and finely-tuned processes from the PC setup or remote access.

Other equipment for processing and device integration:

- 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

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SILICON SOLAR CELL LABORATORY

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

Silicon Cleanroom Lab 1A:

Lab 1A is used for wet chemistry 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)

SERIS' 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 solar cell processing. The tools are compatible up to M6 silicon wafers and can process up to 50 wafers per batch.

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 wafer 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 ºC). The machine can deposit silicon nitride, silicon oxide and aluminium oxide layers on large silicon wafers (M2 - 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). 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 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 product 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 plasma-enhanced CVD tool that allows the deposition of intrinsic and doped (boron, phosphorus) a-Si layers for applications in silicon heterojunction 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:

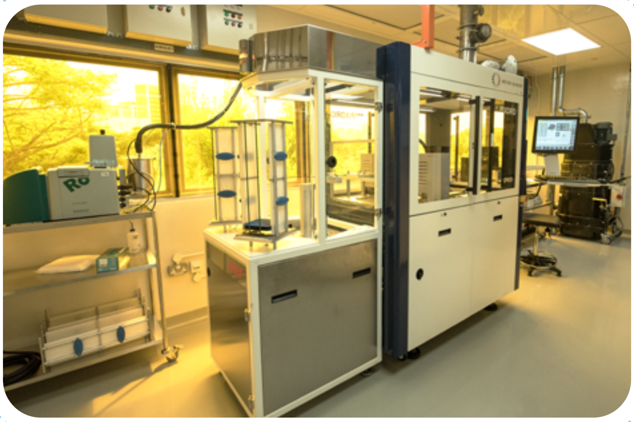
Lab 2A houses tools for precision and advanced processing of high-efficiency solar cells. It has a versatile laser tool and an inkjet printing tool that are used to make advanced features on solar cells.

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. This tool has automated handling for substrates up to M6 size and is also capable of larger wafers (up to G12 size) by 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 up to G12 size substrates is also possible.



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.

Industrial screen-printing line (Eclipse / DEK, UK)

The industrial screen-printing line 'Eclipse' from DEK/ASM Assembly Systems has a throughput of 1200 wafers/hr per print. The fully automated line has a cassette loader to feed Si wafers (up to M2 size) into the Eclipse printing station. After printing, the wafers pass through a dryer (Heller) and are then collected in another cassette loader. The print stations have an alignment accuracy of ±10 μm and the prints can be aligned to the wafer edges or specific patterns on the wafer. A paste mixer facilitates uniform mixing of the metal pastes. The lab is also equipped with a viscometer to determine the paste's viscosity. An upgrade is planned to replace this screen printer with a new flexible screen printer capable of printing onto a range of small or large substrate sizes (from 25 cm^2 up to G12 or larger).

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

Inline multi-chamber sputter machine #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 is a state-of-the-art machine having dedicated chambers for the sputtering of metallic, dielectric and TCO/TMO layers. The processing 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 500°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 a variety of layers, including indium tin oxide, aluminium-doped zinc oxide, Ag, Al, Ti, Cu, In, ZnO and thin oxide and oxynitride tuned to specific requirements. The Line 540 tool has 3 planar magnetron sources, whereby 2 are connected to a DC power supply for DC sputtering of metal layers, while the third is connected to an RF power supply for the deposition of dielectric films such as ZnOS. Substrates of sizes up to 30 cm x 40 cm or up to six M6-size wafers per run can be processed at temperatures of up to 200°C. The tool is also used for deposition of Cu and other metal seed layers onto wafers for subsequent plating.

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PHOTOVOLTAIC DEVICES CHARACTERISATION LABORATORIES

The PV Devices Characterisation laboratories at SERIS are equipped with a comprehensive suite of measurement tools to examine both material and device properties. The characterisation of optical and passivation layers, bulk materials, and solar cell metallisation provides better understanding of their influence on the PV efficiency. This complements device level measurements of silicon and perovskite based solar cells, tandem cells, and single-cell mini-modules. Combining judicious characterisation with specialised simulation techniques enables advanced solar cell analysis to quantify performance limiting factors as well as predict the room for further efficiency improvements.

Materials Characterisation Laboratory

The Materials Characterisation Laboratory houses both general-purpose materials characterisation tools (like optical microscopy, FTIR and Raman spectroscopy) and silicon-based materials characterisation techniques (wafer thickness and resistivity measurement tool, effective minority carrier lifetime tester, and TLM resistance measurement tool). It also houses a small-beam spectral response measurement system to study 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)

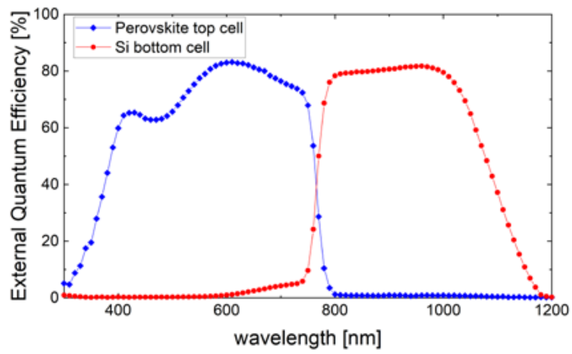
External quantum efficiency (EQE) and total reflectance (R) measurements enable a detailed current loss analysis and the identification of areas of improvement in relation to diffusion lengths and light management. The PVE-300 allows quick and localised measurements of both EQE and R over a wavelength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

Luminescence imaging (BT Imaging, LIS-R2)

Photoluminescence (PL) and electroluminescence (EL) are the "X-ray scanners" of the silicon PV community, capable of producing quick scans for routine inspections, or detailed 2-dimensional data sets amenable to 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, 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 to determine the metal grid resistance.



Measured EQE of a monolithic perovskite-Si tandem cell (sample provided by the Perovskite-based Multijunction Solar Cells Group).

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

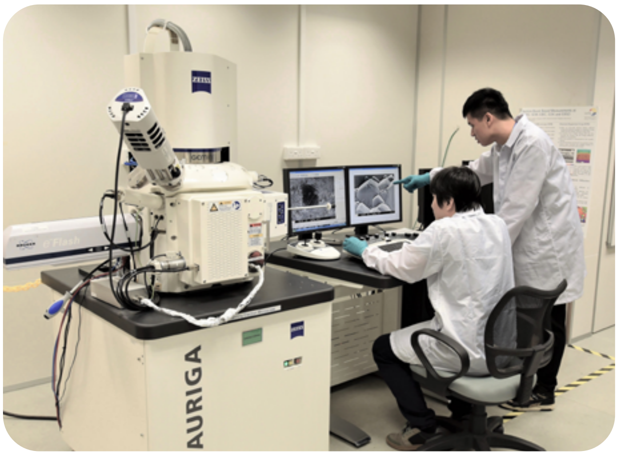
This technique provides fast contactless measurement of interface parameters that affect the passivation quality of dielectric films for PV applications. The metrological capabilities include the mapping of contact potential (in the dark or under illumination), band bending at the semiconductor/dielectric 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

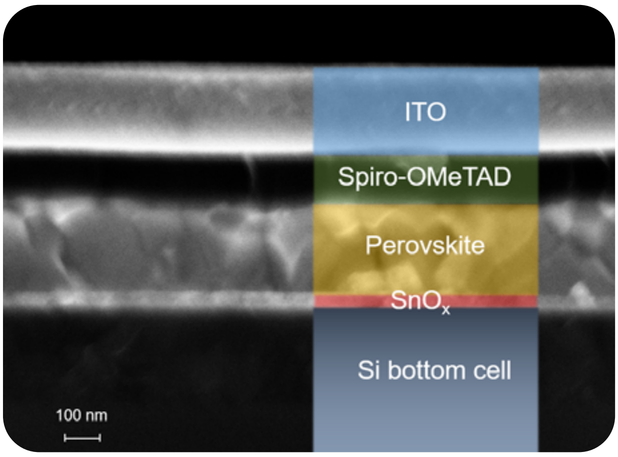
The centre piece of the Electron Microscope Laboratory is a FE-SEM (field-emission scanning electron microscope), which is an electron microscope used to obtain high-magnification images of sub-micron areas of electrically conductive samples. Our SEM has additional accessory ports which are used for 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 techniques like a UV-VIS spectrophotometer, which provides a direct way of measuring the total transmittance and reflectance of a sample. The lab also houses a spectroscopic ellipsometer, which is an advanced method of determining the optical properties (thickness, refractive index, extinction coefficient) of thin films.

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. Our SEM is equipped with the following additional features: Electron back scatter diffraction (EBSD) (Bruker, e-Flash), electron-beam induced current (EBIC) (Kammrath & Weiss), energy dispersive X-ray (Oxford Instruments, Aztec X-MaxN).



Scanning electron microscope



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

Variable angle 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, the technique enables the determination of the complex refractive index (n, k) and the thickness of thin optical coatings. The SE-2000 has an additional tilted sample stage, which is ideal for measurements of the pyramid facets of textured monocrystalline silicon solar cells.

UV-VIS-IR optical spectrophotometer (Agilent Technologies, CARY-7000)

The UV-VIS-IR 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

The Solar Cell Measurement Laboratory focuses on measuring the solar cell efficiency, which is one of the most important parameters of solar cell devices. The lab is separated into two parts. The dark room houses a xenon lamp based steady-state solar simulator, a large-area spectral response measurement tool, and the 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 half of the lab houses LED-based I-V testers, where SERIS researchers can quickly perform their daily I-V measurements (on silicon, perovskite, or tandem solar cells), and a SERIS-built LED 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 highest solar simulator class (‘AAA’), with a spectrum that achieves better than 12.5% spectral match to the AM1.5G solar spectrum. It provides laterally uniform illumination intensity across an area of 300 mm × 300 mm, making it well suited to I-V measurement of solar cells.

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

Two Class AAA solar simulators featuring state-of-the-art LED array technology provide spectrum tunability across 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)

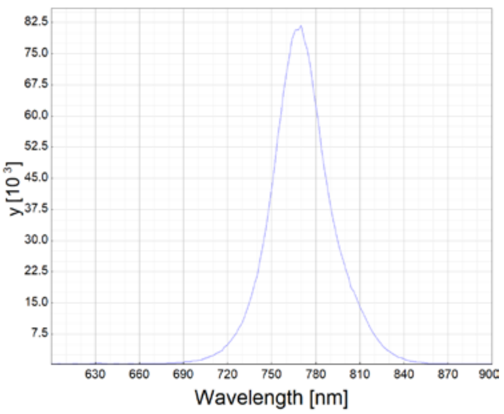
This system projects a large monochromatic beam which overfills the solar cell area for differential spectral response measurement up to 1 Sun bias light intensity. The external quantum efficiency (EQE) extracted from the measured spectral response curve enables the determination of the spectral mismatch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

Advanced Characterisation Laboratory

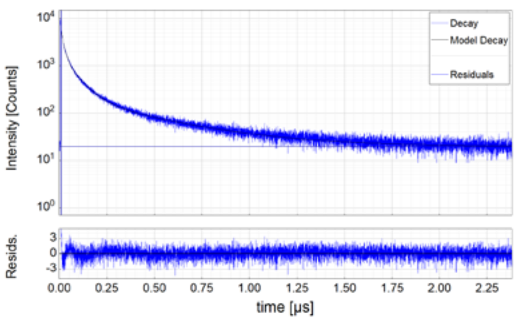
The Advanced Characterisation Laboratory lab houses cutting-edge commercial characterisation tools as well as tools that are currently being developed by SERIS. It contains a time-resolved photoluminescence tool, which is used to measure the luminescence spectrum of perovskite materials and their effective carrier lifetime which ranges from picoseconds to microseconds. It also houses a LED-based modulated PL setup, developed by a Final-Year Project student team from NUS-ECE, and a perovskite luminescence imaging tool developed by a NUS-ECE Masters student.

Time-resolved fluorescence spectrometer (PicoQuant, FT300)

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



Steady-state photoluminescence (PL) emission of a perovskite film.



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.

Electrochemical capacitance-voltage (ECV) profiler (WEP, CVP-21)

ECV enables the extraction of the active doping concentration of doped semiconductors. It can be used to measure the phosphorus or boron doping profile of silicon wafers and silicon thin films. Active dopant densities in the range of $10^{12} – 10^{21}$ cm^{-3} can be detected with a depth resolution of about 1 nm.

Three-dimensional optical microscope (Zeta Instruments, ZETA-300)

The Zeta optical profiler is a 3D true colour imaging tool that can image large areas of a sample surface and provide accurate topography information contactlessly. It allows measurements of lateral dimensions, step heights and wall angles, and is ideally suited to obtain high-resolution 3D shapes of metallisation lines and pyramid textures.

