NUS National University of Singapore

SERIS Solar Energy Research Institute of Singapore

ANNUAL REPORT 2022

National Research Foundation
Prime Minister's Office
Singapore

Energy Market Authority
Smart Energy, Sustainable 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).

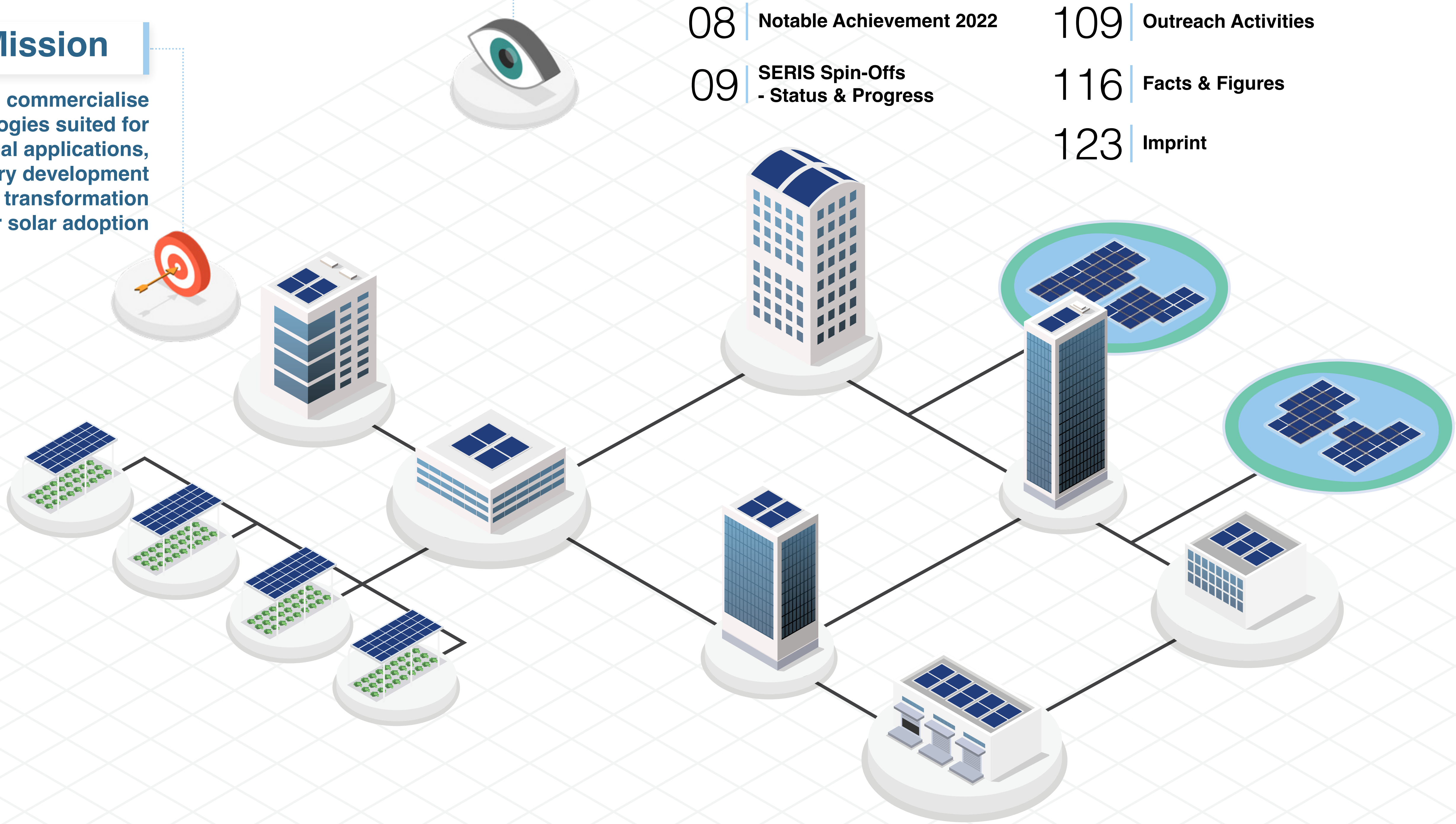
SOLAR ENERGY RESEARCH INSTITUTE OF SINGAPORE (SERIS)

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)

"At NUS, we are committed to advancing sustainability solutions and contributing to the global fight against climate change. As a world-leading solar energy research institute, SERIS has been instrumental in shaping Singapore's efforts towards reducing greenhouse gas emissions and carbon intensity. SERIS will continue to develop and commercialise solar technologies suited for urban and tropical applications, enhancing the solar ecosystem in Singapore, Asia-Pacific and the world."

Professor CHEN Tsuhan, Deputy President (Research and Technology), National University of Singapore (NUS)

Energy Market Authority of Singapore (EMA)

"SERIS plays a key role in supporting Singapore's energy transition to decarbonise our power sector, through their continuous research efforts in solar technologies. Its work and achievements in high-efficiency solar cells and innovative urban solar deployments are important in helping maximise solar adoption both in Singapore and globally."

Mr Ralph FOONG, Deputy Chief Executive, Energy Market Authority of Singapore (EMA) and member of the SERIS Supervisory Board

National Research Foundation Singapore (NRF)

"SERIS's R&D contributions, in partnership with academia, industry and government agencies, continue to play an important role in Singapore's decarbonisation efforts. The innovative sustainability technologies and urban solutions developed by SERIS support Singapore's national solar deployment plans as well as the growth of the solar industry, which in turn contribute to the nation's efforts to achieve net-zero emissions."

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

Singapore Economic Development Board (EDB)

"SERIS continues to support Singapore's solar ambitions through its holistic research across the solar value chain with major industry partners, in areas such as next-generation high efficiency cells and modules, solar forecasting, and innovative solar deployment solutions (e.g. building-integrated PV, floating solar). SERIS' efforts and achievements are critical to the solarisation of Singapore and industry development for the clean energy sector."

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

Global warming is accelerating. According to the latest United Nations Environment Programme (UNEP) report published on 3rd November 2022, climate impacts are intensifying across the globe and hence nations must dramatically increase funding and implementation of actions designed to help vulnerable nations and communities adapt to the climate storm. Furthermore, according to UNEP's recently released Emissions Gap Report, Nationally Determined Contributions (NDCs) under the Paris Agreement now point towards global warming of 2.4 - 2.6 °C by the end of the century. Such temperatures would be a disaster, as they have never occurred on our planet in the last 3 million years and would mean that a significant part of the planet would effectively become uninhabitable.

The reasons for the rapidly rising temperatures are known, and so are the solutions. In parallel to implementing energy efficiency measures, as many countries as possible must stabilise their carbon emissions during this decade, and achieve net-zero emissions by 2050. Singapore is part of these global efforts, as announced by Deputy Prime Minister Lawrence Wong in October during the 2022 Singapore International Energy Week. In 2021, to accelerate the local energy transformation, the government launched the *Singapore Green Plan 2030*, which 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 solar PV power installed locally by 2025, and at least 2 GW_p by 2030. In parallel, Singapore will work with neighbouring countries towards the import of reliable, competitive and low-carbon electricity, with a target of 4 GW of total imports by 2035.

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. The institute is thus a key element of Singapore's journey into a low-carbon future.

On 31st March 2022 SERIS completed its third funding phase (FY2018 - FY2021), whereby all KPIs (key performance indicators) have been achieved. On 1st April 2022 SERIS started its fourth funding cycle, which runs for 5 years (FY2022 - FY2026) and provides core funding for the three flagship projects and developing and testing several "Urban Solar" deployment options.

This report presents SERIS' major achievements in calendar year 2022 and the R&D plans for 2023. It also describes the institute's research departments ("clusters") and groups, as well as its facilities & laboratories, services, and outreach activities.

In 2022, SERIS' R&D focus was on its three flagship projects (tandem solar cells, BIPV modules and systems, floating solar systems), several "Urban Solar" deployment options such as colourful PV modules (e.g. in Peranakan and Italian designs), "agrivoltaics" (combining agriculture and solar PV) and on collaborative research projects with industry partners.

Notable SERIS achievements in 2022 include: 23.2% efficiency for a large-area monoPoly™ silicon solar cell made on a thin wafer (110 μm); a certified world record efficiency of 23.4% for a perovskite-organic tandem solar cell (0.05 cm^2, 2-terminal); 25.2% efficiency for a p-i-n structured perovskite solar cell (0.05 cm^2); 28.5% efficiency for a perovskite-silicon tandem cell (1 cm^2, 2T); a strongly increased popularity of the "Peranakan BIPV modules" (showcased both regionally & internationally), which are now also part of the collection of one of Europe's largest science museums; implementation of a fully operational SERIS-developed solar forecasting system at the Energy Market Authority's Power System Control Centre; setting up a soil-based agrivoltaics testbed at the Singapore Discovery Centre (SDC) expansion of research collaborations in Floating Solar with leading industry partners (such as Sunseap, Keppel Infrastructure and Fred.Olsen Renewables), and surpassing the threshold of 100,000 downloads from readers around the world of the SERIS-World Bank Group reports on Floating Solar ("Where Sun Meets Water").

I would like to thank all SERIS staff, adjunct researchers and students for their numerous contributions 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 global installed solar PV capacity has passed 1 terawatt-peak (TW_p) in 2022, and the solar industry is on track to reach a deployment rate of 1 TW_p/year within 10 years. Considering that 50 - 100 TW_p of combined solar and wind installations are needed to decarbonise the global economy by 2050, it is almost certain that - beyond 2030 - the annual solar industry revenues will be above USD 500 billion per year. Given these tremendous opportunities for people and institutions in the industry, SERIS and NUS will continue to work hard on developing innovative solar energy technologies, transferring them to industry, and contributing to the solarisation of Singapore, Asia-Pacific and the world.

With sunny regards,
Prof Armin ABERLE
SERIS CEO
22 December 2022

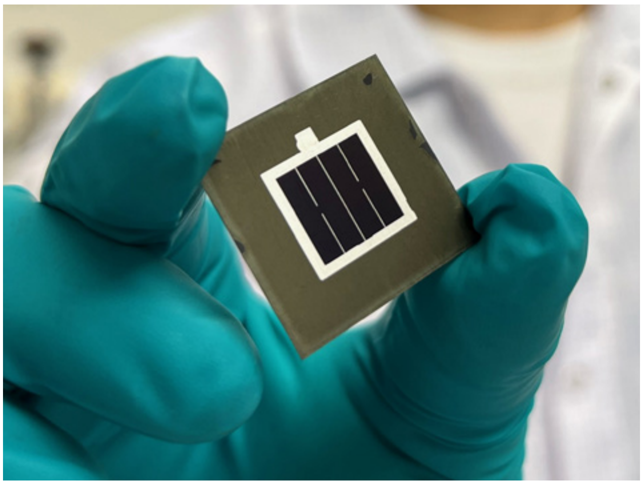
HIGHLIGHTS 2022

Jan: A technological innovation that improves the efficiency of perovskite-organic tandem solar cells to > 23% is published in the journal **Nature Energy**. The research was led by Assistant Prof HOU Yi, Head of SERIS' Perovskite-based Multijunction Solar Cells Group and a faculty at the NUS Department of Chemical and Biomolecular Engineering.

Image credit: Ministry of Defence, Singapore

Feb: Dr Thomas REINDL receiving the formal letter of appointment from Ministry of Defence Permanent Secretary (Defence), Mr CHAN Heng Kee to serve as member of the Ministry's newly formed External Advisory Panel for Environmental Sustainability (EAPES). Dr REINDL will represent SERIS in the panel to provide assessments and recommendations on Mindef and SAF sustainability policies, as well as share knowledge on the latest developments, technologies and best practices.