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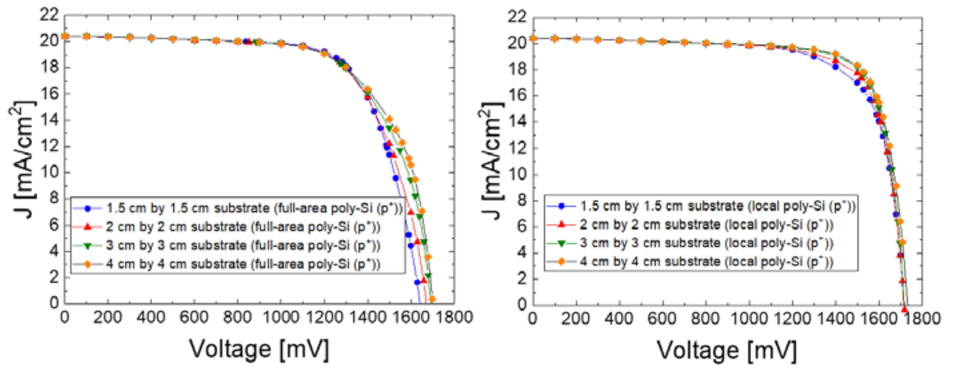
PV DEVICE MODELLING AND SIMULATION

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 contact-passivated 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 dependant 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, contact passivated, perovskite, perovskite-Si tandem
- 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-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 contact-passivated silicon solar cells (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

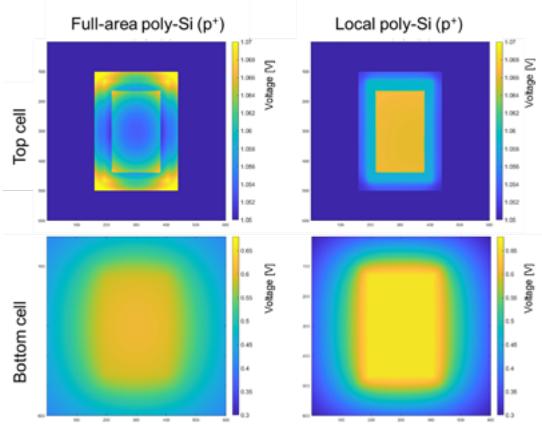
We have developed various programmes for reliable simulations of the PV device characterisation methods in use at SERIS. For example, we can simulate injection dependent carrier lifetime measurements, bias and injection dependent quantum efficiency (EQE/IQE) measurements, as well as injection and bias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

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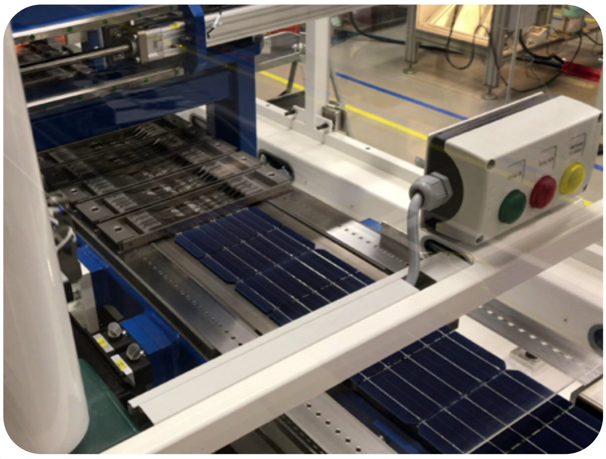
PV MODULE DEVELOPMENT LABORATORY

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 the 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.

PV module multi-level laminator (Bürkle, YPSATOR 1222-5 HKV)

The laminator possesses separate heating and cooling chambers enabling good control of process temperatures. In addition, its fourth chamber with a metal flat press for glass-glass lamination applies even pressure throughout to ensure good lamination quality. The tool is currently housed at an industry partner where it is used for collaborative PV module R&D as well as for SERIS' internal module research.

Bürkle multi-level laminator

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

This single-chamber semi-automatic laminator has a larger lamination area of up to 2600 mm 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)

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SERIS' ISO/IEC 17025 LABORATORY FOR PV MODULE TESTING

The PV Module Characterisation & Reliability (PVMC&R) Group at SERIS offers testing of PV modules to the PV industry. It also collaborates in research projects, offering high-accuracy characterisation and consultancy on PV module reliability. The Laboratory is accredited since 2012 to ISO/IEC 17025 for the electrical testing of PV modules. In 2018 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 bifacial modules, potential induced degradation, and the classification of solar simulators. 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:

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

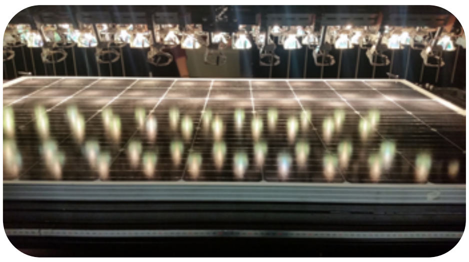
"Golden module" certificates can be produced by combining the results from both simulators, giving the world-class uncertainty of ±1.4% for the module's measured maximum power.

"Golden module" testing at SERIS

Spectral responsivity and spectral mismatch correction for the highest accuracy

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

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



Spectral responsivity measurement system

Incident Angle Modifier (IAM)

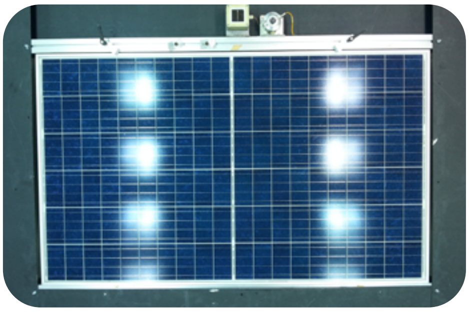
The level of irradiance that a PV module receives varies with the Sun's position in the sky throughout the day and over the seasons. It is therefore important to analyse the impact of the angle of incidence on the output of PV modules and determine a correction factor, commonly referred to as the Incident Angle Modifier (IAM). To investigate this effect at commercial-size module level, a novel measurement procedure was designed and validated versus IEC 61853-2, including a chopped and spot-like collimated light beam, a customised angle probe holder, bias light illumination of the solar cells in the module that are not under measurement, and a data acquisition system to filter the chopped signal from the bias light generated background signal.

Measurement of IAM of 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) and hot-spot endurance tests can be performed indoors on a continuous solar simulator. Both are important tests to assess the reliability of PV modules.

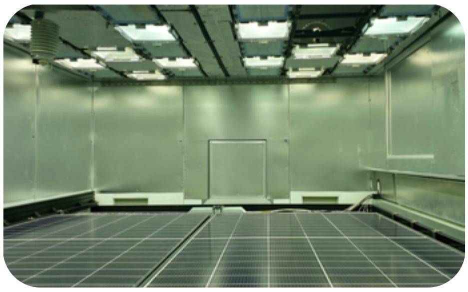


Module stabilisation

UV Exposure

The UV preconditioning test is an ageing test that aims at identifying any susceptibility to UV degradation.

The PV module under test is irradiated with at least 15 kWh/m^2 to as high as multiple runs of 60 kWh/m^2 of UV irradiation. In a typical test flow, the tested module is then checked against damages (visual inspection, insulation, wet leakage, electrical characterisation if required).



UV exposure test

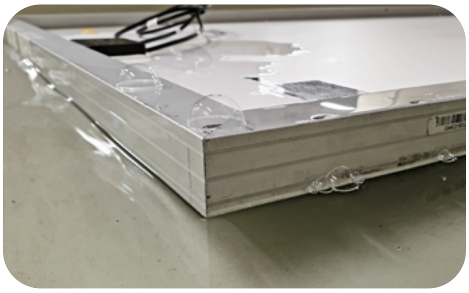
Insulation Tests

Insulation test, wet leakage test, impulse voltage, reverse current, insulation thickness check: All these tests are performed to assess the electrical insulation resistance of a PV module.

The insulation test is a “dry test”, aiming to assess module electrical insulation between active parts and accessible parts. A voltage of either 500 V or the maximum system voltage (whichever is greater) is applied to the module for 2 minutes and the insulation resistance is measured.

The wet leakage test assesses the module’s electrical insulation in a “wet” environment, to verify that moisture from rain, fog, dew or snow does not enter the active parts of the module, and is thus particularly relevant for PV modules in the tropics. The test is carried out essentially as for the insulation test, except that the module is tested while immersed in a water solution of given resistivity.

Both tests also act as “control tests”, as they are often performed after many of the other stress tests listed below.

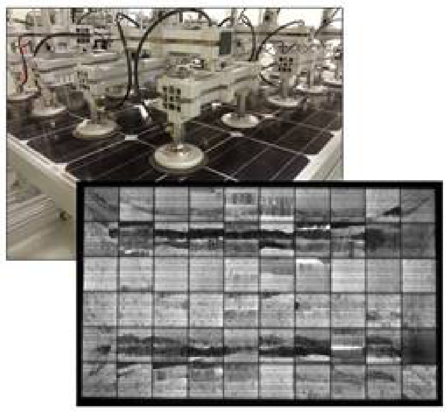


Wet leakage test

Mechanical stress tests

Our equipment covers the following industry standard tests:

- Static Mechanical Load Test (MLT) of up to 5400 Pa;
- Dynamic MLT (cyclic pressures exerted on the module for 1000 times at prefixed air pressure), to simulate the effects of extreme weather conditions (tropical storms and typhoons);
- Hail test – Ice ball projectiles are shot with speeds of up to 30 m/s onto the module under test, according to IEC 61215;
- Retention of the junction box – to assess the capability of the cables to the junction box to safely withstand tensions;
- Module breakage – a destructive test, to ensure safe operations when replacing a broken module. It entails a bag filled with steel balls to ‘pendulum swing’ into a module from known height.



Damages after dynamic MLT

PV module reliability and durability testing

Thermal reliability tests, PID and LeTID

Climate chambers are the workhorses in reliability and durability testing of PV modules. Tests such as damp heat, thermal cycling, humidity-freeze, hot and cold conditioning with 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 prenormative Light and Elevated Temperature Induced Degradation (LeTID) test, a novel degradation mechanism that may slowly deteriorate PV module performance in hot climates.

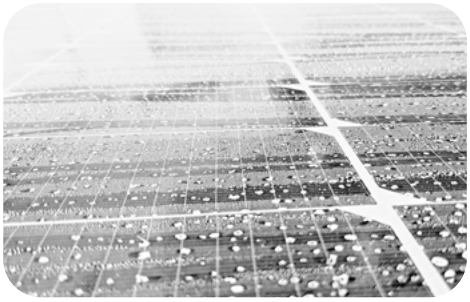
Given the PV industry trend to larger modules, the Laboratory's climate chambers were upgraded in 2022 to larger volumes, now capable of testing modules up to 3 m long and 2 m wide.

Large-volume climate chambers for reliability testing

Extended reliability for tropical regions

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

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



Salt mist test

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OUTDOOR PV MODULE AND SYSTEM TESTING FACILITIES IN DIFFERENT CLIMATES

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

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

The various PV module and system data (available in intervals as short as 10 seconds) include:
- Module temperature
- DC characteristics: V_{oc}, V_{mpp}, I_{sc}, I_{mpp}, P_{mpp}, I-V curve
- AC characteristics: voltage, current, active and reactive power, etc.
- Cumulative energy yield (DC and AC side)

In addition, every site location has a state-of-the-art meteorological station, using the following equipment:
- Pyranometer (horizontal and in-plane)
- Silicon sensor (horizontal and in-plane)
- Pyrheliometer
- Spectro-radiometer
- UV radiometer
- Ambient temperature
- Other meteorological sensors (wind speed & direction, humidity, rainfall)

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

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

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

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

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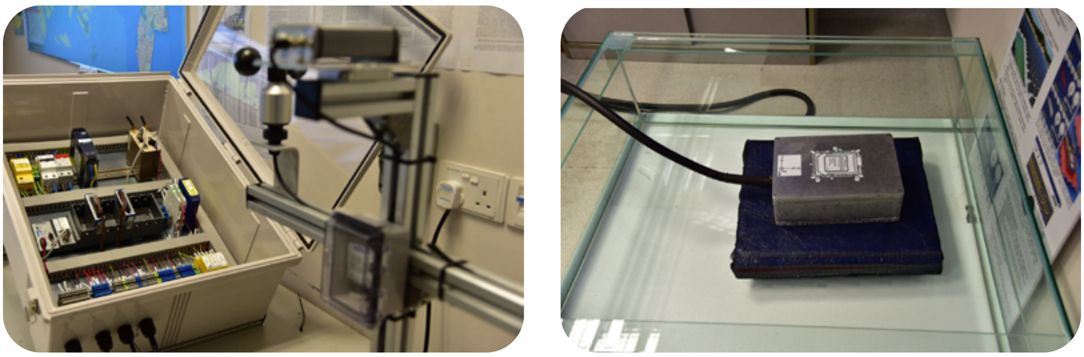
PV SYSTEM MONITORING LABORATORY

The PV System Monitoring Laboratory showcases SERIS'real-time analytical monitoring capabilities of photovoltaic systems as well as meteorological parameters. SERIS' proprietary award-winning monitoring system is based on rugged industrial-grade National Instruments hardware 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 various 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 various DC and AC parameters of PV systems, power quality parameters, and meteorological parameters, such as irradiances measured with different sensor devices and inclinations, module and ambient temperatures, relative humidity, wind speed, wind direction, air pressure, etc.
- ± 150 ms time synchronisation with SERIS' time server
- Greater than 99% data acquisition reliability annually
- 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)
- 6-degrees of freedom floating platform motion monitoring system, designed especially for floating PV systems
- 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).

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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. Large-scale 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

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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 M6 wafer size (up to 166 mm x 166 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, 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
- LPCVD of intrinsic or doped (boron, phosphorus) poly-Si layers
- ALD of Al_2O_3, SnO_2 and AZO layers
- PVD of various thin films (metals, TCOs, TMOs) by sputtering and 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

SERIS' batch wet-chemistry tools (left of photo) and inline wet-chemistry tool (right of photo) for single-side processing of silicon wafers.

PECVD tool for deposition of intrinsic and doped amorphous silicon layers for applications in heterojunction solar cells.

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.

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

Magnetron sputtering is a 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 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 chambers for the sputtering of metallic, dielectric and transparent conductive oxide (TCO) layers. The processing chambers are equipped with planar magnetron sources for DC sputtering of metals, oxides and oxynitrides in the reactive mode, and with a cylindrical dual-magnetron source and planar sources for pulsed DC (DC+) and RF sputtering of dielectrics and TCOs, with substrate heating up to 400°C. This allows to deposit thin layers of metals, TCOs and dielectrics onto various substrates. It is also possible to deposit graded layers, 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 heterojunction silicon wafer solar cells. The 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

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CHARACTERISATION AND TESTING OF PV MATERIALS AND SOLAR CELLS

An efficient solar cell maximises the conversion of photons in the sun's spectrum into energetic charge carriers, and minimises undesirable recombination processes that reduce the cell's current and voltage output. SERIS is equipped with a comprehensive suite of tools that can deduce the optical properties (related to photon-to-charge carrier conversion) and electrical properties (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)

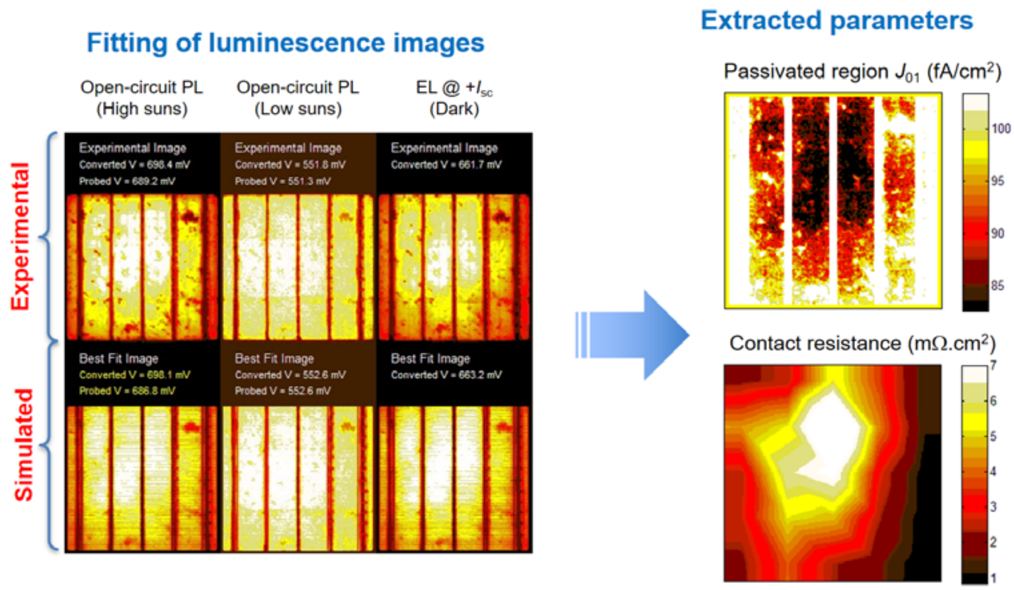
- High-precision steady-state light I-V and spectral response measurements for solar cell devices
- Solar Cell Doctor: Detailed health check for solar cells
- Photoluminescence and electroluminescence imaging
- Determination of thickness and optical properties of thin films by spectroscopic ellipsometry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

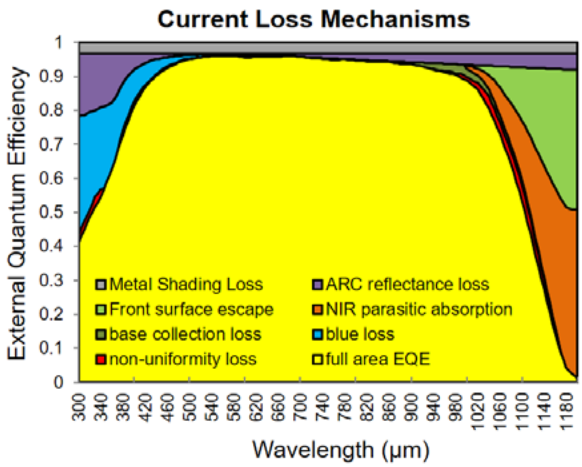
- Technical consultancy for industrial silicon solar cell development, process optimisation, metal grid design, production yield improvement
- Analysis and simulation of advanced silicon solar cell concepts such as the heterojunction architecture, passivated contacts (TOPCon), local back-surface-field (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.

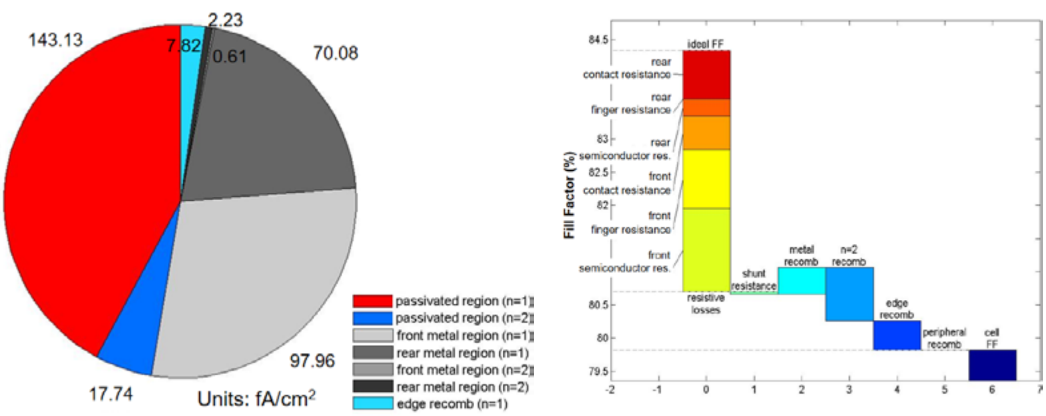


Fitting of Griddler simulated luminescence images to experimental data allows the extraction of device parameters in this p-type multicrystalline silicon solar cell. This includes the spatial distribution of the saturation current density J_{01} of the passivated region and the contact resistance.

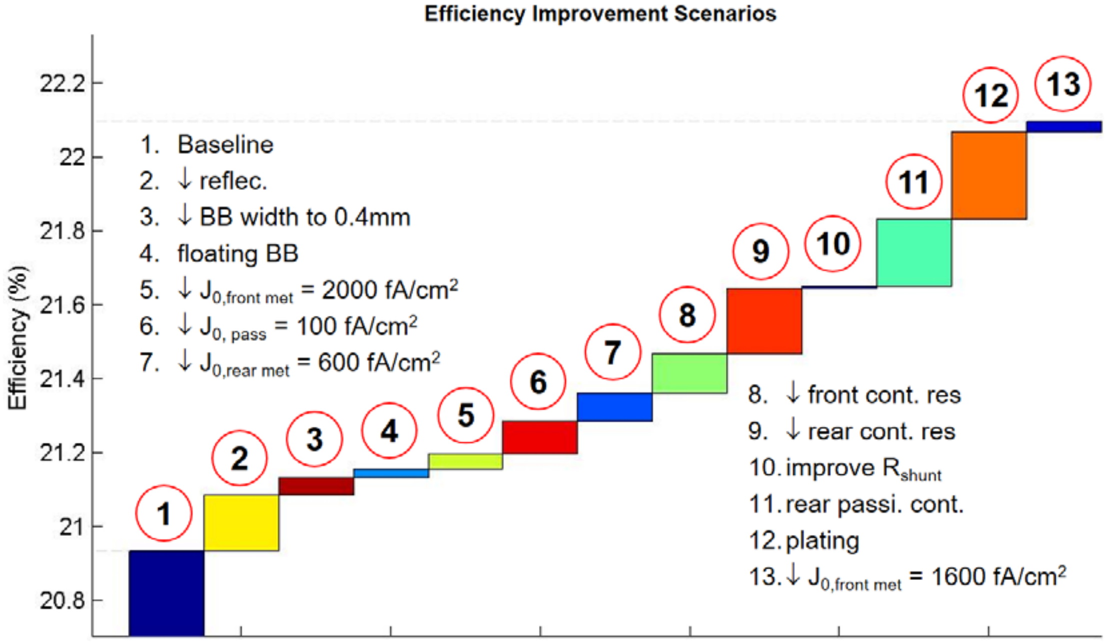


J_{sc} Breakdown (mA/cm²)	
Cell Current	40.062
Base collection loss	0.314
NIR parasitic absorb	1.550
Front surface escape	1.287
ARC reflectance	0.977
Blue loss	0.464
Metal shading	1.567
Non-uniformity loss	0.207
WAR (300-1000nm) %	1.762
Base eff. diffusion length (μm)	3478

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.



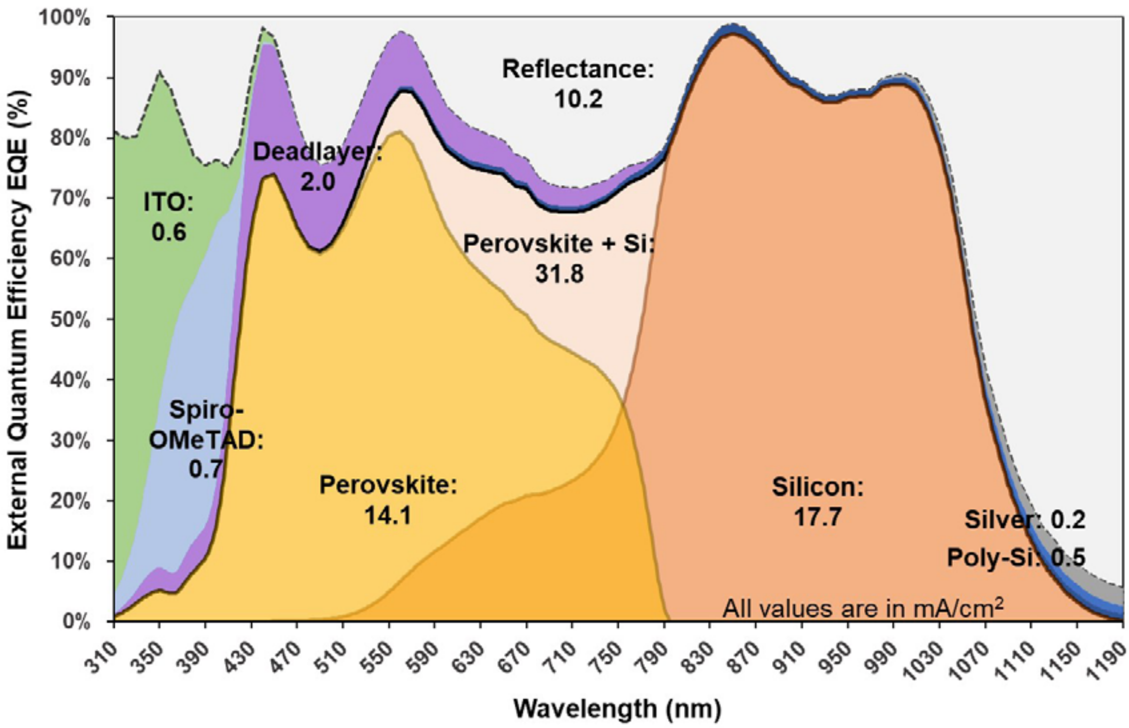
The accurate representation of a crystalline silicon solar cell allows the precise quantification of the various recombination currents at open circuit that affect its voltage, as well as the myriad of factors which influence its fill factor.



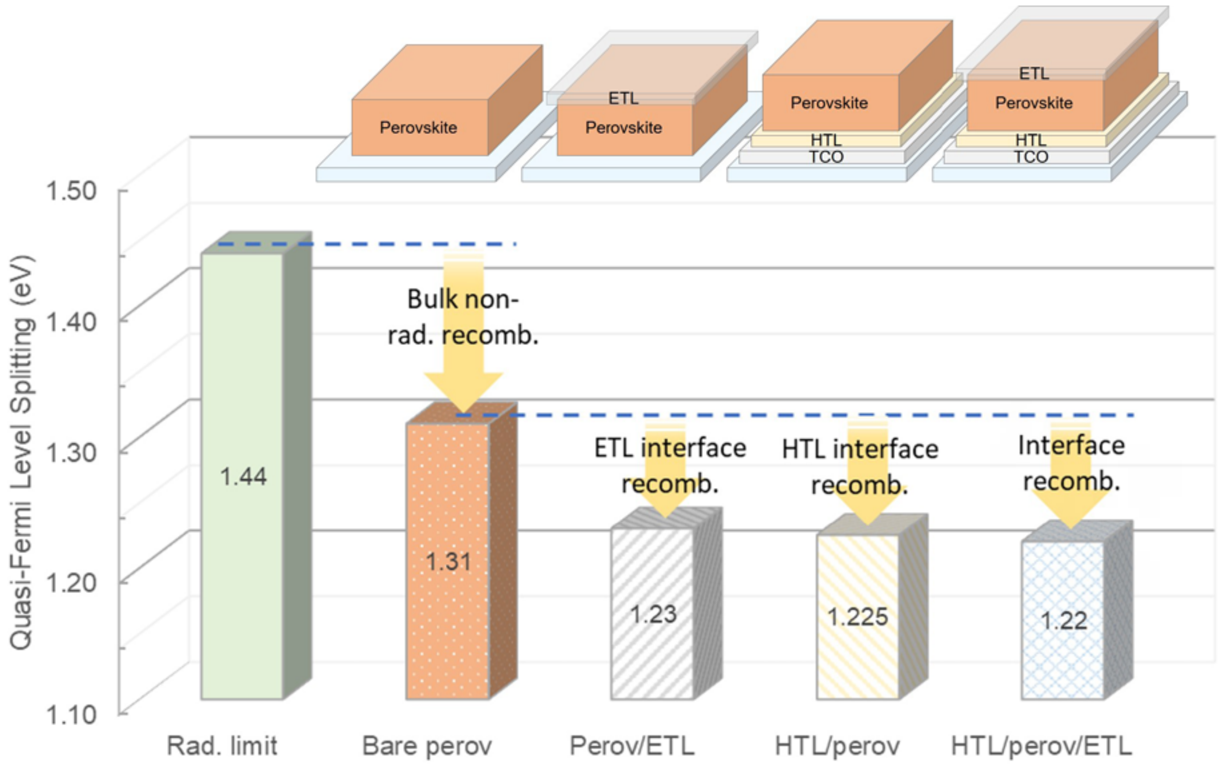
Griddler prediction of incremental silicon solar cell efficiency improvements due to specific process or cell design changes.