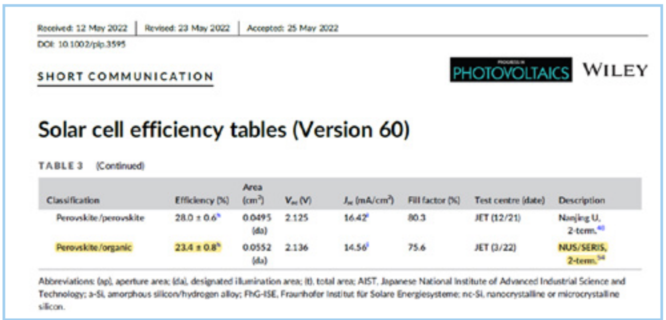
Jan: Dr Thomas REINDL, representing SERIS, receives a token of appreciation from Senior Minister of State for Defence, Mr ZAQY Mohamad, in appreciation of SERIS' contributions to the Community Facility at National Service Resort & Country Club (NSRCC) Kranji, in response to the nation's fight against the pandemic. The facility contained various types of novel light-weight solar panels and energy storage solutions to support the energy requirements and contributes to environmental sustainability while caring for the COVID-19 patients.



Mar: Assistant Prof HOU Yi's research group at SERIS achieves **28.0% efficiency for a perovskite-silicon tandem solar cell** with an area of 1.0 cm^2. The bottom cell is a heterojunction silicon cell made by an industrial partner on an n-type silicon wafer textured on both sides. The perovskite top cell was made at SERIS in the p-i-n sequence, using spin coating for the deposition of the perovskite absorber layer. The measured 1-Sun parameters of the 2-terminal tandem cell are: Open-circuit voltage 1.93 V, short-circuit current density 19.2 mA/cm^2, fill factor 0.756, efficiency 28.0%.

HIGHLIGHTS 2022

Mar: SERIS successfully completes its third funding phase (FY2018 - FY2021) on 31 March 2022, with all key performance indicators (KPIs) of the Phase-3 core grant achieved.



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DOI: 10.1002/pip.3595

SHORT COMMUNICATION

PROGRESS IN PHOTOVOLTAICS WILEY

Solar cell efficiency tables (Version 60)

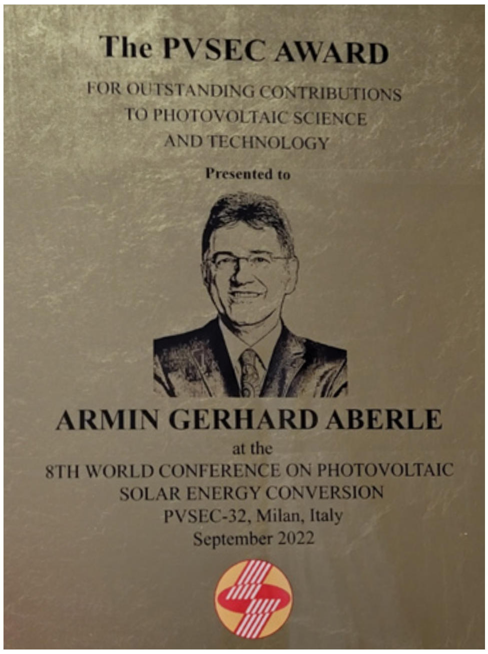
TABLE 3 (Continued)

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill factor (%)	Test centre (date)	Description
Perovskite/perovskite	28.0 ± 0.6[b]	0.0495 (da)	2.125	16.42[f]	80.3	JET (12/21)	Nanjing U, 2-term.[40]
Perovskite/organic	23.4 ± 0.8[b]	0.0552 (da)	2.136	14.56[j]	75.6	JET (3/22)	NUS/SERIS, 2-term.[34]

Abbreviations: (ap), aperture area; (da), designated illumination area; (t), total area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; a-Si, amorphous silicon/hydrogen alloy; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon.

May: Certified by Japan's Electrical Safety and Environment Technology Laboratories (JET), SERIS achieves a **world-record efficiency of 23.4% for a perovskite-organic tandem solar cell**. The result has been included in the latest Solar cell efficiency tables (version 60) of the journal Progress in Photovoltaics. The 2-terminal tandem cell has an area of 0.055 cm^2 and was made by Assistant Prof HOU Yi's Perovskite-based Multijunction Solar Cells Group at SERIS, using an organic bottom cell from an external collaborator.

Sep: SERIS showcases an innovative PV module technology ("**Peranakan module**") at the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8) in Milan, Italy. These colourful PV modules enhance the aesthetic appeal of building facades while generating clean & sustainable energy. SERIS' patented technology also allows the transformation of a conventional PV module into a module with user-desired pattern or image, for example with an image of Leonardo da Vinci (see the front module in the photo of the SERIS booth at WCPEC-8).



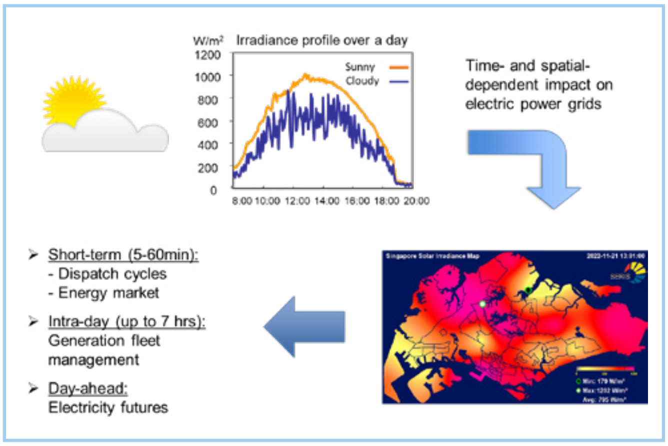
Sep: SERIS CEO Prof Armin ABERLE wins a **PVSEC Award (PVSEC-32)** for "*his outstanding contributions to the development of photovoltaic science and technology*". Prof ABERLE was selected by the International Advisory Committee of the International Photovoltaic Science and Engineering Conference (PVSEC) according to nominations. The 32nd PVSEC was part of the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8) held during 26-30 Sep 2022 in Milan, Italy.

Oct: Three BIPV modules, designed and fabricated by SERIS, become part of the collection of the Museo Nazionale Scienza e Tecnologia "Leonardo da Vinci" in Milan, Italy's largest science museum and world famous for its permanent exhibition of Leonardo's machines. The specially designed "Leonardo PV module" and two "Peranakan BIPV modules" showcase SERIS' innovative printing technologies to the museum's visitors.

HIGHLIGHTS 2022

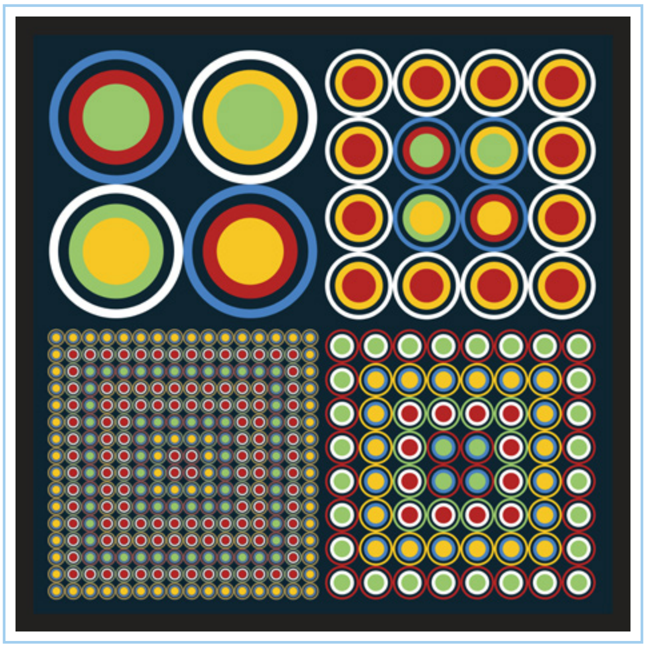
Image credit: Keppel

Oct: NUS-SERIS signs a MOU with Keppel Infrastructure and ERI@N Nanyang Technological University (NTU) to jointly conduct a study on the feasibility of developing a **new type of hybrid renewable energy generation system** which harnesses a combination of solar, wind and tidal energies in Singapore. The consortium plans to design and deploy a pilot system with up to 100 MW of renewable energy capacity, which can be scaled up over time. After implementing the novel system in Singapore, the aim is to roll out the floating hybrid renewable energy system innovation to other regions in Asia and beyond.



Nov: SERIS completes a 1-year trial of a **Solar Forecasting tool** to anticipate solar intermittency and enhance Singapore's power grid resilience. The trial was supported by the Energy Market Authority of Singapore (EMA) and the Meteorological Service Singapore (MSS) of the National Environment Agency (NEA). The SERIS developed tool has strong potential to be scaled up and commercialised to support the operation of solar PV farms in Asia.

Nov: The international magazine MIT Technology Review includes SERIS' Group Head Assistant Prof HOU Yi in its "**Innovators Under 35 Asia Pacific List 2022**" (category Pioneers), for his development of perovskite-organic tandem solar cells with efficiencies exceeding 23%.



Nov: The Conference Chairs of the 2022 MRS Fall Meeting in Boston, USA select SERIS' image "The Powers of Four" as a finalist in the conference's Science as Art competition. Putting graphics on solar PV modules for building integration is challenging as current mismatch between the individual solar cells must be avoided. Borrowing the technique from Gavin Rain's neo-pointillism and geometric art, this novel scheme allows a wider range of combinations of scale and colours while maintaining identical sunlight transmittance. This picture shows 4 different tiles, each covering one solar cell, with the 4 print designs consisting of 4, 4^2, 4^3 and 4^4 multicolour dots. Each of the 4 solar cells has the same 16% relative transmittance loss due to the print design.

Notable Achievement 2022

Fully operational Solar Forecasting tool implemented at EMA

Dr Mert YAGLI, Dr Thomas REINDL

To enhance Singapore's solar adoption and grid reliability, SERIS has developed and implemented a fully operational Solar Forecasting tool, which is described in Figure 1.

Supported by the Energy Market Authority of Singapore (EMA) and the Meteorological Service Singapore (MSS) of the National Environment Agency (NEA), the tool successfully completed its one-year trial at EMA's Power System Control Centre in September 2022. First of its kind, the model is able to forecast Singapore's island-wide solar irradiance up to one hour ahead, with an average error rate (expressed as nRMSE = normalised root mean square error) lower than 10%, one of the lowest for solar forecasting in the tropics.

Unlike conventional power generation plants, solar power generation cannot be moderated according to energy demand. Its power generation is dependent on Singapore's tropical weather conditions which fluctuate depending on environmental factors such as cloud cover, rain, and humidity. This can lead to imbalances between electricity demand and supply output from solar photovoltaic (PV) systems.

The Solar Forecasting tool allows EMA, as Singapore's power system operator, to anticipate the solar power output ahead of time and take pre-emptive actions to manage solar intermittency and balance the power grid. This is another step towards maintaining grid reliability as Singapore scales up solar deployment. It also allows the electricity market to procure additional reserves or adjust the output of power generation plants and energy storage systems to increase electricity supply ahead of time to meet demand.

Following the completion of the trial, EMA is upgrading its Energy Management System (EMS) to incorporate solar generation forecasts produced by the Solar Forecasting Tool by 2023. These forecasts will also be provided to the Energy Market Company (EMC), Singapore's wholesale electricity market operator, to be factored into the market clearing process to ensure more accurate dispatch schedules for power generators to meet power system demand. For more details, please refer to EMC's information at:
https://www.emcsg.com/f2165,162493/EMC371-EMA-CY.pdf

For easy reference and further explanation of the Solar Forecasting tool, SERIS has created a video which can be found at:
https://www.youtube.com/watch?v=dnMoCj8HPRY

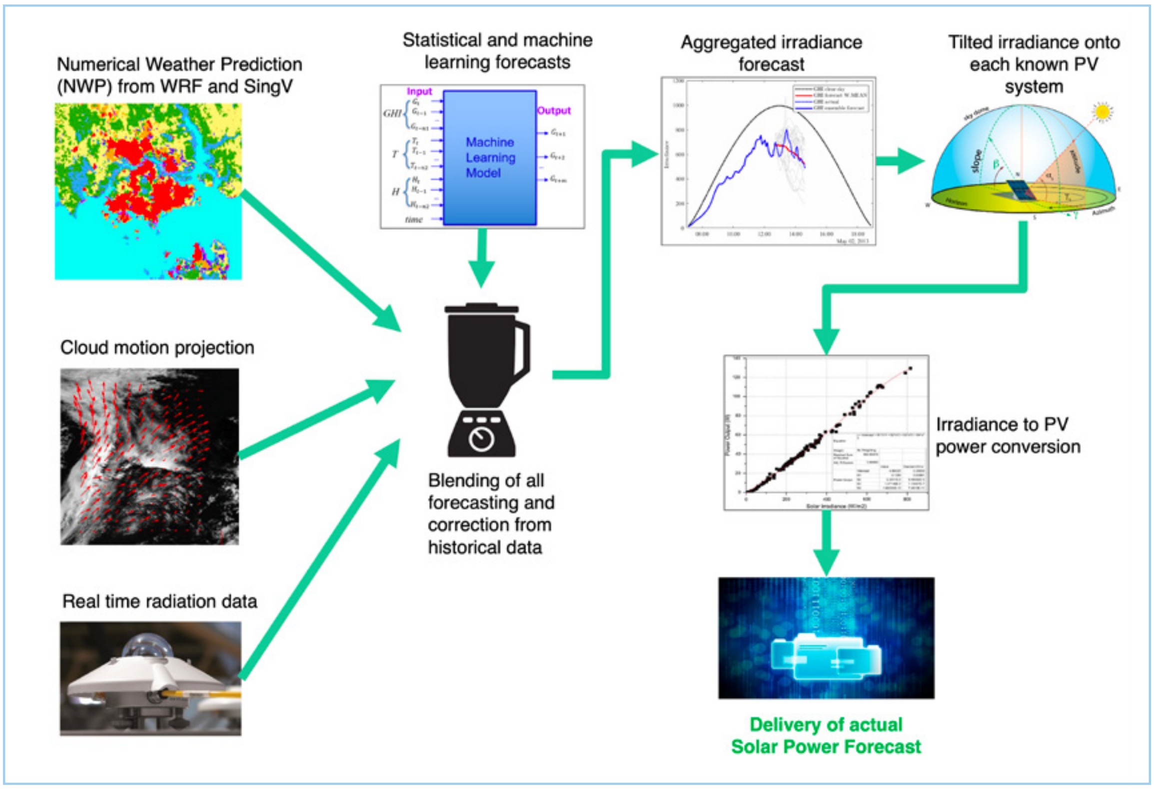


Figure 1. The Solar Forecasting Tool utilises data from real-time irradiance sensors installed on rooftops of buildings and electrical substations across Singapore. It also incorporates numerous dynamic solar forecasting techniques such as satellite imagery and machine learning algorithms. Combining outputs from MSS' numerical weather prediction system, known as SINGV, the Solar Forecasting Tool is able to aggregate the various types of data to generate round-the-clock solar irradiance forecasts at regular intervals from 5 minutes to 24 hours ahead of schedules.

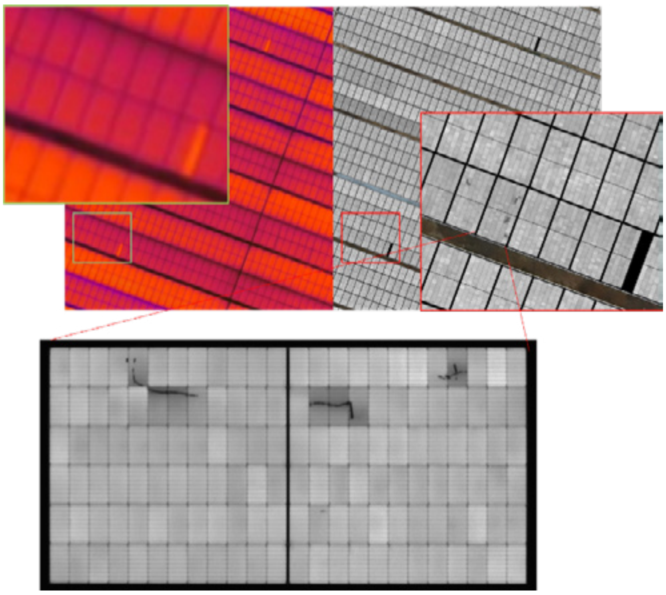
SERIS Spin-Offs - Status & Progress

Quantified Energy Labs Pte Ltd (QE-Labs)

QE-Labs is a Singapore-based cleantech start-up founded by several solar researchers from SERIS, NUS. The company develops digital solutions - in particular autonomous drone-based electroluminescence (EL) mapping for the fast, cost-effective and accurate identification of defective modules in PV farms - to support its clients in de-risking their solar PV investments. The technologies developed by QE-Labs are protected by international patents.

QE-Labs' drone-based EL solution has successfully been demonstrated in Singapore on a 60-MW floating PV system and a 18-MW ground-mounted PV installation. Beyond its success in the home market, QE-Labs has also made good progress with its global expansion, by partnering with PVEL, a leading independent testing lab and member of the Kiwa Group, to bring its solutions to the USA market. This partnership was established based on a drone-enabled "Data-as-a-Service" (DaaS) business model where PVEL will perform the front-end field inspection while QE-Labs will provide the data processing and analysis services. In August 2022 QE-Labs successfully secured USD1.5 million of funding in an angel round, which enables QE-Labs to continually improve its technical solutions and expand into additional major markets such as Europe, Australia, Japan, India and China.

The angel round funding will also be used in developing a 3D model-based PV system design work flow which could prevent unrecoverable losses due to inherent flaws in suboptimal designs. This R&D work is supported by EMA, ESG, and Shell through an EMA-Shell Startup Engine programme, and is now being demonstrated in Singapore where PV systems are installed in highly distributed urban settings.



Comparison of drone-based infrared imaging (top left) and drone-based EL imaging (top right) of PV modules in solar farms. Module level sub-string failures are detectable with both imaging technologies; however, localised defects such as scratches on individual solar cells due to module mishandling during PV farm construction are only visible in the EL images (top right & bottom).

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

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.

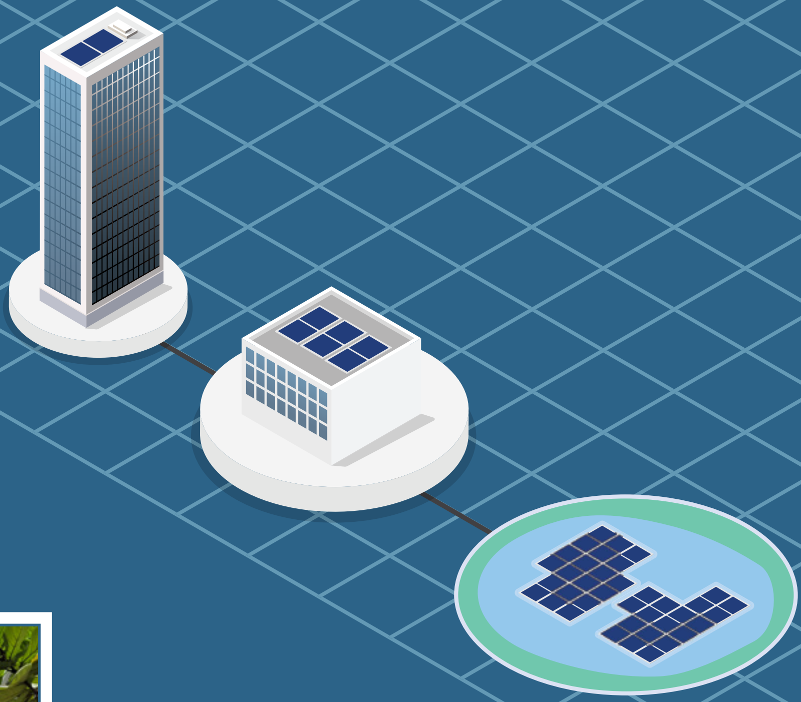
The graph below provides an overview of the comprehensive services of the PV DOCTOR™.

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.

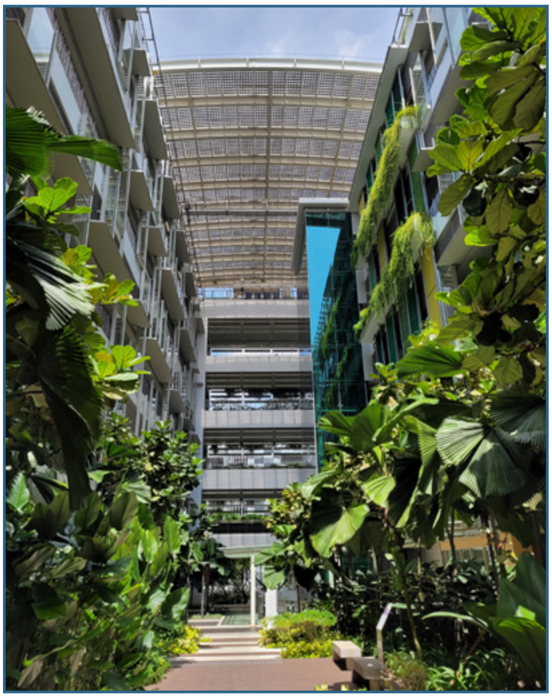
In 2022, the spin-off managed to get first commercial contracts from industry partners which were successfully implemented. In collaboration with SERIS, the team also further advanced its "smart O&M" activities and is currently implementing a detailed analysis of a 10-year-old under-performing PV installation in Singapore, where the specific yield of individual sub-systems is between 9-21% below expectations (i.e. projected energy yield after degradation). Apart from root cause analysis using in-house simulation tools and a range of on-site measurements, the team also advises the client on the economic viability of the proposed rectification measures and provides a detailed techno-economic assessment of potentially "re-powering" the entire PV system.

In the area of solar forecasting, a first trial for a so-called "point forecast" is being implemented, which evolves the fully operational solar forecasting developed for EMA's Power System Operation Centre from an island-wide forecast to one for individual solar farms.

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



INSTITUTE IN BRIEF



Introduction

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) is the city-state's national institute for applied solar energy research. Since its inception in 2008, the institute has emerged as one of the leading solar energy laboratories in the world. 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). 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.

SERIS conducts research, development, deployment, testing and consulting on solar energy technologies and their integration into urban infrastructures, buildings, and power systems. The institute's R&D spectrum covers industrially relevant materials, components, processes, systems, and services, with an emphasis on solar photovoltaic (PV) cells, modules, and systems. This serves the nation's need for solar adoption and industry development, and also supports the Singapore government's pledge to reduce the nation's carbon emissions.

SERIS 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' multi-disciplinary research team comprises more than a hundred scientists, engineers, technicians, and PhD students. In addition, the institute has formal research links with more than 10 professors from NUS ("Adjunct Researchers").

SERIS is globally active but focuses on technologies and services for tropical regions, in particular for Singapore and South-East Asia.

SERIS has been playing a critical role in building Singapore's solar ecosystem – by carrying out cutting-edge research and providing technical expertise to government agencies and the solar industry. SERIS has also been instrumental in driving several strategic government initiatives aiming at fostering the solarisation of Singapore, for example the SolarNova programme and the Floating PV Testbed at Tengeh reservoir. The institute has contributed significantly towards training and nurturing solar energy research talents for the nation's cleantech sector. Over the years, SERIS has trained more than 110 PhD students and more than 100 engineers and scientists, many of whom are working in Singapore and contribute to the growth of the nation's cleantech ecosystem.