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.)

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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 can be fabricated. Services offered by the lab include:

- PV module fabrication
- Processing of individual module components into full 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 along expressways)
- Design of visually appealing PV modules (Peranakan PV, pointillism PV, etc)
- 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

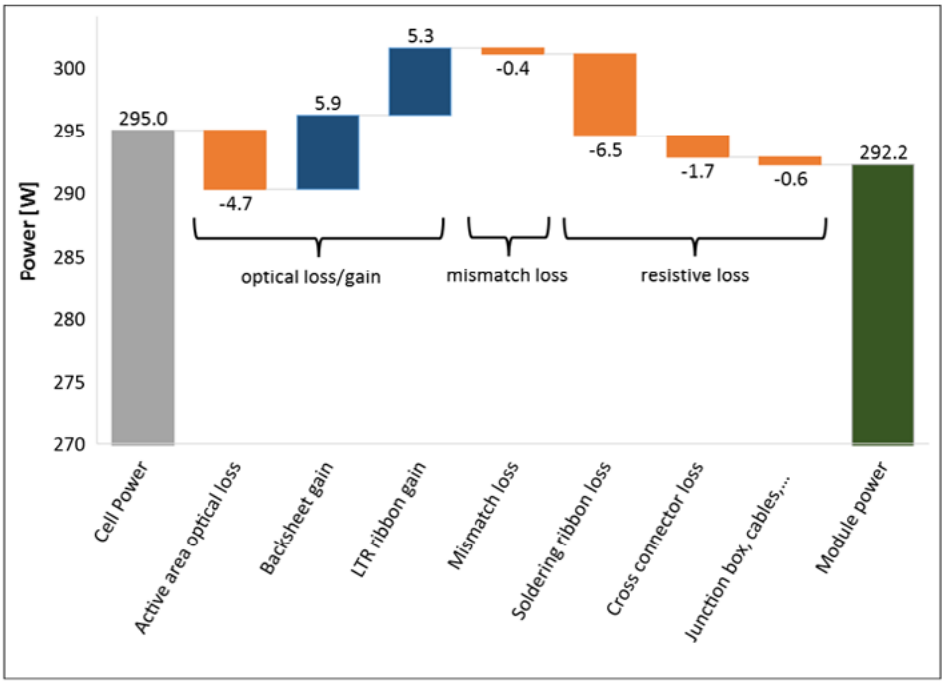
Quantify the light harvesting from inactive areas of a PV module (e.g. cell-gap area, ribbon) using EQE line scans.

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

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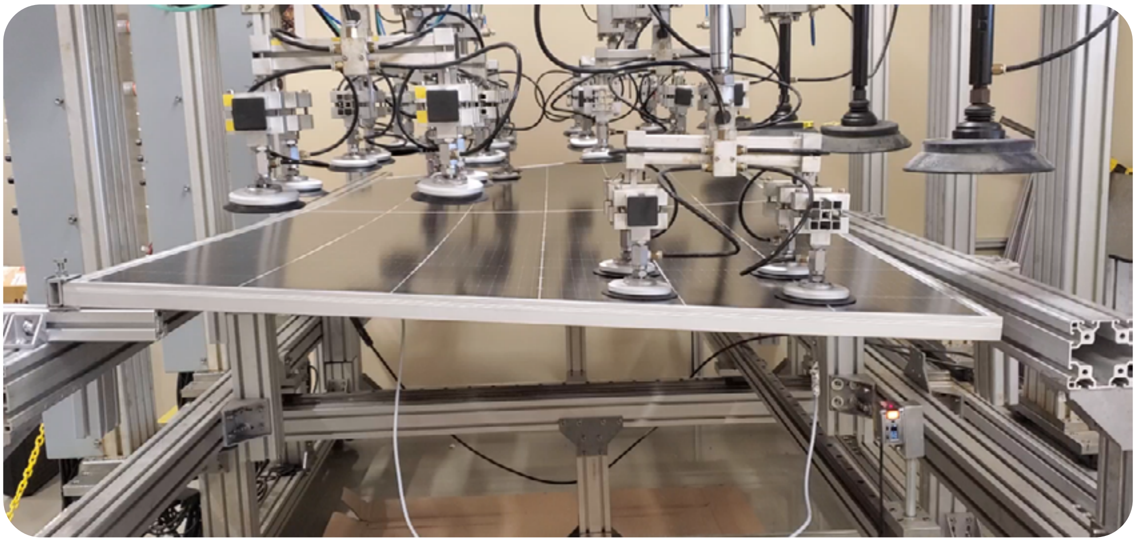
ADVANCED RELIABILITY TESTING OF PV MODULES

The fast pace of development of PV modules, with new materials, module and 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, etc.), leading to a renewed importance of reliability studies. Alongside the usual testbed for Potential Induced Degradation (PID), in 2023 SERIS has enlarged its reliability research at the module level to the reliability of modules for floating PV, introducing new stress methods that include vibrations, torsion tests, and 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 Singapore, the temperature of PV modules in operation 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 Singapore, and modules that are usually considered "PID-free" in temperate climates may exhibit PID in Singapore. SERIS has therefore set up an Outdoor Module PID Test Facility to monitor PV modules for PID. In this set-up, a bias voltage corresponding to the module's rated maximum system voltage is applied. The modules are also connected to load resistors to keep them near their maximum power point (MPP), to simulate the real-life operation. In addition, PV module temperature, ambient temperature, relative humidity, wind speed, irradiance and leakage current are being measured.

SERIS' Outdoor Module PID Test Facility

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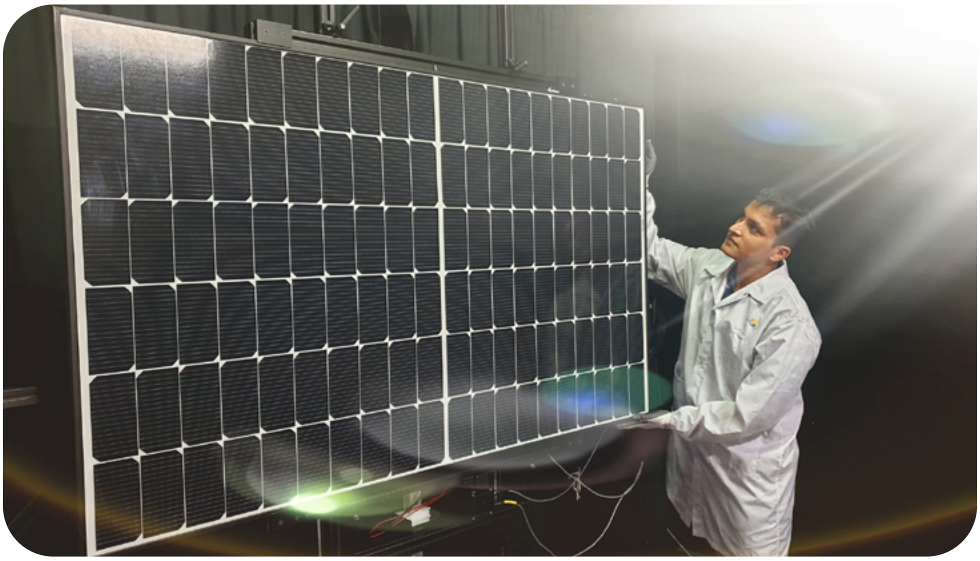
CHARACTERISATION AND RELIABILITY OF PV MODULES

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 the standard testing, research activities such as on Potential Induced Degradation (PID), measurement of the Incident Angle Modifier (IAM), and reliability of modules for floating PV applications enable the Laboratory to address specific concerns of the research partners. The Laboratory is ISO/IEC 17025 accredited by 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

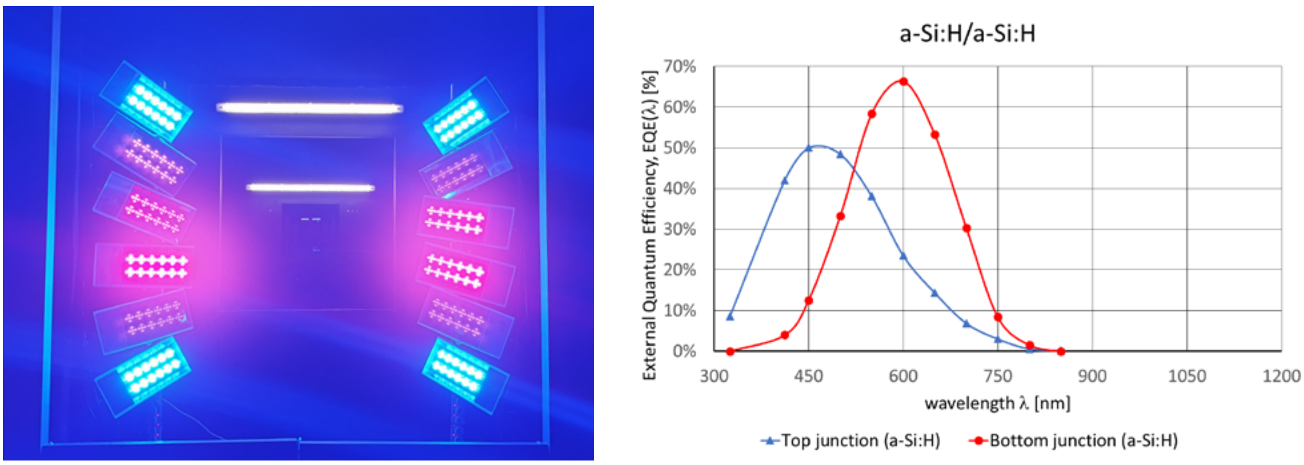
Equipped with two Class A+ large-area pulsed solar simulators (a 10-ms Pasan SunSim 3B and a 100-ms halm solar simulator), the Laboratory can characterise all types of commercially available PV modules at Standard Test Conditions (STC), including bifacial and heterojunction modules. This is particularly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



"Golden module" characterisation at SERIS

Electrical characterisation of multi-junction modules

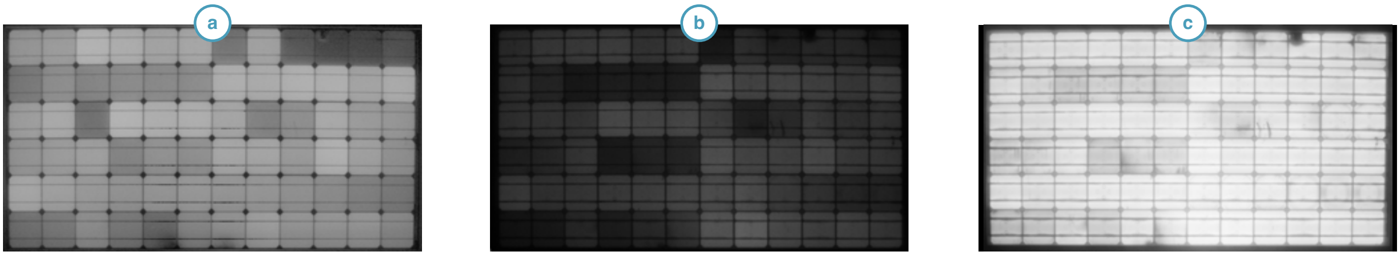
In view of the possible future revival of multi-junction terrestrial PV modules, and aligned with the new frontiers of research on perovskite-silicon tandem solar cells, SERIS' Laboratory is now equipped with an External Quantum Efficiency (EQE) measurement system for multi-junction modules, with additional coloured bias light as required for measuring the EQE of multi-junction structures. Validation was performed on old-generation amorphous silicon double-junction PV modules.