A researcher of the Perovskite-based Multijunction Solar Cells Group showing a single-junction organic solar cell and a perovskite/organic tandem solar cell.

SERIS showcased its innovative "Peranakan theme" Building Integrated Photovoltaic (BIPV) module at the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8) in Milan, Italy and at the Asia Clean Energy Summit Exhibition in Singapore.

Photograph of Singapore's Tengeh reservoir showing the 1-MWp floating solar testbed (front part) designed and built by SERIS in close collaboration with PUB and EDB. SERIS' scientific evaluations of the 1-MWp testbed were vital for the large-scale deployment of Floating PV in Singapore, including a 60-MWp floating solar farm in Tengeh reservoir built by Sembcorp Solar (one segment can be seen in the back). (Image credit: Sembcorp Industries).

Business Areas

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

4 Research Clusters:

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

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

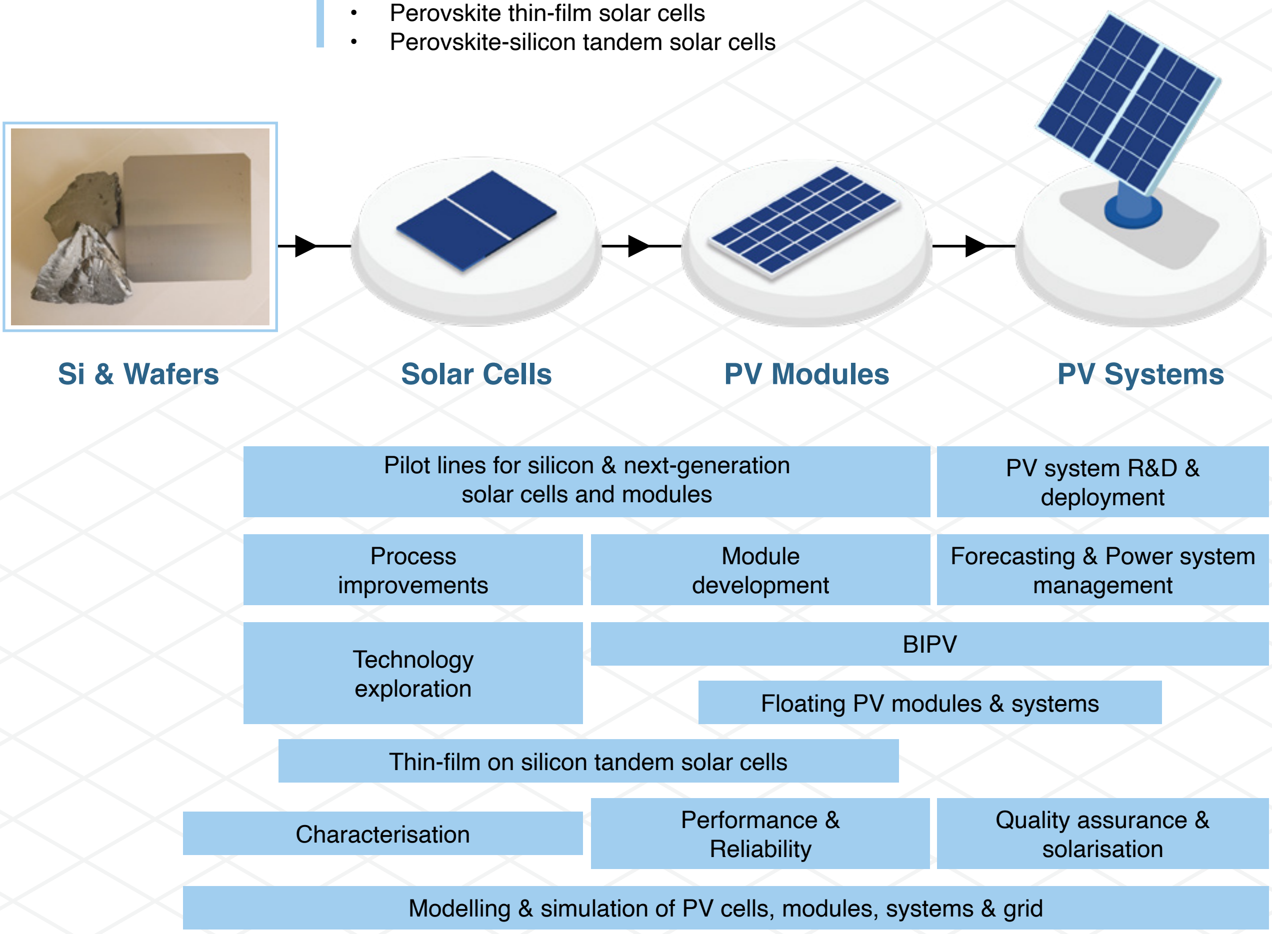
3 Business Areas

- 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 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
- Building integrated photovoltaics (BIPV)
- Solar potential analysis
- Solar 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



Overview of SERIS' R&D activities in the areas of solar cells, PV modules and PV systems

Finances

For Financial Year (FY) 2022, core funding from the National Research Foundation Singapore (NRF) - via the Energy Market Authority of Singapore (EMA) - and the National University of Singapore (NUS) is anticipated at SGD 13.8 million. The core funding is complemented by grants from public competitive R&D programmes and funds from industry contracts of approximately SGD 9.4 million and SGD 2.4 million, respectively. These are projected amounts, as FY 2022 will end on 31 March 2023. The breakdown of the projected SERIS funding of SGD 25.6 million for FY 2022 is displayed in Figure 1.

Figure 2 shows the usage of the projected available SERIS funding of SGD 25.6 million in FY 2022: SGD 9.8 million for manpower, SGD 6.8 million for equipment, SGD 7.9 million for operating expenses, and SGD 1.1 million for other expenses, which include infrastructure, indirect research costs, and non-refundable GST (Goods and Services Tax).

The evolution of SERIS' industry income over the last 8 financial years is shown in Figure 3.

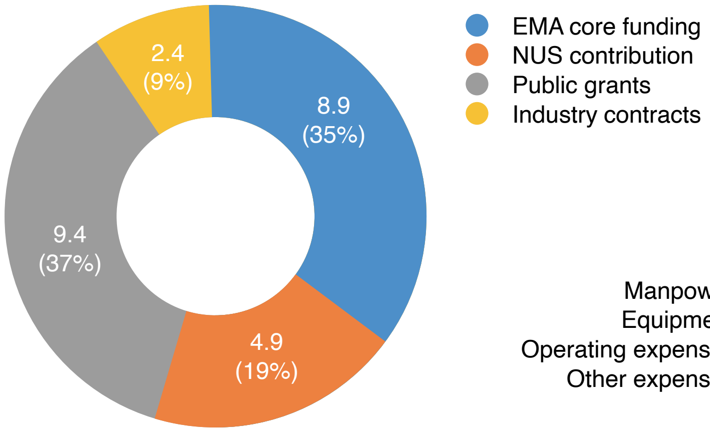


Figure 1. Projected SERIS funding for FY 2022 (1 Apr 2022 to 31 Mar 2023, in SGD million)

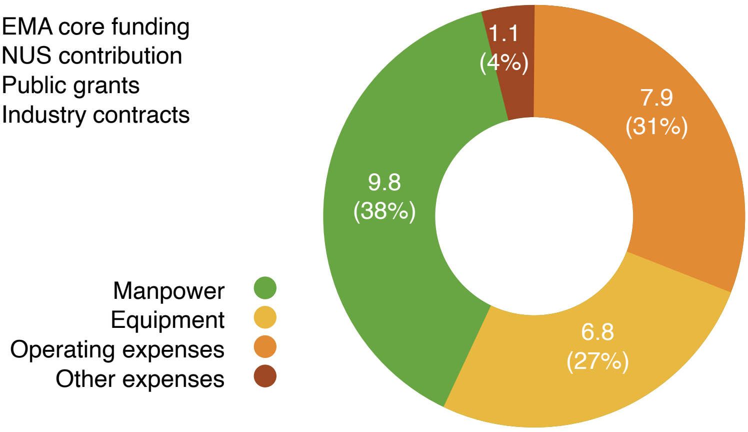


Figure 2. Projected expenses for FY 2022 (1 Apr 2022 to 31 Mar 2023, in SGD million))

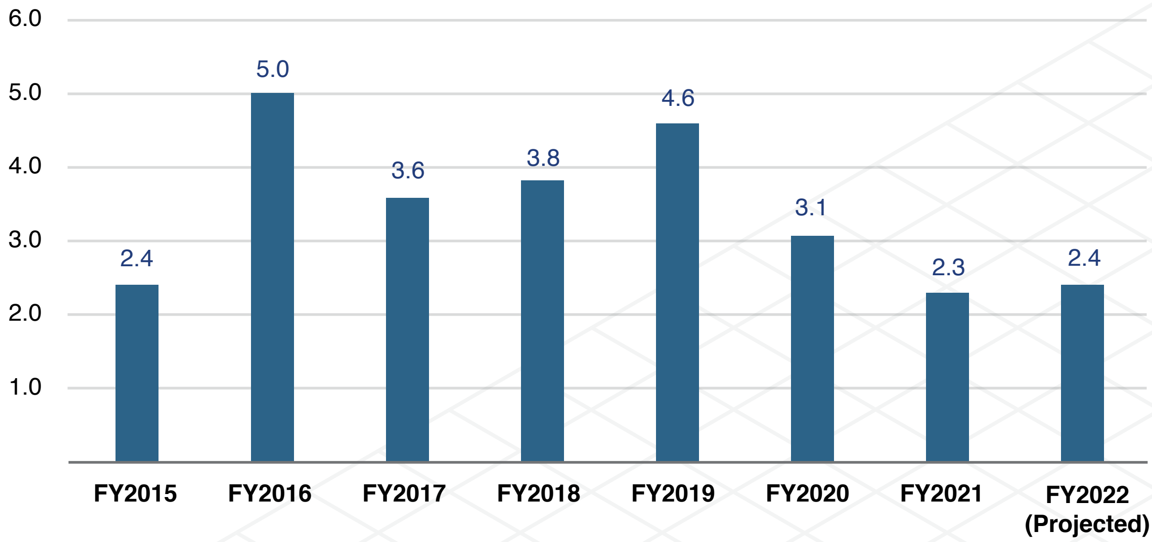
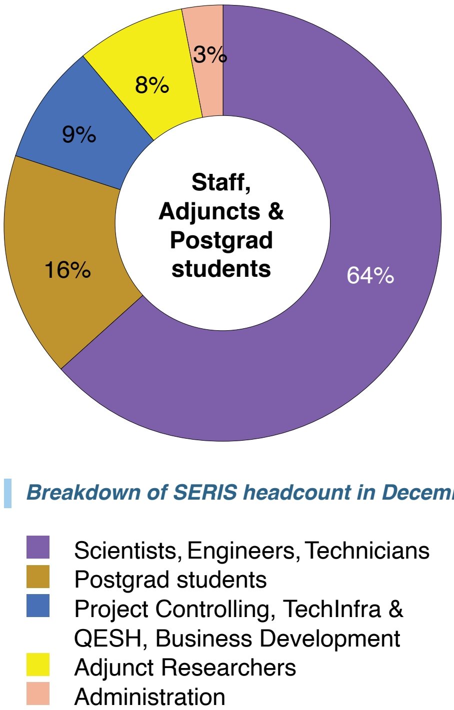


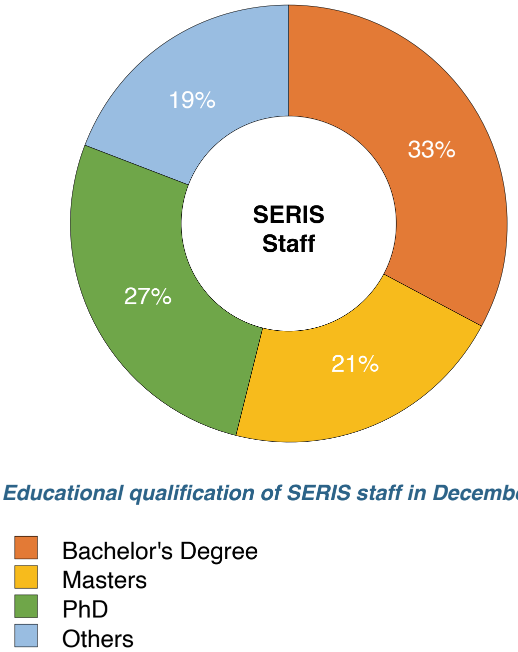
Figure 3. Evolution of SERIS' industry income since FY 2015 (in SGD million)

Headcount

At the end of calendar year 2022, the SERIS headcount was 127, 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 2022



Educational qualification of SERIS staff in December 2022

Laboratory, Office and Rooftop Space

SERIS occupies approximately 5,160 m² of space in the E3A building on the main NUS campus, including offices, laboratories and laboratory support facilities. SERIS also rents about 1,370 m² of laboratory and office space at its off-campus location at CleanTech Park where the PV Module Development and Testing laboratories as well as the BIPV Group reside. In addition, SERIS utilises about 3,330 m² 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.

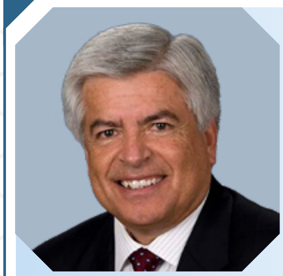
Chair of the SERIS IAP

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

Chancellor
New Mexico State University System
USA

Mr Steve O'NEIL

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

Dr SHI Zhengrong

Chairman and Founder
Sunman Energy Co. Ltd.
PR China

Prof Sarah KURTZ

Professor
University of California, Merced
USA

Mr Frank PHUAN

Business CEO,
EDPR Sunseap,
Co-Founder,
Sunseap Group,
Singapore

Prof Eicke R. WEBER

Chair, European Solar Manufacturing Council ESMC
Former Director, Fraunhofer ISE, Freiburg
Prof. emeritus, Dept. of Materials Science, UC Berkeley

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 LIU Bin

Senior Vice Provost (Faculty & Institutional Development)

NUS, Singapore

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)

Mr HONG Howe Yong

Head, Group Centre of Excellence

Sembcorp Industries Ltd

Dr KOH Shuwen

(since 18 May 2022)

Director, IP Management and Commercialisation

Industry Liaison Office (ILO)

National University of Singapore

Deputy Group Chief Technology Officer and Director of Innovation

National University Hospital System (NUHS)

Mr NI De En

Director, Urban Solutions & Sustainability

National Research Foundation Singapore (NRF)

Mr Ralph FOONG

Deputy Chief Executive

Energy Planning & Development Division

Energy Market Authority of Singapore

Er Edwin KHEW Teck Fook

Chairman of the Sustainable Energy Association of Singapore (SEAS)

Co-Founder and Chairman of AirCarbon Pte Ltd

Emeritus President of The Institution of Engineers, Singapore

Mr LIM Wey Len

Senior Vice President

Head, Energy & Resources, and Environmental Sustainability

Singapore Economic Development Board (EDB)

Dr Shankar SRIDHARA

Chief Technology Officer

REC Solar Pte Ltd, Singapore

Dr Subramanian VENKATRAMAN

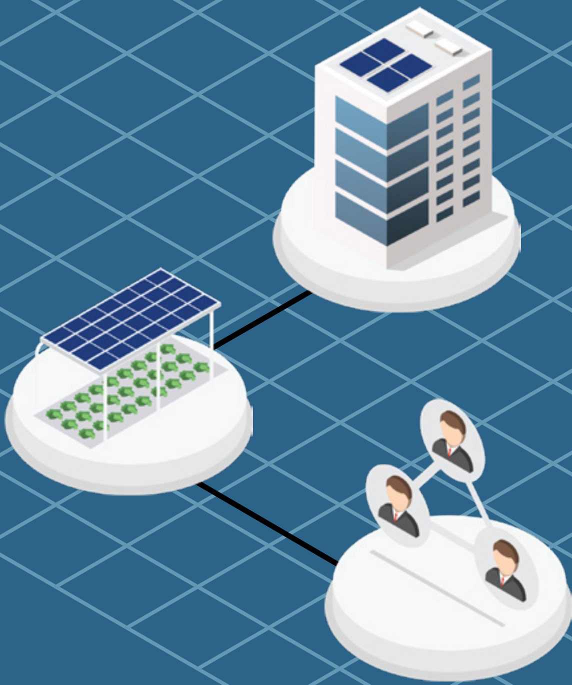
(until 17 May 2022)

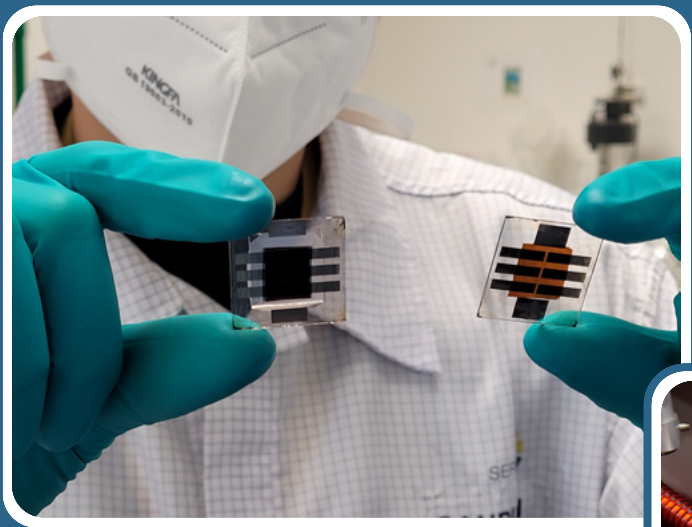
Executive Director, IPM and Commercialisation

Industry Liaison Office (ILO)

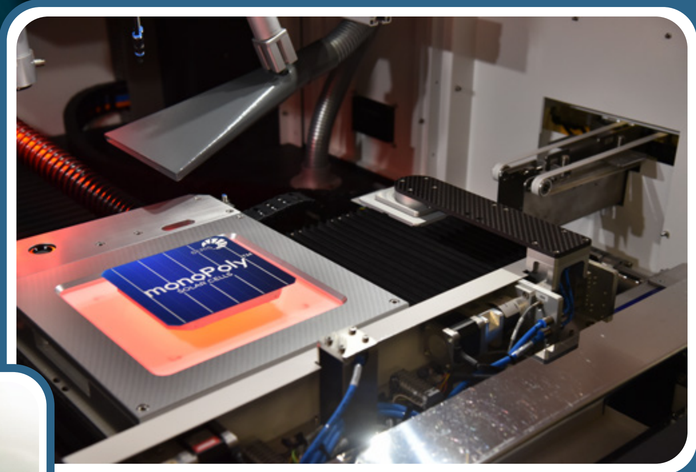
National University of Singapore

ORGANISATION STRUCTURE

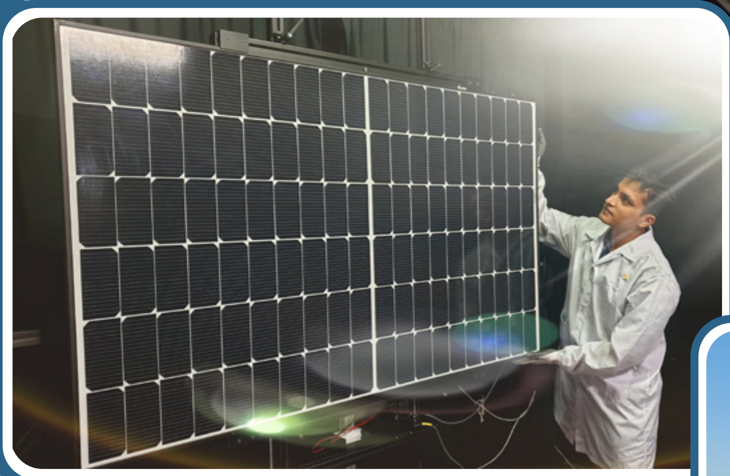




Novel PV Concepts Cluster



Next-Generation Industrial Solar Cells & Modules Cluster



PV Modules for Urban Solar Cluster

Solar Energy Systems Cluster

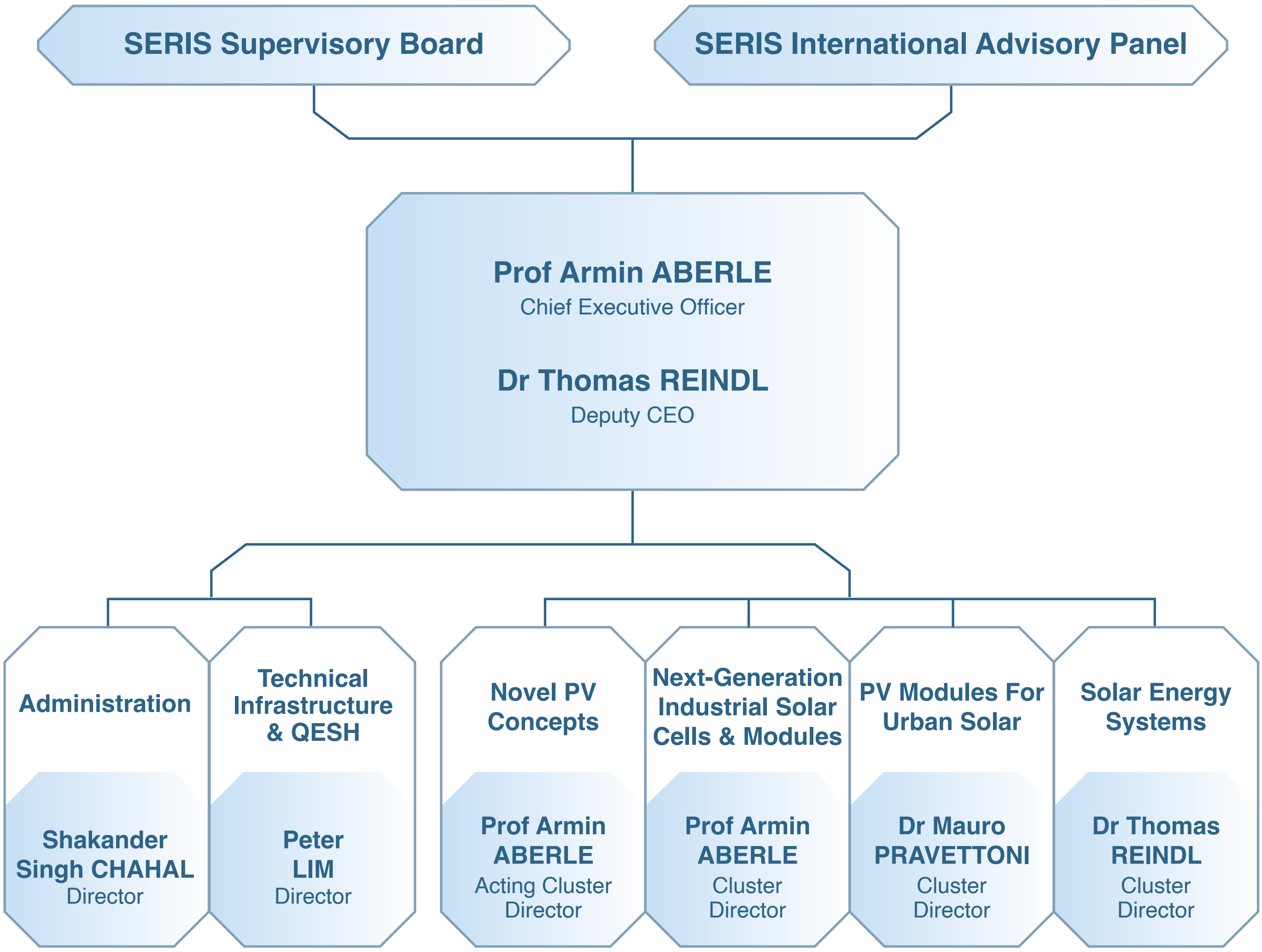
Organisational Chart

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, technical infrastructure & QESH (Quality, Environment, Safety and Health) management.