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

Photoluminescence (PL) of PV modules

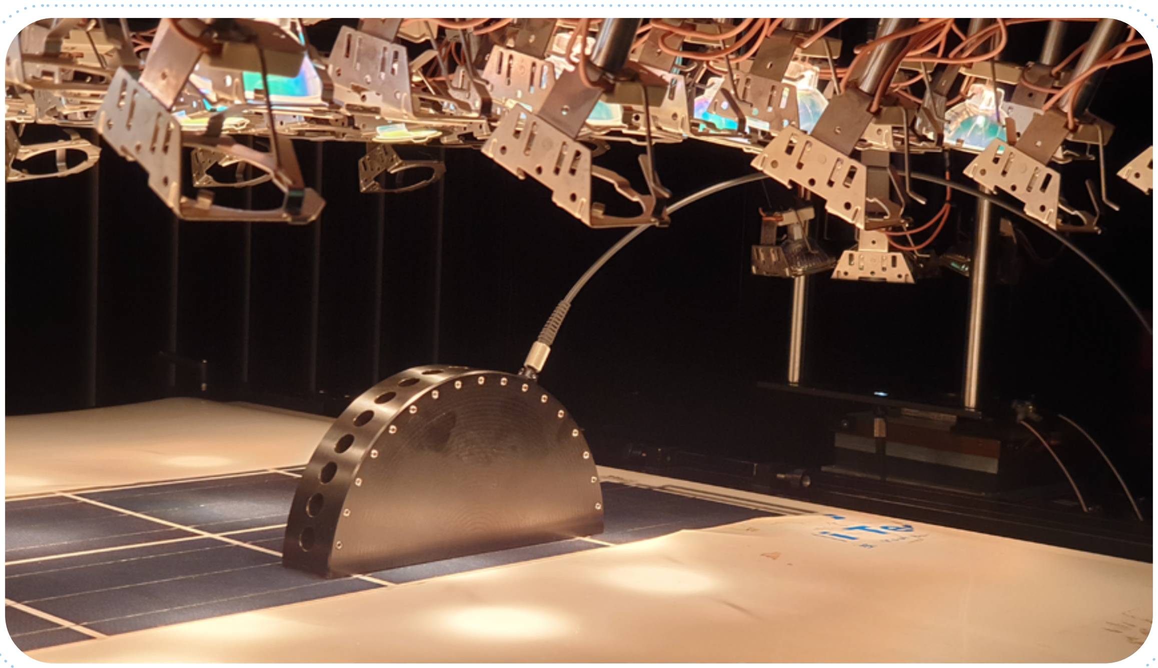
Reliability studies often require to detect the origin of failures or degradations in module performance. Electroluminescence (EL) is a well-known imaging technique that allows to easily identify defects such as microcracks, corrosion, or missing/delaminated contacts. In EL the infrared (IR) emission 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 (see the section "Update on R&D Projects 2023" of this SERIS Annual Report 2023 for more details). 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 testing module, and also gives an indication of the root cause for power degradation.



Comparison between PL and EL imaging of the same testing 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 is now under review at IEC for possibly inclusion as standard procedure for IAM measurements as per IEC 61853-2.



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

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Dr LEOW Shin Woei (swleow@nus.edu.sg), for PV Module Reliability

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 10 seconds) 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)

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 Carlos RODRÍGUEZ (carlos.rodriguez@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 installations. SERIS, for example, designed and commissioned a photovoltaic (PV) system in Singapore that has been functioning with an extraordinarily high-performance ratio (PR) of about 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 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 <u>Optional:</u> • 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 <u>Optional:</u> • 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

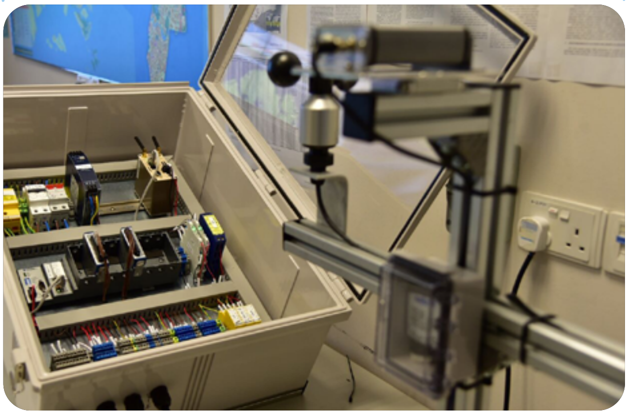
We offer a cloud-based real-time Analytical Monitoring of PV installations - from small rooftop systems to large ground-based PV power plants to floating PV systems in the multi-MW range. SERIS has developed a highly reliable and scalable monitoring platform to accommodate multiple deployments in different 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, Indonesia, 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. Singapore's Energy Market Authority (EMA)
- ± 150 ms time synchronisation with SERIS' time server

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

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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 irradiation. The inspection and testing findings are also compared to local and/or IEC standards. Among our services are:

- 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

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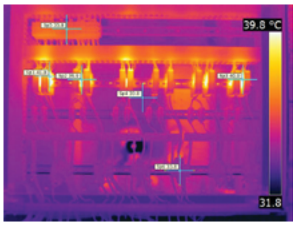
Thermographic Analysis of PV Systems

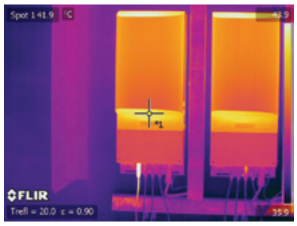
SERIS provides thermographic analysis of PV systems at both system and component levels. This allows for the identification of different types of thermal stresses inside a PV system. Thermal strains can be a sign of an underlying problem with the PV system, affecting system performance or posing safety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

- PV string and module temperature measurements: This helps in determining if a DC string contains damaged solar 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), overloaded cable tray (bottom left image), and 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 reduce the performance of the PV system and increase the risk of a fire.

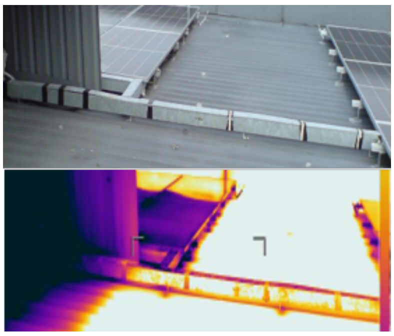
Silicon PV modules in operation, with some solar cells having a significantly increased temperature ("hot spot") due to a bird dropping. Left: Photograph. Right: Thermographic image



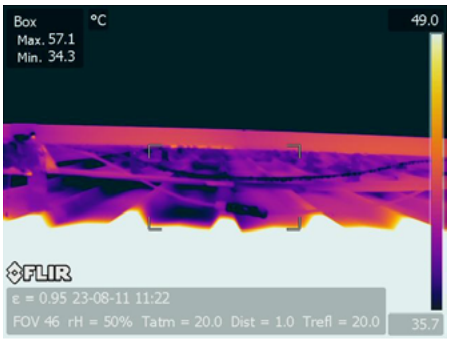
Thermographic image of overheated components in a DC distribution box



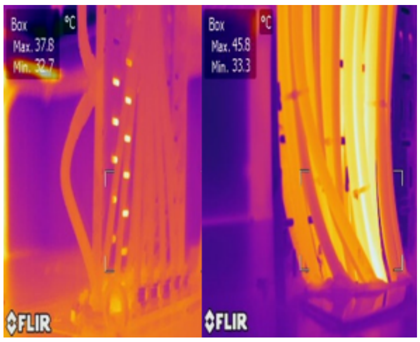
Thermographic analysis showing the overheating of a DC cable and a connector



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 2 DC connectors that are in contact with the metal roof



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

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Specialised **Services**

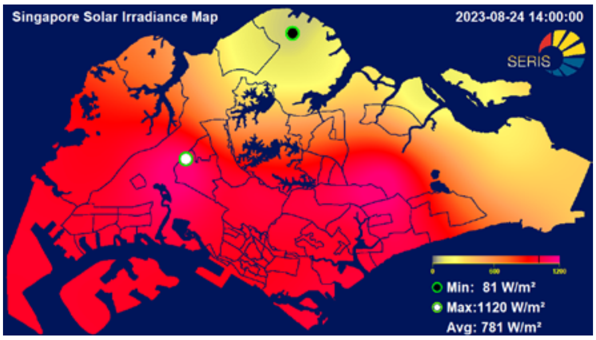
Real-Time Monitoring System of Meteorological Parameters

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

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

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

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



Snapshot of a typical irradiance distribution in Singapore

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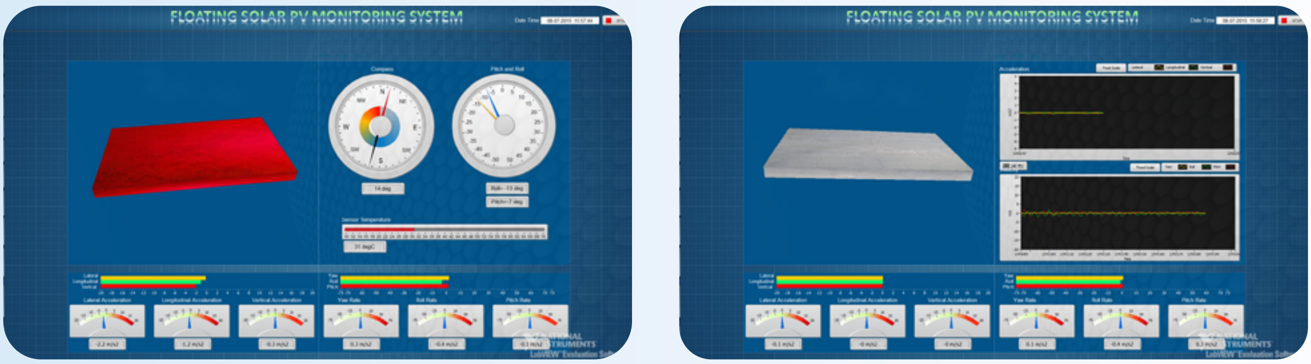
Six-Degree Freedom Motion Monitoring for Floating PV System Applications

One very fast-growing market segment in the solar industry is "Floating PV" on reservoirs, lakes, and increasingly also in near-shore areas. Once implemented, these multi-million-dollar assets need to be properly monitored for their positioning on water, to instantly detect drifts or a possible sinking of the float.

SERIS has developed a system which uses an inertial measurement unit to track motions of floating platforms along the six degrees of freedom. The features of the system are:

- Monitoring of translational movement in three perpendicular axes (surge, heave, sway);
- Monitoring of rotational movement about three perpendicular axes (roll, pitch, yaw);
- Additionally, acceleration rates are monitored for the various parameters, for extreme cases.

Readings are processed by software designed in LabVIEW and displayed in numerical and graphical representation in SERIS' Control Centre, allowing visualisation of the platform movements in real time as well as triggering an alarm system in case of emergencies. Such a system protects the assets by instantaneously evaluating if a floating setup is, for example, partially sinking due to a puncture in a buoyancy element, or if the anchoring system is damaged causing the setup to drift away. Additionally, conditions of extreme motion are detected and can serve as a warning to maintenance personnel, so that platforms are not accessed during those times.



Six-degree freedom monitoring system developed by SERIS – screenshot from LabVIEW showing platform movements in real time

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 (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 reducing 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 80 for more details on this project.

For the testbeds, SERIS has designed a unique type of solar panel which mimics rotatable louvers to track the Sun during the day to maximise solar energy generation but also to manage rainwater, and to control the microclimate around the plants. With this innovation, the traditional meshes 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 resolution. The 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 system.
- 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 panels 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 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' Control Centre, allowing visualisation of the energy generation and plant's health in real-time as well as triggering alarms in case of emergencies.

The SERIS Agri-PV testbeds have a unique type of solar panel which mimics rotatable louvers to track the Sun during the day to maximise solar energy generation.

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

Glare Analysis of PV Installations

With increasing deployment of 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 systems 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 or along highways.

In view of this challenge, SERIS has developed an in-house capability to analyse the effects of glare at several observation points together with 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 arising 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 in or near Changi and Seletar airports. SERIS' track record in relation to glint and glare consultations is listed below.

Track record:

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

2. Project references for glint and glare analysis involving commercially available glare assessment tools:
    i. Singapore – 114 locations
    ii. Malaysia – 20 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 ATCTs*, the runway positions and the flights paths (both inbound and outbound)
Government Regulator/Authority	Discuss results from assessment and provide mitigation measures if needed

** ATCT: Air Traffic Control Tower*

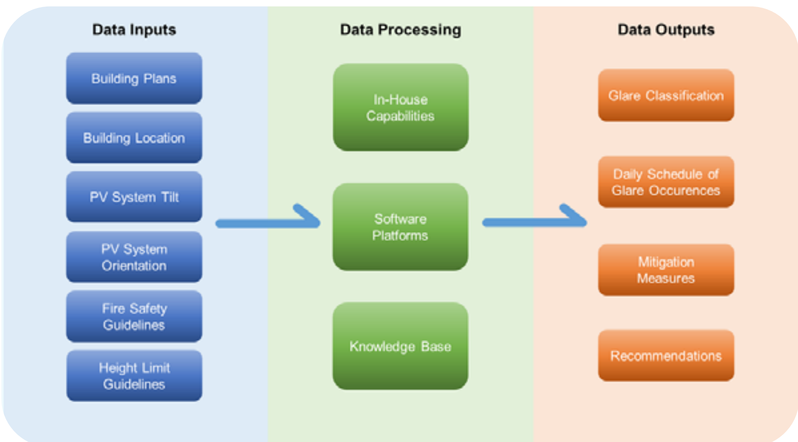


Fig. 1: Glare analysis framework at SERIS. Customised solutions can be designed to suit the needs of individual clients.

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**

Conferences, Workshops, Symposia and Webinars Co-Organised by SERIS

2nd International Integrated-PV Workshop (Virtual), 27-28 March 2023

The 2nd International Integrated-PV (IPV) workshop was jointly organised by the Solar Energy Research Institute of Singapore (SERIS), Forschungszentrum Jülich, the Yangtze Institute for Solar Technology (YIST), and Solarbe Global. Dr Thomas Reindl, Deputy CEO of SERIS was the General Chair of this online IPV workshop.