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

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

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



SERIS Senior Management:
- CEO
- Deputy CEO

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

Central Service Units:
- Administration
- Technical Infrastructure & QESH (Quality, Environment, Safety and Health)

Management Team

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

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, Next-Generation Industrial Solar Cells & Modules Cluster and Novel PV Concepts Cluster

Corporate Relations

TAN Mui Koon
Scientific Manager
Corporate Relations

Kesha Jane DRYSDALE
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 Serena LIN Fen

Head, Tandem Solar Cells Group, NPVC Cluster

lin.fen@nus.edu.sg

Dr HO Jian Wei

Head, PV Devices Characterisation Group, NPVC Cluster (until May 2022)

Team Leader, Advanced Characterisation (until May 2022)

Assoc Prof TAN Zhi Kuang

Team Leader, Perovskite Devices

Emerging Solar Technologies Group, NPVC Cluster

chmtanz@nus.edu.sg

Dr Pradeep PADHAMNATH

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

pradeep_p@nus.edu.sg

Dr Nitin NAMPALLI

Team Leader, Heterojunction Solar Cells, Advanced Solar Cells Group, NISCM Cluster

nitin.nampalli@nus.edu.sg

Dr LEOW Shin Woei

Head, BIPV Group, PV Modules for Urban Solar Cluster

swleow@nus.edu.sg

(since May 2022)

Asst Prof HOU YI

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

yi.hou@nus.edu.sg

Dr CHOI Kwan Bum

Head, PV Devices Characterisation, NPVC Cluster (since May 2022)

Team Leader, Solar Cell Testing

Team Leader, Advanced Characterisation (since May 2022)

bum@nus.edu.sg

Dr Rolf STANGL

Head, Machine Learning & Novel Solar Cell Concepts

Group, NPVC Cluster

(until Mar 2022)

Dr XUE Hansong

Team Leader, Thin-Film Device Modelling; Novel Cell Concepts

Simulation, NPVC Cluster

(until Feb 2022)

Dr Jeremie WERNER

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

(since July 2022)

jeremie.werner@nus.edu.sg

Dr Shubham DUTTAGUPTA

Deputy Director, NISCM Cluster

Head, Advanced Solar Cells Group, NISCM Cluster

(until June 2022)

Dr Veronika SHABUNKO

Head, Centre of Competence for Building-integrated PV, SES Cluster (until Mar 2022)

Business Development Manager, PV Modules for Urban Solar Cluster (until Aug 2022)

Extended Management Team

Dr LONG Jidong

Laboratory Manager,
PV Modules for Urban Solar Cluster, SERIS laboratory at CleanTech Park

jidonglong@nus.edu.sg

Dr Carlos RODRÍGUEZ

Head, Solar System Technology Group, SES Cluster

carlos.rodriguez@nus.edu.sg

Dr KAM Zhi Ming

Head, PV Quality Assurance Group, SES Cluster
(until June 2022)

Eddy BLOKKEN

Business Development
SES Cluster

eddy.blokken@nus.edu.sg

Nicole YAO Baozhen

SERIS Business Partner
Finance, NUS

nybz@nus.edu.sg

(since July 2022)

HOO Shan Shan

SERIS Business Partner

Finance, NUS

(until June 2022)

Dr TAI Kong Fai

Head, PV Module Development Group, PV Modules for Urban

Solar Cluster

(until Apr 2022)

Rachel TAN

Head, PV Quality Assurance, Group, SES Cluster
(since June 2022)

racheltan@nus.edu.sg

SOE Pyae

Team Leader, PV Monitoring, Digitisation of Energy Group, SES Cluster
soepyae@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

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.

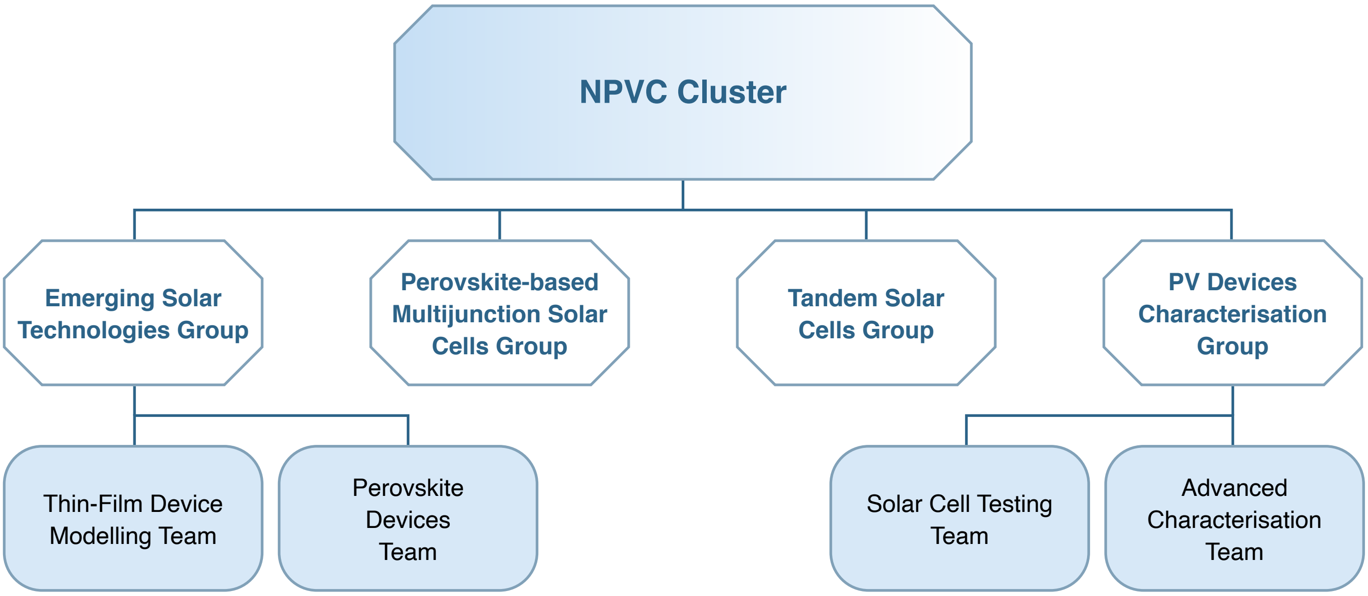
In 2022, the following Adjunct researchers from NUS have been working with SERIS:

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
Prof HONG Minghui (until Mar 2022)	Electrical and Computer Engineering	Fabrication and characterisation of solar cells
Asst Prof HOU Yi	Chemical and Biomolecular Engineering	Perovskite-based multijunction solar cells
Assoc Prof Ashwin KHAMBADKONE	Electrical and Computer Engineering	Analysis and solutions for PV grid integration through energy system modelling and advanced power electronics & control for smart grids
Assoc Prof Sanjib Kumar PANDA	Electrical and Computer Engineering	High-performance control of power electronic converters
Prof Seeram RAMAKRISHNA	Mechanical Engineering	PV modules
Prof Dipti SRINIVASAN	Electrical and Computer Engineering	Analysis of impacts of solar PV integration into the medium- and low-voltage power distribution systems
Assoc Prof TAN Zhi Kuang	Chemistry	Perovskite devices
Dr 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

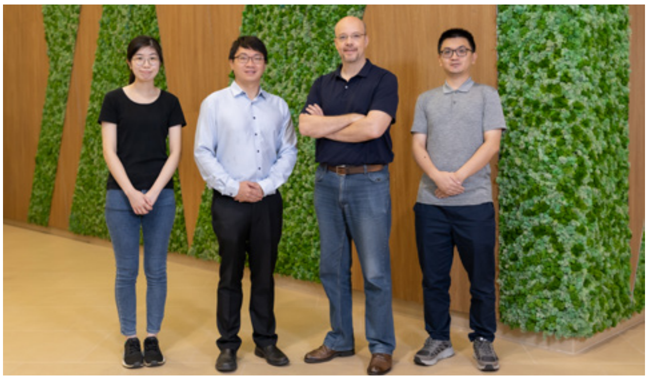
This Cluster researches novel and emerging solar PV materials, devices and applications that have the potential to gain market entry within the next 5-10 years. The experimental work in the semiconductor laboratories focuses on novel thin-film solar cells such as perovskite devices (both single- and 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 Device Modelling Team that operates a state-of-the-art simulation infrastructure. In December 2022, the Cluster had 41 members (including 20 PhD students) spread over four R&D Groups.



Organisation chart of the Novel PV Concepts Cluster (in Dec 2022)

Cluster Director's Office	
Prof Armin ABERLE, Acting Cluster Director	
Ann Mythel ROBERTS, Cluster Secretary	
Group Heads	**Team Leaders**
Assoc Prof Karl Erik BIRGERSSON, Emerging Solar Technologies	**Assoc Prof TAN Zhi Kuang,** Perovskite Devices
Asst Prof HOU Yi, Perovskite-based Multijunction Solar Cells	**Assoc Prof Karl Erik BIRGERSSON,** Thin-Film Device Modelling (since Mar 2022)
Dr Serena LIN Fen, Tandem Solar Cells	**Dr CHOI Kwan Bum,** Solar Cell Testing; Advanced Characterisation (since May 2022)
Dr CHOI Kwan Bum, PV Devices Characterisation (since May 2022)	**Dr XUE Hansong,** Thin-Film Device Modelling; Novel Cell Concepts Simulation (until Feb 2022)
Dr HO Jian Wei, PV Devices Characterisation (until May 2022)	
Dr Rolf STANGL, Machine Learning & Novel Solar Cell Concepts (until Mar 2022)	
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)	
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 researches promising solar photovoltaic materials, devices and applications that have the potential to gain significant market share in the next 5-10 years. Examples are novel fabrication methods and device architectures for perovskite solar cells. Another focus area is the modelling and simulation of emerging solar cells based on novel semiconductor materials such as perovskites. The group comprises two teams:

(i) The Perovskite Devices Team studies and develops novel optoelectronic devices such as high-efficiency perovskite tandem solar cells, luminescent solar concentrators, and light-emitting diodes.

(ii) The Thin-film Device Modelling Team develops and solves novel mathematical models for thin-film tandem solar cells.

Group Head

- Assoc Prof Karl Erik BIRGERSSON

Team Leaders

- Assoc Prof TAN Zhi Kuang (Perovskite Devices)
- Assoc Prof Karl Erik BIRGERSSON (Thin-Film Device Modelling, since Mar 2022)
- Dr XUE Hansong (Thin-Film Device Modelling, until Feb 2022)

PhD Students

- ONG Woan Yuann Evon
- TAN Hu Quee
- TAY Shao En, Timothy
- ZHAO Xinhai

Perovskite-based Multijunction Solar Cells Group

The group's research efforts bridge broad chemistry, physics and engineering disciplines, and are primarily focused on materials, assembling, and device innovation for perovskite multijunction solar cells. Our research directions consist of three main thrusts:

1. Materials innovation: The core of this thrust is novel materials for enabling new functionalities in devices. We focus on developing new wide-bandgap perovskite absorbers, interface materials, flexible electrodes, self-assembled monolayers, and metal oxides with the potential for efficient conversion of solar energy to electricity.
2. Emerging device structures and assembling processes: We explore new schemes of manipulating, processing, and assembling materials to create new optical and electrical properties. We are targeting a set of reproducible, inexpensive and fast processing techniques that are compatible with large-scale and high-throughput fabrication in the solar industry.
3. Tandem solar cells: We integrate the learnings from the above thrusts into perovskite-based tandem solar cells with reliable, efficient, and inexpensive approaches. To harness solar energy more efficiently, we innovate different tandem architectures, new recombination junctions, electrical contacts, TCOs, passivating layers, and encapsulants in dual- and triple-junction tandem solar cells.

Group Head

- Asst Prof HOU Yi

Research Scientists

- Dr Guo Renjun (since Oct 2022)
- Dr FENG Jiangang (until Aug 2022)
- Dr JIA Xiangkun (since Mar 2022)
- Dr JIA Zhen Rong (since Nov 2022)
- Dr Donny LAI Jiancheng
- Dr LI Jia
- Dr LIU Shunchang

PhD Students

- Ezra ALVIANTO
- CHEN Jinxi
- DONG Zijing (since Aug 2022)
- GUO Xiao
- LIANG Haoming
- LUO Ran
- SHI Zhuojie
- WANG Xi
- WANG Yuduan
- ZHANG Yan
- ZHOU Qilin (since Aug 2022)

Tandem Solar Cells Group

The group focuses on the research and development of cost-effective small-area high-efficiency (> 30%) perovskite-silicon tandem solar cells and mini-modules that can be upscaled to large-area devices with good long-term stability. It is dedicated to the optimisation and innovation of the materials, architectures and fabrication techniques for both crystalline silicon and perovskite solar cells, in order to develop reliable, reproducible and industrially viable low-cost solutions for perovskite-Si tandems. The group's research includes the development of perovskite solar cells and mini-modules suitable for either single-junction or tandem applications, specially designed & optimised silicon bottom cells and interconnection layers for tandem integration, as well as encapsulation, reliability and outdoor performance studies of perovskite and tandem solar cells and mini-modules.

Group Head

- Dr Serena LIN Fen

Research Scientists

- Dr Cho Fai Jonathan LAU (until Aug 2022)
- Dr LI Xin
- Dr Samuel NG Xin Ren (until Mar 2022)
- Dr Firdaus Bin SUHAIMI (until Feb 2022)
- Dr WANG Puqun (until Sep 2022)

Research Engineers/Associates

- LEE Ling Kai
- Damien LIU Tianyuan
- YAP Qi Jia

PhD Students

- Laxmi NAKKA
- SHEN Guibin
- TIAN Siyu
- WEI Zhouyin

Masters Student

- Nikhil PAPINENI (50%, until Sep 2022)

PV Devices Characterisation Group

The PV Devices Characterisation Group focuses on the research & development of innovative characterisation & analysis solutions for solar photovoltaic materials and devices. The Group's activities involve disciplines of science and engineering, with applications covering the entire PV value chain. It is equipped with a raft of measurement, diagnostics and analysis tools. Selected R&D activities in 2022 were:

(i) Performing high-quality standard measurements (such as 1-Sun solar cell efficiencies) in accordance to established standards, e.g. IEC 60904.
(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/metrology methods, for both inline and offline applications.
(v) Advanced data analysis. When combined with strategic metrology, this can provide valuable insights for evaluating solar cell manufacturing processes.

Group Head

- Dr CHOI Kwan Bum (since May 2022)
- Dr HO Jian Wei (until May 2022)

Team Leaders

- Dr CHOI Kwan Bum (Solar Cell Testing)
- Dr CHOI Kwan Bum (Advanced Characterisation)

Project Manager

- Dr CHAN Keng Siew (until Mar 2022)

Research Scientists/Engineers

- CHUAH Tuang Heck (until Mar 2022)
- HENG Ming Xuan Clarence (until July 2022)
- Elisaveta UNGUR
- Dr WANG Puqun (since Oct 2022)
- YE Jiayi

PhD Students

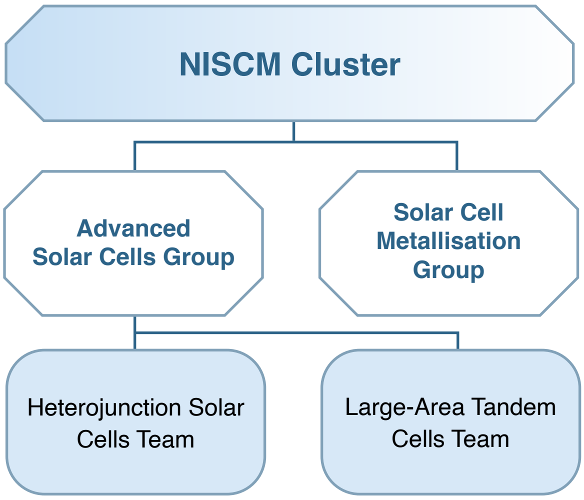
- Sai Prasanth JOYSULA
- LAN Yuchi

Masters Students

- Ziqiong HUANG (until Sep 2022)
- Nikhil PAPINENI (50%, until Sep 2022)

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

Solar photovoltaic (PV) electricity generation is booming and poised to become the world's largest source of energy. 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 manufacturability, manufacturing cost, long-term stability and efficiency 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). In December 2022, the Cluster had 22 members (including one PhD student) spread over two R&D groups.



Organisation chart of the Next-Generation Industrial Solar Cells and Modules Cluster (in Dec 2022)

Cluster Director's Office	Deputy Cluster Director
Prof Armin ABERLE, Cluster Director	**Dr Shubham DUTTAGUPTA** (until June 2022)
Ann Mythel ROBERTS, Cluster Secretary	
Group Heads	**Team Leaders**
Dr Pradeep PADHAMNATH, Solar Cell Metallisation	**Dr Nitin NAMPALLI,** Heterojunction Solar Cells
Prof Armin ABERLE, Advanced Solar Cells (acting, since July 2022)	**Dr Jeremie WERNER,** Large-Area Tandem Cells (since July 2022)
Dr Shubham DUTTAGUPTA, Advanced Solar Cells (until June 2022)	
Adjunct Researchers, NUS	
Prof Armin ABERLE, Dept of Electrical and Computer Engineering (PV materials, devices and modules)	
Assoc Prof Aaron DANNER, Dept of Electrical and Computer Engineering (Application of ultra-thin films to high-efficiency silicon wafer solar cells)	
Prof HONG Minghui, Dept of Electrical and Computer Engineering (Fabrication and characterisation of solar cells) (until Mar 2022)	

Advanced Solar Cells Group

The Advanced Solar Cells Group focuses on the development and commercialisation of low-cost high-efficiency solar cells. The group comprises two teams:

(i) The Heterojunction Solar Cells Team develops novel or advanced processes and technologies that help to approach the practical 1-Sun efficiency limit of ~27% of silicon-based single-junction cells while maintaining low cell manufacturing costs ($/W_p$).

(ii) The Large-Area Tandem Cells Team develops and upscales process technologies for large-area (> 200 cm²) perovskite-silicon tandem cells with an efficiency target of > 30%. The group collaborates with several solar cell, equipment, automation and materials companies to jointly develop new processes and technologies. A large cleanroom lab (> 1200 m²) enables silicon and tandem cell fabrication on n- and p-type industrial Cz silicon substrates. Both rigid (~180 μm thick) and flexible (< 100 μm) wafers are used. Selected research topics include development of novel or advanced heterojunction layers or layer stacks (e.g. transparent metal oxides), novel ultra-thin charge carrier transport layers, and upscaling of next-generation thin-film semiconductors (e.g., perovskites) & related equipment R&D.

Group Head

- Prof Armin ABERLE (acting, since July 2022)
- Dr Shubham DUTTAGUPTA (until June 2022)

Team Leaders

- Dr Nitin NAMPALLI, Heterojunction Solar Cells
- Dr Jeremie WERNER, Large-Area Tandem Cells (since July 2022)

Research Scientists/Engineers

- ANG Pun Chong (until Nov 2022)
- John Derek Dumaguin ARCEBAL (until June 2022)
- Jamaal Kitz BUATIS
- Gabby Alonzo DE LUNA (until June 2022)
- Jeffrey ISON
- Maria Luz Loria MANALO (until June 2022)
- Mohd Asri Bin MOHD HAMDAN (until June 2022)
- Marvic John Santos NAVAL (until March 2022)
- Delio Justiniani PEREZ
- Kaylynn SEW
- Dr Krishna SINGH (since Nov 2022)
- Ranjani SRIDHARAN
- TAN Chuan Seng (until June 2022)
- Bobby Salinas UNGOS
- Dr Selvaraj VENKATARAJ

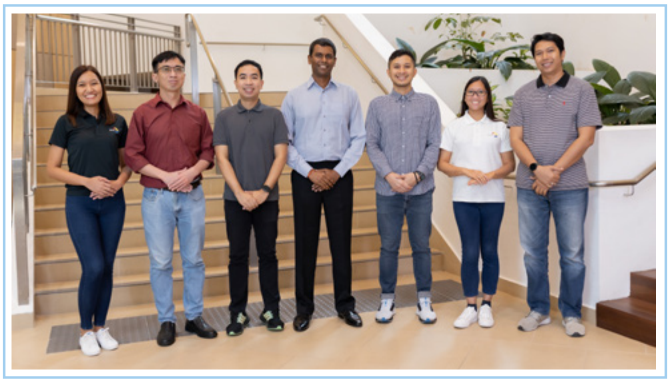
PhD Student

- Erik Maurits SPAANS (since Aug 2022)

Technician

- CHOY Woon Loong

Solar Cell Metallisation Group



The Solar Cell Metallisation Group develops novel industrial metallisation solutions for both established and next-generation solar cell technologies. SERIS' Solar Cell Metallisation Lab is equipped with state-of-the-art process equipment, including an industrial screen print line (with inline dryer and firing furnace), an inline plating tool, and advanced sputtering and evaporation tools for metal contacts. The group's research activities include developing industrial low-cost metallisation solutions for advanced silicon solar cells based on SERIS' biPoly™ technology platform. The group also works closely with other research groups in SERIS to develop next-generation metallisation solutions for heterojunction silicon solar cells and perovskite-silicon tandem cells. Furthermore, the group collaborates with several solar cell companies and metal paste manufacturers.

Group Head

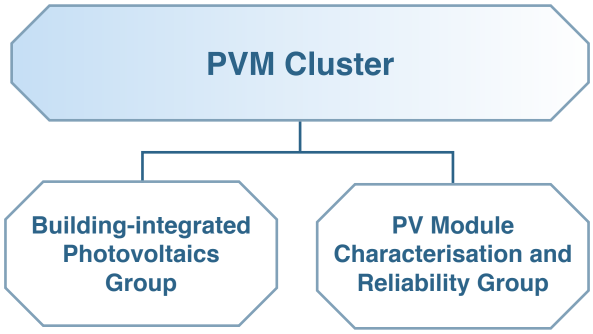
- Dr Pradeep PADHAMNATH

Research Scientists/Engineers

- John Derek Dumaguin ARCEBAL (since July 2022)
- Edwin Decena CARMONA (until June 2022)
- Gabby Alonzo DE LUNA (since July 2022)
- Michelle Liwanag ESBER (until Feb 2022)
- Rosalie Cleofe GUERRA
- Maria Luz Loria MANALO (since July 2022)
- Mohd Asri Bin MOHD HAMDAN (since July 2022)
- Balaji NAGARAJAN (until Mar 2022)
- Rowel Vigare TABAJONDA (until Mar 2022)
- TAN Chuan Seng (until Sep 2022)

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; Potential-induced degradation (PID) and other reliability studies; PV module recycling.