Based on the success of the 1st online IPV Workshop held in 2022, the 2nd edition focused on latest innovations that will help shaping the IPV technologies – a new but fast-growing segment within the solar PV industry. IPV Technologies include Building-integrated PV (BIPV), Floating PV, Agrivoltaics, and Vehicle-integrated PV (VIPV). The workshop brought together 24 speakers and experts from all over the world, providing them with a platform to share their latest research findings and exchange ideas on the latest advancements, current trends, and future R&D needs in integrated PV technology.

The 2-day online event was well attended by about 5,000 people from around the world.

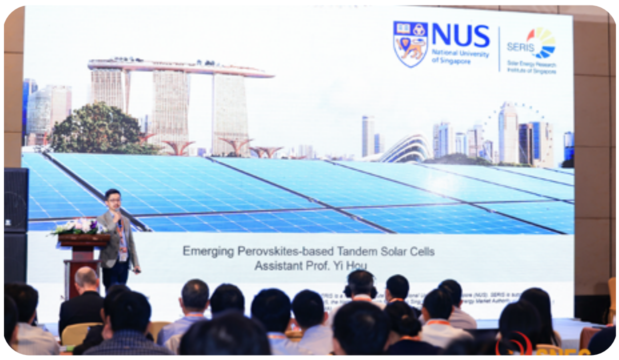
Dr Thomas REINDL (Deputy CEO, SERIS, NUS) delivered his welcome and opening message at the 2nd virtual IPV workshop.

Dr Mauro PRAVETTONI, Director of the PV Modules for Urban Solar Cluster at SERIS, presented the "Peranakan PV module" – the next frontier in aesthetic photovoltaics.

16th Global Advanced PV Technology Conference, 24-26 May 2023 at the SNEC 16th (2023) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition, Shanghai, China, 23-26 May 2023

SERIS co-organised the 16th Global Advanced PV Technology Conference at the world's largest PV tradeshow in 2023, the SNEC 16th (2023) 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 8 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 as well as CTOs and technical experts from world-leading solar companies.

SERIS' Deputy CEO Dr Thomas REINDL delivering the welcome speech (on behalf of the CEO of SERIS and the Conference Chairman Prof Armin ABERLE) to welcome all participants at the opening ceremony of SNEC 2023.
Photo credit: Asian Photovoltaic Industry Association (APVIA)



The invited talk "Emerging Perovskite-based Tandem Solar Cells" was presented by Assistant Prof HOU Yi at the 16th Global Advanced PV Technology Conference.
Photo credit: Asian Photovoltaic Industry Association (APVIA)

The 1st Korea-Singapore Joint Photovoltaic Symposium, South Korea, 6 September 2023

This half-day symposium, co-organised by the Korea Photovoltaic Society (KPVS) and SERIS, was held as a satellite event of the 12th Global Photovoltaic Conference (GPVC 2023) in South Korea. SERIS researchers presented their research work on perovskite-silicon tandem devices, reliability of modules in floating PV and BIPV. The Korean speakers presented their studies on tin-lead mixed perovskite solar cells, the Korean PV market, research trends of floating PV systems, and the status of Agrivoltaics demonstration systems in South Korea and its future. It was an insightful sharing between the Korean and Singaporean researchers on the various PV topics, their current status and the future prospects.

Dr Mauro PRAVETTONI, Director of the PV Modules for Urban Solar Cluster, SERIS, and a Co-Chair of the event, welcoming participants to the 1st Korea-Singapore joint PV Symposium

SERIS researcher Dr SUN Huixuan gave an invited talk on "AI-assisted visual impact assessment of coloured building-integrated photovoltaics on retrofitted building facades" at the symposium.

SERIS Booths at International Conferences & Exhibitions

Energy Innovation 2023 organised by the Energy Market Authority of Singapore (EMA), 7 July 2023

The Energy Innovation 2023 (EI 2023) event organised by EMA attracted about 300 participants from the local energy industry, research community and government agencies. The theme was "Creating a Future-Ready Clean Energy Sector". Local companies and institutes of higher learning (IHLs) were invited to share the outcomes of successful R&D projects funded by EMA and how they support a future-ready clean energy sector. At the event's Project Showcase segment, SERIS presented its innovative Peranakan BIPV modules.

EMA also issued a press release to launch the 2nd Energy Storage Grant Call at the event. This grant call invites the submission of proposals for industry-led R&D projects to address the challenges in deploying Energy Storage Systems (ESS) in Singapore.

SERIS Deputy CEO Dr Thomas REINDL presenting SERIS' innovative "Peranakan modules" project at the Project Showcase segment of the Energy Innovation 2023.

Visitors of EI 2023 learning more about SERIS' innovative PV module technologies from SERIS researchers Dr LEOW Shin Woei (left) and Mr Gavin Prasetyo RAHARJO (right)

Singapore International Energy Week (SIEW) Conference & Exhibition, Singapore, 23-27 Oct 2023

As one of the key exhibitors of SIEW 2023, NUS set up a booth to showcase the University's selected research projects, innovations, technologies and solutions that contribute and support the nation's goal towards a net-zero emissions future. SERIS, a research institute of NUS, was one of the participants at this NUS Pavilion. SERIS showcased solar PV panels with Peranakan-inspired motifs, which provide an innovative way for building designers to harmonise the integration of solar panels into architectural concepts of buildings ("Building-Integrated Photovoltaics", BIPV). This innovative solution aims to stimulate the proliferation of BIPV in the building industry, and thereby accelerate the global deployment of solar PV systems.

The NUS booth at the SIEW 2023 exhibition highlighted a selection of the University's research projects and innovations that support Singapore's decarbonization efforts.

SERIS researchers sharing with a visitor the versatility of SERIS' innovative BIPV module technology that could potentially be applied on the facades of residential and commercial buildings, curtain walls and sun shades.

Asia Clean Energy Summit (ACES) Conference & Exhibition, Singapore, 24-26 Oct 2023

SERIS set up a 18 m^2 booth to showcase some of its innovations in PV cells, modules and systems. Visitors had the opportunity to view a mini-replicate of a sustainable urban farming setup (the actual setup is at the Yuhua Agritech Solar (YAS) Living Lab, at the rooftop of an HDB carpark) that utilises solar photovoltaics to support urban farming (Agrivoltaics = Agriculture + Photovoltaics).

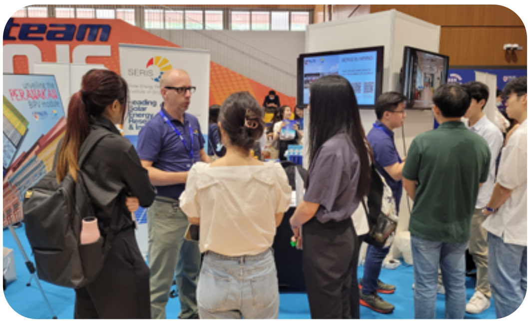
SERIS' booth at ACES 2023, showcasing various innovative projects such as sustainable urban farming (Agrivoltaics), perovskite solar cell technology, next-generation photovoltaics and the "Peranakan PV Modules" suitable for BIPV applications.

Dr LIN Fen, Head of SERIS' Urban Solar Solutions Group, giving a talk on "Agrivoltaics (Agriculture + PV): Multiple use of space in dense urban setting like Singapore" at the technical session of the ACES 2023 Exhibition.

Outreach Activities to Non-Scientific Communities

SERIS regularly engages in outreach activities targeting non-scientific communities and schools to increase the awareness of solar energy research in Singapore. Our researchers conduct talks and organise laboratory tours for students and visitors from Singapore and abroad to demonstrate solar research capabilities at SERIS, and to inform about the progress of solar energy research in Singapore. Below is a collection of photos from selected outreach activities organised by SERIS in 2023. A full list of our outreach activities can be found in the Facts and Figures chapter of this Annual Report.

NUS Career Fest 2023, Singapore, 10 Feb 2023



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

Visit by delegation from the Bank Syariah Indonesia, 22 Feb 2023

A delegation from the Bank Syariah Indonesia (BSI) visited SERIS to understand the institute's research work, innovations and contributions to energy sustainability. This visit was part of the BSI-NUS MMDP IMMERSION PROGRAMME 2023 organised by the NUS Business School.

Visit by students from Nanyang Girls High School, 10 Mar 2023

SERIS Senior Research Fellow Dr Donny Lai hosted the visit and shared with the students what a career in the sustainable energy sector (including solar energy research) entails.

Visit by students from the University of Texas-Austin, USA, 10 May 2023

SERIS Deputy CEO Dr Thomas REINDL delivering a guest lecture on "Sustainable energy and land use in Singapore", followed by a guided tour of SERIS' facilities and laboratories at NUS.

Outreach at River Valley High School (RVHS), Singapore, 25 May 2023

SERIS' Senior Business Development Manager Eddy BLOKKEN visited the River Valley High School Singapore and shared with the students on the topic of solar energy research and adoption in Singapore at a workshop organised by the school.
(Photo credit: River Valley High School Singapore)

Visit by participants from the NUS Sustainability CONNECT event, 4 Sep 2023

Dr CHOI Kwan Bum, Head of SERIS' PV Devices Characterisation Group, explaining to the participants on how crystal defects in solar cells are measured at SERIS.

Participants viewing the mechanical stress tests conducted in the SERIS Laboratory at CleanTech Park.

Visit by lecturers from the Institute of Technical Education (ITE College East), Singapore, 7 Nov 2023

SERIS' Senior Business Development Manager Eddy BLOKKEN hosted a team of educators from the School of Engineering, ITE College East and shared with them the latest technologies in solar photovoltaics.

Visit by students from the NUS Environmental Studies Course, 17 Nov 2023

Dr LEOW Shin Woei, Head of SERIS' BIPV Group, giving an overview presentation on "Deployment of PV in Singapore".

Site visit to the T2 Lab (located at Kent Vale, opposite the NUS Campus), a test bed for innovative building and facade systems. The project on Building Integrated PV (BIPV) shows various technologies that address technical, aesthetic and economic aspects of BIPV. The T2 Lab was implemented by NUS's College of Design and Engineering in collaboration with SERIS and funded by City Developments Limited (CDL).

FACTS AND **FIGURES**

AWARDS AND ACHIEVEMENTS

Jan 2023: The Jury of the World CleanTech Awards (WCA) announced the Winners of the Edition 2022 (WCA2022) during its Black-Tie Gala Ceremony. SERIS at NUS wins the Visionary CleanTech R&D Institution Distinction Award.

Jan 2023: The oral presentation "A novel pixelation approach to integrate PV for urban architecture conservation" by SERIS researcher Gavin Prasetyo Raharjo, and co-authored by SERIS researchers Dr Saw Min Hsian, Dr Leow Shin Woei and Dr Mauro Pravettoni, won the "Best In-Person Contributed Talk" prize for EN06: Silicon for Photovoltaics Symposium at the Material Research Society conference held in Boston, Dec 2022. The Organising Committee announced the award in Jan 2023.

Apr 2023: Erik Spaans, a first-year PhD student at SERIS, was one of the 6 Best Poster Award winners at the 13th International Conference on Crystalline Silicon Photovoltaics (SiliconPV Conference), held on 11-14 Apr 2023 at Delft, Netherlands. His poster was entitled 'Practical J_{sc} limits for silicon heterojunction devices: insights from modelling'. The award recognises excellence in "design, scientific quality and overall presentation of the poster".

Jun 2023: The poster entitled "Patterning the front polysilicon contact for silicon solar cells using laser oxidation" won a Best Poster Award at the 50th IEEE Photovoltaic Specialists Conference (PVSC-50), USA, 11-16 Jun 2023. The poster was co-authored by researchers from the Solar Energy Research Institute of Singapore (SERIS, NUS), Georgia Institute of Technology, USA and Korea Institute of Energy Research, Republic of Korea.

Aug 2023: National Day Awards 2023, Singapore – Mr Aung Myint Khaing, Manager, Solar Energy Research Institute of Singapore (SERIS), National University of Singapore (NUS), was one of the recipients of the Efficiency Medal 2023.

Nov 2023: A paper entitled "A study of module degradation from a 15-year installation in the tropical environment and coastal area" co-authored by Rammdarshan S/O Ramesh (NUS) and Dr Mauro Pravettoni, SERIS, won the Best Paper Award at the 1st Middle East and North Africa Solar Conference (MENA-SC), Dubai, UAE, 15-18 Nov 2023

MEDIA COVERAGE

3 Feb 2023: Singapore launches SE Asia's largest energy storage System. OPIS net.com

16 Mar 2023: Singapore, Indonesia sign MOU to develop renewable energy for domestic use and export. The Edge Singapore

19 Mar 2023: Chinese version of CNA Documentary on Food, Energy, Water.

22 Mar 2023: 'Severe financial impact': Singapore solar panel providers alarmed by rooftop fire safety rules. Eco-Business

16 Jun 2023: 国大最新企业合作研究室 开发更具成本效益光伏太阳能技术. Zaobao

16 Jun 2023: 国大推出7700万元研究计划 研发新太阳能电池技术. 8World.com

16 Jun 2023: Launch of REC@NUS Corporate R&D laboratory for next generation photovoltaics. Bioengineer.org

16 Jun 2023: New research lab in Singapore to raise efficiency, cost-effectiveness of solar panels I CNA Video

17 Jun 2023: $77 million solar research lab launched to improve efficiency, cost-effectiveness of solar panels. The Straits Times

17 Jun 2023: $77m research lab launched to improve efficiency of solar panels. MAGZTER

19 Jun 2023: Making solar energy more affordable. CNA 938 Live

19 Jun 2023: REC launches new corporate laboratory for next generation PV in Singapore. Renewable Energy Magazine

19 Jun 2023: National University of Singapore and REC Solar launch US$57.4 million solar research initiative. PV-Tech

19 Jun 2023: Launch of REC@NUS Corporate R&D laboratory for next generation photovoltaics. PV Magazine

23 Jun 2023: Singapore researchers set 24.35% efficiency record for perovskite PV cell. PV Magazine

27 Jun 2023: NUS develops perovskite solar cells with conversion efficiency of 24.35%. PV Tech

28 Jun 2023: National University of Singapore achieves 24.35 percent efficiency perovskite solar cell. PHOTON newsletter

18 Sep 2023: EUPVSEC: Cautious optimism over local production. PV Magazine

4 Nov 2023: 停车场屋顶太阳能种菜 - 裕华首推农光实验室. 8world.com

4 Nov 2023: 多层停车场顶楼设实验农场 以太阳能供电测试可持续耕作法. Zaobao

26 Nov 2023: Lab on Yuhua carpark rooftop pushes frontiers in harnessing solar energy, urban farming. The Straits Times

20 Dec 2023: Scientists achieve 29.9% efficiency for four-terminal perovskite-CIS tandem solar cell. PV Magazine

7 Dec 2023: Insight 2023 /2024 - China's green energy revolution, CNA

PRESS RELEASES / JOINT PRESS RELEASES

16 Jun 2023: Launch of REC@NUS Corporate R&D Laboratory for Next Generation Photovoltaics (NUS News)

22 Jun 2023: Perovskite solar cells invented by NUS scientists set new world record for power conversion efficiency (NUS News)

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)
- Energies - Special Issue: Characterisation and Reliability of Photovoltaic Module for Hot Environments (Dr Mauro PRAVETTONI, Guest Editor)

Committees

- International Advisory Committee for the Asia-Pacific Forum on Renewable Energy (AFORE 2023) (Prof Armin ABERLE, member)
- Academic Committee of the Asian Photovoltaic Industry Association (APVIA) (Prof Armin ABERLE, Executive Chairman)
- Advisory Board for the Zero-Carbon Energy for the Asia-Pacific Grand Challenge at the Australian National University (ANU), Canberra (Prof Armin ABERLE, member)
- 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 16th (2023) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2023), 16th Global Advanced PV Technology Conference (Prof Armin ABERLE, Chairman)
- 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)
- Executive Committee of Asia Clean Energy Summit 2023 (ACES) (Dr Thomas REINDL, invited member)
- 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 Thomas REINDL, attendee)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 14 (Dr Thomas REINDL, Rachel TAN, attendee)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 15 (Dr LEOW Shin Woei)
- International Electrotechnical Commission (IEC) Technical Committee (TC) 82 ("Solar Photovoltaic Energy Systems"), (Dr Thomas REINDL and Dr Mauro PRAVETTONI, Singapore representatives)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/WG 2 and IEC-TC82/WG 6 (Dr Mauro PRAVETTONI, member)
- International Electrotechnical Commission (IEC) Technical Committee IEC-TC82/JWG 11 (Dr Thomas REINDL and Dr Mauro PRAVETTONI, members)
- 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 Mauro PRAVETTONI, member)
- National IEC Mirror Committee TC 1 WG10 ("Solar PV Product & Accessories"), Enterprise Singapore Dr Mauro PRAVETTONI, 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 Review" working group organised by SCDF, Singapore (Dr Thomas REINDL, member)
- 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 11th Metallisation & Interconnection Workshop, Switzerland, 2023 (Dr Pradeep PADHAMNATH, member)
- Program Committee of Optica Advanced Photonics Congress - Solar Energy and Light-Emitting Devices, 2023 (OPTICA SOLED) (Dr Donny LAI, member)

SERIS MEMBERSHIPS / PARTNERSHIPS

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

VISITORS

5 Jan 2023: Delegation from the Ministry of Sustainability and the Environment, Singapore; Prime Minister's Office and CapitaLand Investment

11 Jan 2023: Prof Alex Jen, Director of City University of Hong Kong's Clean Energy Institute

20 Feb 2023: Delegation from Suzhou, China

22 Feb 2023: Delegation from Bank Syariah, Indonesia

9 Mar 2023: Group President for the Manufacturing Business of ReNew

9 Mar 2023: Delegation from ExxonMobil

9 Mar 2023: Delegation from Concord New Energy, PR China

10 Mar 2023: Student delegation from Nanyang Girls High School, Singapore

12 Apr 2023: Student delegation from ITE College West, Singapore

17 Apr 2023: Visit by faculty members and researchers from Northwestern Polytechnical University in Xi'an, China

19 Apr 2023: Student delegation from St Joseph Institution

10 May 2023: Student delegation from University of Austin, Texas

22 May 2023: Delegation from the symposium organised by the Singapore-German Chamber

7 Jun 2023: Overseas Government official from developing countries

24 Aug 2023: Overseas Government official – participants from Climate Change Adaptation and Mitigation Strategies

4 Sep 2023: Participants from NUS Sustainability CONNECT

10 Oct 2023: Government official from Suzhou, China

7 Nov 2023: Lecturers from ITE College East

8 Nov 2023: Delegation from VOKA Limburg

14 Nov 2023: Delegation from Brunei Prime Minister Office

17 Nov 2023: Students from NUS Environmental Studies Course

6 Dec 2023: Senior Director of the Energy Sector Office, the Asian Development Bank (ADB)

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

27-28 Mar 2023: 2nd IPV Workshop (virtual)

6 Sep 2023: The 1st Korea-Singapore Joint Photovoltaic Symposium (Satellite Symposium of Global Photovoltaic Conference 2023), South Korea

24-26 Oct 2023: Asia Clean Energy Summit (ACES 2023), Singapore

TEACHING / GUEST LECTURES AT UNIVERSITIES

Prof Armin ABERLE, for Electrical and Computer Engineering Course EE4438 Solar Cells and Modules, AY22/23 Semester 2, National University of Singapore (NUS)

Dr CHOI Kwan Bum, Solar Cell Characterisation. Guest Lecture for SUTD Term 3 elective Designing Energy Systems, 7 Nov 2023 (invited)

PATENT APPLICATIONS IN 2023

Nitin Nampalli, Shubham Duttagupta. Multi-layer contact structure, photovoltaic cell and method of fabrication of multi-layer contact structure. PCT application number PCT/SG2023/050160, filing date 13 Mar 2023

Naomi Nandakumar, Shubham Duttagupta, Pradeep Padhamnath. High-efficiency solar cells and the fabrication methodology. Non-provisional, Singapore, application number 10202300669R, filing date 13 Mar 2023

Mauro Pravettoni. Apparatus for characterisation of photovoltaic modules. PCT application number PCT/SG2023/050206, filing date 29 Mar 2023

Nitin Nampalli, Krishna Singh. Method of forming boron containing thin films and devices made thereof. Non-provisional, Singapore, application number 10202301700T, filing date 15 Jun 2023

Nitin Nampalli, Jeremie Werner, Shubham Duttagupta. Electrodes for halide perovskite devices. Non-provisional, Singapore, application number 10202301844Y, filing date 28 Jun 2023

Pradeep Padhamnath, Shubham Duttagupta, Nitin Nampalli. Surface treatment method for forming a passivated contact of a solar cell. Nationalised PCT, USA, application number 18/284,647, filing date 28 Sep 2023

Wang Puqun, Ho Jian Wei, Choi Kwan Bum. Method for luminescence characterisation of optoelectronic materials and devices based on modulated optical excitation. Non-provisional, Singapore, application number 10202251380W, refiling date 17 Oct 2023

Nitin Nampalli, Krishna Singh. Hole selective contacts, photovoltaic devices made thereof and methods of formation. Non-provisional, Singapore, filing date 17 Nov 2023

Nitin Nampalli, Krishna Singh. Carrier selective contacts, photovoltaic devices utilising them and methods of forming thereof. Non-provisional, Singapore, filing date 17 Nov 2023]

PUBLICATIONS

Book Chapter

Chen, T.Y., Heng, C.K., Leow, S.W. Reimagining building facades: the prefabricated unitised BIPV walls (PUBW) for high-rises. Book chapter in book: Facade design - challenges and future perspective (pp.1-12). Publisher: IntechOpen. Sep 2023. DOI:10.5772/intechopen.112878; License: CC BY 3.0

Industry Report

Zhang, W., Inglin, C., Reindl, T. et al. SEAS-SCDF PV Fire Safety Handbook (Preliminary version) - Best Industry Practices: Part I: Fire Safety Requirements for roof-mounted Photovoltaic (PV) Panel Installations. Published online by the Sustainable Energy Association of Singapore (SEAS) with input from Singapore Civil Defence Force (SCDF), Nov 2023

Journal papers

Shen, G., Dong, H., Yang, F., Ng, X.R., Li, X., Lin, F., Mu, C. Application of an amphipathic molecule at the NiO_x/perovskite interface for improving the efficiency and long-term stability of the inverted perovskite solar cells. Journal of Energy Chemistry, vol. 78, pp. 454-462 (2023)

Pravettoni, M., Rajput, A.S. On the metastability of silicon heterojunction solar photovoltaic modules. MRS Bulletin (2023), https://doi.org/10.1557/s43577-023-00475-x

Saw, M.H., Soh, H.L., Ng, A., Birgersson, E., Tay, E.R., Pravettoni, M. A spot-area method to evaluate the incidence angle modifier of photovoltaic devices – Part 1: cells. IEEE Journal of Photovoltaics, vol. 13, no. 2, pp. 267-274 (2023)

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Haegel, N.M., Verlinden, P., Victoria, M., Altermatt, P., Atwater, H., et al. Photovoltaics at multiterawatt scale: Waiting is not an option. Sustained global growth in PV of 25% over the next decade. Science vol. 380, issue 6640, pp. 39-42 (2023)

Padhamnath, P., Choi, W.J., De Luna, G., Arcebal, J.D., Rohatgi. A. 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 vol. 256, 112351 (2023)

Nakka, L., Luo, W., Aberle, A.G., Lin, F. Study of potential-induced degradation in glass-encapsulated perovskite solar cells under different stress conditions. Solar RRL, 2300100 (2023)

Tian, I.S.P., Ren, Z., Venkataraj, S., Cheng, Y., Bash, D. et al., Tackling data scarcity with transfer learning: a case study of thickness characterisation from optical spectra of perovskite thin films. Digital Discovery, 2, pp. 1334-1346 (2023)

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Feng, J., Wang, X., Li, J., Liang, H., Wen, W. et al. Resonant perovskite solar cells with extended band edge. Nat. Commun. 14, 5392 (2023). https://doi.org/10.1038/s41467-023-41149-1

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Huang, Z., Ho, J.W., Choi, K.B., Danner, A., Chan, K.S. Predicting loss analysis from luminescence images in Si solar cells with convolutional neural networks. Solar RRL, 2300396 (2023)

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Gandhi, O., Zhang, W., Kumar, D.S., Rodríguez-Gallegos, C.D., Yagli. G.M. The value of solar forecasts and the cost of their errors: A review. Renewable and Sustainable Energy Reviews, vol. 189, Part B, 113915 (published online 8 Nov 2023)

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Conference papers / proceedings

Spaans, E., Venkataraj, S., Aberle, A., Nampalli, N. Practical J_{sc} limits for SHJ devices: Insights from modelling. Proceedings of the SiliconPV 2023, Netherlands, 11-13 Apr 2023 (in press)

Nakka, L., Shen. G., Aberle, A.G., Lin, F. Mitigation of potential induced degradation in perovskite solar cells. Proceedings of the 50th IEEE Photovoltaic Specialists Conference (PVSC 50), Puerto Rico, 11-16 Jun 2023 (in press)

Toh, W.W., Saw, M.H., Birgersson, E., Pravettoni, M. A comparative study of the reflectance of commercial photovoltaic modules. Proceedings of the 50th IEEE Photovoltaic Specialists Conference (PVSC 50), Puerto Rico, 11-16 Jun 2023 (in press)

Zhao, S., Low, Y.M., Rodríguez-Gallegos, C.D., Reindl, T. Potential root causes for failures in floating PV systems. Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2023), 11-16 Jun 2023, Australia (in press)

Dahiya, V., Nampalli, N., Sridharan, R., Sharma, R., Aberle, A.G. High accuracy optical ray-tracing models for single-junction perovskite solar cells. Proceedings of the 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Saw, M.H., Cynthia, A., Pravettoni, M. Photoluminescence imaging on silicon modules using blue LED floodlights. Proceedings of the 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Sharma, R., Nampalli, N., Dahiya, V., Aberle. A.G. Exploring efficient deposition techniques for large-area perovskite-silicon tandem solar cells. Proceedings of the 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Singh, K., Yea, J. Y., Spaans, E., Manalo, M.L., Guerra, R., Ison, J., Buatis, J.K., Ungos, B., Venkataraj, S., Aberle, A.G., Nampalli, N. Rapid illuminated annealing process to improve the efficiency of silicon heterojunction solar cells. Proceedings of the 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Yap, Q.J., Cleofe, R.G., Garcia, J.I., Buatis, J.K., Maria, L.L.M, Venkataraj, S., Liu, T., Jang, Y., Singh, K., Nampalli, N., Aberle, A.G. Interfacial engineering and capping of vanadium oxide hole transport layers for silicon solar cells. Proceedings of the 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Ramesh, R., Pravettoni, M. A study of module degradation from a 15-year installation in the tropical environment and coastal area. 1st Middle East and North Africa Solar Conference (MENA-SC), UAE, 15-18 Nov 2023

TALKS AT CONFERENCES, WORKSHOPS AND SEMINARS

(Speaker's name underline)

Reindl, T. International security of supply workshop. Scenario building workshop organised by the Energy Studies Institute, Singapore, 12-13 Jan 2023 (invited)

Pravettoni, M. New reliability challenges for the deployment of solar modules in the urban environment. International Conference on Clean Energy for Carbon Neutrality 2023 (ICCECN-2023), Hong Kong, PR China, 07-10 Mar 2023 (keynote)

Reindl, T. Opportunities for Solar PV in Singapore. Powering Cities with a Greener Future Session at the Green Engineering Conference 2023 @NTU, Singapore, 16 Mar 2023 (invited)

Reindl, T. Opening introduction and the case for integrated PV. 2nd International Integrated-PV Workshop, 27-28 Mar 2023 (invited, virtual)

Pravettoni, M. "Peranakan PV", the next frontier in aesthetics photovoltaics. 2nd International Integrated-PV Workshop, 27-28 Mar 2023 (invited, virtual)

Rodriguez, C.D. Overview & Latest Trends in Floating PV. 2nd International Integrated-PV Workshop, 27-28 Mar 2023 (invited, virtual)

Reindl, T. Opening remarks. Solar Assets - South East Asia 2023 Conference, Singapore, 20 Apr 2023 (invited)

Padhamnath, P. State-of-the-art screen-printing technology in solar cell manufacturing. Metallisation and Interconnection Workshop, Switzerland, 8-9 May 2023 (invited speaker and moderator)

Aberle, A., Reindl, T. Welcome speech at SNEC 2023 (invited)

Aberle, A., Padhamnath, P., Reindl, T. monoPoly™ and biPoly™ technology ("TOPCon") at SERIS - Recent developments and future outlook. 16th Global Advanced PV Technology Conference, SNEC2023, China, 22-26 May 2023 (invited talk)

Hou, Y. Emerging perovskites-based tandem solar cells. 16th Global Advanced PV Technology Conference, SNEC2023, China, 22-26 May 2023 (invited talk)

Leow, S.W. Barrier and opportunities of BIPV in Singapore. 16th Global Advanced PV Technology Conference, SNEC2023, China, 22-26 May 2023 (invited talk)

Pravettoni, M. Qualifying solar modules for floating applications: stresses and severities. 16th Global Advanced PV Technology Conference, SNEC2023, China, 22-26 May 2023 (invited talk)

Reindl, T., Rodriguez, C., Gandhi, O. Overview and latest Trends in Floating PV. 16th Global Advanced PV Technology Conference, SNEC2023, China, 22-26 May 2023 (invited talk)

Reindl, T. Introduction to Solar PV Road-mapping. SEAS-AESI Workshop on Promoting Solar PV in Indonesia, Indonesia, 5 Jun 2023 (invited talk)

Reindl, T. Solar energy integration into the urban grid. SEAS-AESI Workshop on Promoting Solar PV in Indonesia, Indonesia, 5 Jun 2023 (invited talk)

Reindl, T. Solar Energy: innovations and its challenges. Asia Tech x Singapore, Innovfest x Elevating Founders Track. Singapore, 7-9 Jun 2023 (invited talk)

Pravettoni, M., Long, J., Bettega, G. Reliability of modules in floating photovoltaics: stresses, severities and tests. 50th IEEE Photovoltaic Specialists Conference (PVSC 50), USA, 11-16 Jun 2023 (plenary)

Nakka, L., Shen. G., Aberle, A.G., Lin, F. Mitigation of potential induced degradation in perovskite solar cells. 50th IEEE Photovoltaic Specialists Conference (PVSC 50), Puerto Rico, 11-16 Jun 2023

Toh, W.W., Saw, M.H., Birgersson, E., Pravettoni, M. A comparative study of the reflectance of commercial photovoltaic modules. 50th IEEE Photovoltaic Specialists Conference (PVSC 50), USA, 11-16 Jun 2023

Zhao, S., Low, Y.M., Rodríguez-Gallegos, C.D., Gandhi, O., Reindl, T. Potential root causes for failures in floating PV systems. ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE2023), Australia, 11-16 Jun 2023

Hou, Y. Emerging perovskites-based tandem solar cells. International Conference on Materials for Advanced Technologies (ICMAT 2023), Singapore, 26-30 Jun 2023 (invited)

Hou, Y. China-ASEAN Forum on Emerging Industries. China, 4-5 Jul 2023 (invited panellist)

Reindl, T., Pravettoni, M. The Peranakan module. EMA Energy Innovation 2023 project showcase. Singapore, 7 Jul 2023 (invited)

Leow, S.W. Opportunities and challenges for BIPV. The next frontier: building and infrastructural integrated photovoltaic. Networking session jointly organised by AGC and the Sustainable Energy Association of Singapore (SEAS), Singapore, 17 Jul 2023 (invited)

Pravettoni, M. New reliability challenges for solar deployment in urban environment. Outreach talk invited by The Institution of Engineers, Malaysia, 2 Sep 2023 (invited)

Saw, M.H. Development of aesthetical solar PV modules for building applications – "Peranakan PV". Outreach talk invited by The Institution of Engineers, Malaysia, 2 Sep 2023 (invited)

Pravettoni, M. Ramesh, R., Long, Ji. Reliability of modules in floating photovoltaics: stresses, severities and tests. 1st Korea-Singapore joint Symposium, Korea, 6-8 Sep 2023 (invited plenary)

Chen, T.Y., Heng, C.K., Leow, S.W. A novel design approach to prefabricated BIPV walls for multi-story buildings. 1st Korea-Singapore joint Symposium, Korea, 6-8 Sep 2023 (invited)

Sun, H.X., Heng, C.K., Reindl, T. AI-assisted visual impact assessment of coloured Building-Integrated Photovoltaics on retrofitted building facades. 1st Korea-Singapore joint Symposium, Korea, 6-8 Sep 2023 (invited)

Wang, P., Liu, T., Choi, K.B., Lin, F., Aberle, A. Streamlining the development of perovskite/biPoly™ tandem devices through simulation and characterisation. 1st Korea-Singapore joint Symposium, Korea, 6-8 Sep 2023 (invited)

Reindl, T. Opening panel discussion on perspective "What are the options to deploy all the solar panels? Do we have an area problem (Europe/global)?" 40th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2023), Portugal, 18-20 Sep 2023 (invited panellist, Chair)

Reindl, T. Energy transition and decarbonisation: an overall landscape. ESI Workshop on Energy Transition During Tough Economic Times, Singapore, 4 Oct 2023 (invited)

Reindl, T. Best industry practices to comply with fire safety requirements for PV panels. JTC-SCDF Fire Safety Seminar, Singapore, 12 Oct 2023 (invited)

Lin, F. Agrivoltaics (Agri + PV) – multiple use of space in dense urban settings like Singapore. Asia Clean Energy Summit 2023, Techtalk at Exhibition Hall, Singapore, 25 Oct 2023 (invited)

Reindl, T. TR100:2022: Floating PV power plants. Asia Clean Energy Summit 2023, "Energy Sustainability" track, Singapore, 26 Oct 2023 (invited)

Pravettoni, M. Reliability of modules in floating photovoltaics: stresses, severities and tests. UNSW SPREE talk series, Australia, 1 Nov 2023 (invited)

Tan, R. Opportunity of utilisation of ACPE for cross-border engineering services across ASEAN. ASEAN Chartered Professional Engineers (ACPE) Forum, Indonesia, 2 Nov 2023 (invited)

Reindl, T. Handbook Launch: Best Industry Practices - Part I: fire safety requirements for roof-mounted solar photovoltaic (PV) installations. Clean Energy Committee Meeting organised by the Sustainable Energy Association of Singapore (SEAS), Singapore, 6 Nov 2023 (invited)

Rodriguez, C.D. Floating PV (FPV) Systems: Characteristics and Implementation. Floating PV training course conducted at the Sustainable Association of Singapore (SEAS), Singapore, 6 Nov 2023

Hou, Y. Emerging perovskites-based tandem solar cells. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Saw, M.H., Cynthia, A., Pravettoni, M. Photoluminescence imaging on silicon modules using blue LED floodlights. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Sharma, R., Nampalli, N., Dahiya, V., Aberle. A.G. Exploring efficient deposition techniques for large-area perovskite-silicon tandem solar cells. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Singh, K., Yea, J. Y., Spaans, E., Manalo, M.L., Guerra, R., Ison, J., Buatis, J.K., Ungos, B., Venkataraj, S., Aberle, A.G., Nampalli, N. Rapid illuminated annealing process to improve the efficiency of silicon heterojunction solar cells. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Yap, Q.J., Cleofe, R.G., Garcia, J.I., Buatis, J.K., Maria, L.L.M, Venkataraj, S., Liu, T., Jang, Y., Singh, K., Nampalli, N., Aberle, A.G. Interfacial engineering and capping of vanadium oxide hole transport layers for silicon solar cells. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Singh, K., Yea, J. Y., Spaans, E., Manalo, M.L., Guerra, R., Ison, J., Buatis, J.K., Ungos, B., Venkataraj, S., Aberle, A.G., Nampalli, N. Rapid illuminated annealing process to improve the efficiency of silicon heterojunction solar cells. 2023 Workshop on Advanced Materials and Solar Cell Technology, China, 9-11 Nov 2023 (invited)

Rodriguez, C.D. Sun, H.X., Gandhi, O., Hjetland, E., Söderström, W., Mignot, C., Ali, J., Vinayagam, L., Blokken, E., Balzer, A., Johansen, B., Reindl, T. Offshore Floating PV: status, challenges and potential. forum for off-shore photovoltaics. CPIA Offshore Photovoltaics Forum 2023, China, 10 Nov 2023 (invited keynote, recorded)

Aberle, A. Status of solar PV in Singapore. APVIA Annual General Meeting. 13 Nov 2023, hybrid meeting (invited)

Gandhi, O., Rodriguez, C.D., Reindl, T. Singapore photovoltaic market and future prospects. ASEAN Photovoltaic & Storage Conference & Expo, Indonesia, 14-16 Nov 2023 (invited)

Gandhi, O., Rodriguez, C.D., Reindl, T. Navigating the potential of floating solar photovoltaics with energy storage (panel discussion). ASEAN Photovoltaic & Storage Conference & Expo, Indonesia, 14-16 Nov 2023 (invited panellist)

Guo, R., Wang, Xi., Jia, X., Guo, X., Li, J., Li, Z. et. al. Surface morphology regulation enabling highly-efficient p-i-n perovskite solar cells. ANSTO User Meeting-AUM 2023, Australia, 27-29 Nov 2023

Saw, M.H., Pravettoni, M. Measurement of angular response in IEC 61853-2: challenges for bifacial modules. Bifacial PV Workshop 2023, Qatar, 3-6 Dec 2023 (invited)

Reindl, T. PV magazine Roundtables Europe 2023 (virtual). Panel discussion: Handling harsh environments. 5 Dec 2023 (invited panellist)

Pravettoni, M. Invited panellist at ISA Pavilion, COP28. UAE, 11 Dec 2023 (invited)

POSTERS AT CONFERENCES AND SEMINARS

(Presenter's name underlined)

Pravettoni, M., Sundar Das, M.M., Long, J. New stresses and severities for the reliability of modules in floating PV. 2023 NREL Reliability Workshop, USA, 28 Feb – 3 Mar 2023

Spaans, E., Venkataraj, S., Aberle, A., Nampalli, N. Practical J_{sc} limits for SHJ devices: insights from modelling. SiliconPV 2023, Netherlands, 11-13 Apr 2023

Lan, Y., Padhamnath, P., Arcebal, J.D., De Luna, G., Danner, A. Development of biPoly™ solar cells on ultra-thin silicon substrates. ICMAT, Singapore, 26-30 Jun 2023

Clement, C.E., Liang, T.S., Leow, S.W. BIPV elements for prefabricated prefinished volumetric construction. 40th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2023), Portugal, 18-20 Sep 2023

Lan, Y., Padhamnath, P., Arcebal, J.D., De Luna, G., Danner, A. Investigation of ultra-thin solar cells with polysilicon based passivated contacts on both front and rear. 40th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2023), Portugal, 18-20 Sep 2023

Sun, H.X., Reindl, T. 3D Glare assessment tool for PV deployment in high-density urban environments. 40th European Photovoltaic Solar Energy Conference and Exhibition (EU PVSEC 2023), Portugal, 18-20 Sep 2023

Lin, F., Pandian, H., Liu, T., Reindl, T. "Agrivoltaics" – the best of two worlds (agri, solar). SFA-NUS Science Day, Singapore, 25 Sep 2023

Rodríguez, C., Gandhi, O., Sun, H.X., Reindl, T. Floating solar: huge potential for SG and the world. SFA-NUS Science Day, Singapore, 25 Sep 2023

Dahiya, V., Emelieu, T.W., Sridharan, R., Sharma, R., Aberle, A.G., Nampalli, N. Spectrometric validation of ellipsometry-extracted refractive index of thin-films for perovskite solar cells. 34th International PV Science and Engineering Conference (PVSEC-34), China, 6-10 Nov 2023

Saw, M.H., Pravettoni, M. Photoluminescence imaging for degradation analysis of bifacial photovoltaic modules. Bifacial PV Workshop 2023, Qatar, 3-6 Dec 2023

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