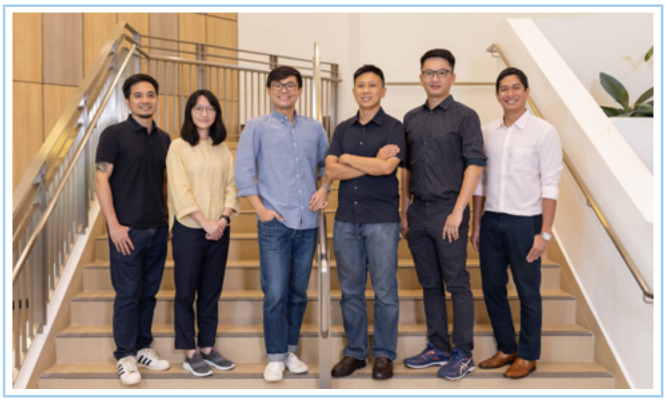


Organisation Chart of PV Modules for Urban Solar Cluster (in Dec 2022)

Cluster Director's Office
Dr Mauro PRAVETTONI, Cluster Director
Mabel LEOW, Cluster Secretary
Dr LONG Jidong, Laboratory Manager
Dr Veronika SHABUNKO, Business Development Manager (until Aug 2022)

Group Heads
Dr LEOW Shin Woei, Building Integrated Photovoltaics Group (since May 2022)
Dr Mauro PRAVETTONI, PV Module Characterisation and Reliability
Dr TAI Kong Fai, PV Module Development (until Apr 2022)
Adjunct Researchers, NUS
Prof Seeram RAMAKRISHNA, Dept of Mechanical Engineering (PV modules)
Assoc Prof Karl Erik BIRGERSSON, Dept of Mechanical Engineering (Modelling of PV modules)

Building Integrated 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, noise barriers and other unconventional surfaces. The group's work pays particular attention to PV modules installed in the tropical environment 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 (since May 2022)
- Dr TAI Kong Fai (until Apr 2022)

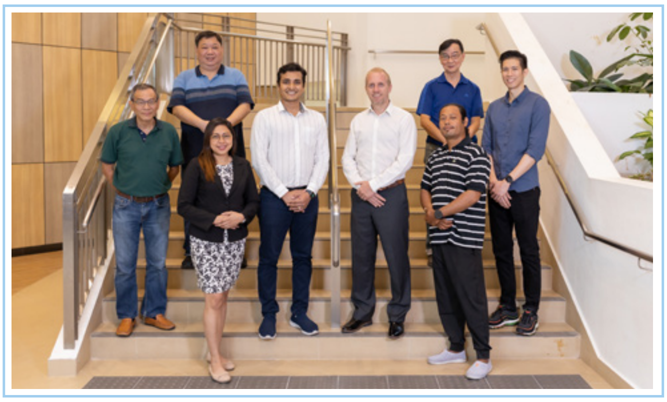
Research Scientists/Engineers

- Ryan ALINSOD
- ANG Kim Wee (until July 2022)
- Dr Carlos Enrico Cobar CLEMENT
- Dr LIANG Tian Shen (since Aug 2022)
- Srinath NALLURI
- Gavin Prasetyo RAHARJO

PhD Students

- SAW Min Hsian
- LIANG Tian Shen (until July 2022)
- Vundrala Sumedha REDDY
- Jovan TAN

PV Module Characterisation & Reliability Group



The group performs research on new and pre-normative methods for the characterisation of PV modules. It also operates SERIS' ISO/IEC 17025 accredited laboratory for PV module testing. The research focuses on two main topics:

(i) Electrical characterisation of PV modules and
(ii) 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 degradation modes in high-humidity and high-UV regions 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 started in 2022. Furthermore, pre-normative 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
- Jack VILLANUEVA

R&D Project Executive

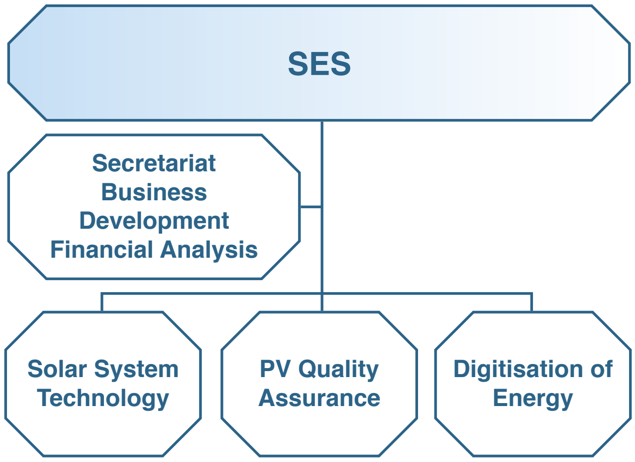
- Zuraidah Binte JA'AFAR

Technicians

- CHUAH Tuang Heok (since Apr 2022)
- 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 Floating Solar 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.



Organisation Chart of Solar Energy Systems Cluster (in Dec 2022)

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

Group Heads	Team Leader
Dr Carlos RODRÍGUEZ, Solar System Technology	**SOE Pyae,** PV Monitoring
Rachel TAN Yek Wha, PV Quality Assurance (since June 2022)	
Dr Thomas REINDL, Digitisation of Energy (acting)	
Dr KAM Zhi Ming, PV Quality Assurance (until June 2022)	

Centre Head
Dr Veronika SHABUNKO, Centre of Competence for Building-integrated PV (BIPV)(until Mar 2022)

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 and 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)

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, be it for pure electricity generation or in combination with other uses such as fish farming or desalination. Beyond that, the group also works on developing and testing novel urban deployment concepts such as 'agrivoltaics' or the multi-purpose use of existing infrastructures with PV, for example through over-arching of car parks, roads and flood canals.

Group Head

- Dr Carlos RODRÍGUEZ

Research Scientists/Engineers

- Myint Khaing AUNG
- Dr Oktoviano GANDHI (since Oct 2022)
- Naga Sravani ISUKAPALLI (until Mar 2022)
- Haresh PANDIAN (since Nov 2022)
- Rachel TAN Yek Wha (until June 2022)
- TING Shi An
- 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 includes a wide range of aspects, from components via systems all the way to operation & maintenance (O&M) and its economic viability. The group has developed proprietary software tools that enable accurate energy yield projections, which are of great benefit to project developers as well as investors. Also acting as a Lender's Engineer, the group offers economic assessments and a variety of technical services, ranging from independent third-party evaluation of system design & implementation and energy yield assessments of PV systems to feasibility studies and full due diligence evaluations. Other key activities are the assessment & evaluation of PV installations during deployment ("Owner's Engineer") and the testing & commissioning according to local and international best practices and standards. These services provide peace of mind to system owners, lenders, as well as government agencies.

Group Head

- Rachel TAN Yek Wha (since June 2022)
- Dr KAM Zhi Ming (until June 2022)

Research Scientists/Engineers

- Stanley PHUA Chee Siang
- Lutfi Irawan Bin RAWAN (since Nov 2022)

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 trialled 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 (since Nov 2022)
- Dr Oktoviano GANDHI (until Sep 2022)
- Sasi Kala GNANAMUTHU (until Aug 2022)
- Dr HE Yaohua
- Julia KHIN Thu Zar Zaw (until Nov 2022)
- KYAW Zin Win
- David LEE Soon Kiat
- Ivan POON Kin Ho
- Sholihin Bin SANI
- Dr SUN Huixuan
- Dr Gokhan Mert YAGLI
- Dr ZHAN Yanqin (until June 2022)

SERIS Central Services Units

Administration

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

Director
- Shakander Singh CHAHAL

Team
- CHUA Ai Leng
- Sherlyn LOW Si Ning
- 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.

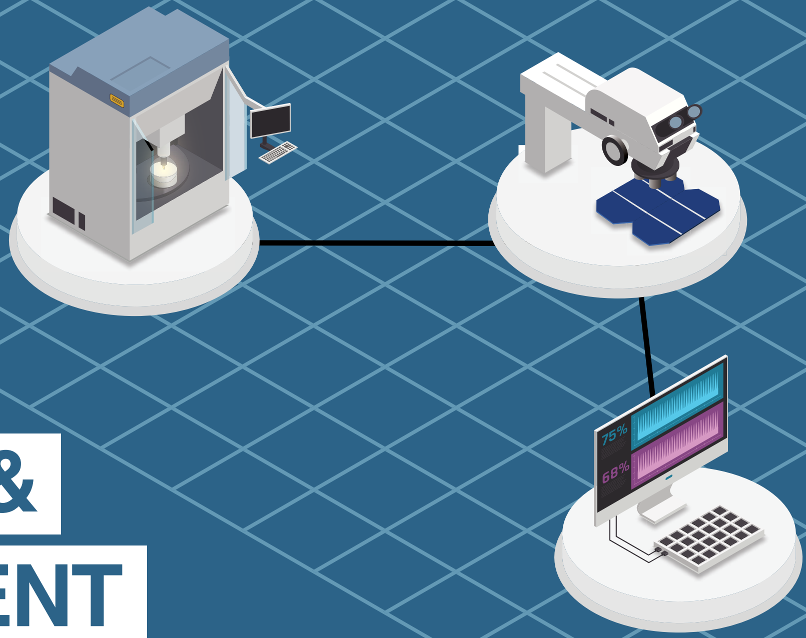
Director
- Peter LIM Young Leng

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

Laboratory Manager
- Dr Firdaus Bin SUHAIMI (Perovskite Solar Cells)

Staff, Technical Infrastructure Team
- Anja Marion ABERLE
- CHEANG Kong Heng
- CHEW Siow Choen
- Muhammad Shaheer HARDIP
- Ma Luisa OPENA
- 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 cost-effective double- and triple-junction perovskite-silicon solar cells with 1-Sun efficiencies greater than 30% and good potential for long-term stability."

Research Focus / R&D portfolio of NPVC Cluster:
In 2022, the Cluster's research focused on (i) novel or advanced perovskite single-junction thin-film solar cells and (ii) double-junction ("tandem") and triple-junction solar cells, in particular perovskite-silicon tandems (SERIS flagship project). The device fabrication works were supported by a well-equipped Characterisation Laboratory for PV materials and cells, as well as a Device Modelling Team that operates a state-of-the-art computer simulation infrastructure.

1. Major activities/achievements in 2022

Emerging Solar Technologies Group

In 2022, this group researched promising solar PV materials, devices and applications that have the potential to gain significant market share in the next 5-10 years. Examples are novel fabrication methods and device architectures for perovskite solar cells. Another focus area has been the modelling and simulation of emerging solar cells based on novel semiconductor materials such as perovskites. The group comprises two teams:

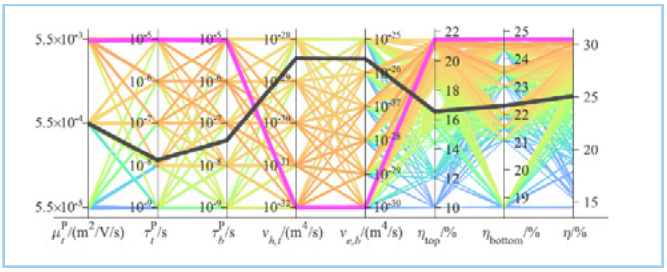
(i) The Perovskite Devices Team studies and develops novel optoelectronic devices such as high-efficiency perovskite tandem solar cells, luminescent solar concentrators, and light-emitting diodes.
(ii) The Thin-film Device Modelling Team develops and solves novel mathematical models for thin-film tandem solar cells.

Major achievements in 2022:

- Developed an experimentally validated opto-electronic-electric model for 4T perovskite-based tandem solar cells that allows for fast optimisation of efficiency and tuning of fabrication parameters
- Developed experimentally validated optoelectronic models for 2T perovskite-perovskite and perovskite-organic tandem solar cells with interconnecting layers for current matching and optimisation of efficiency
- Deployed machine learning to predict geometric parameters from external quantum efficiency measurements of perovskite solar cells

Selected publications:

- T. Wang *et al.*; The role of subsurface valence band localisation in the passivation of perovskite nanocrystals; Advanced Optical Materials 10, p. 2101914 (2022)
- H.Q. Tan *et al.*; Optimising bifacial all-perovskite tandem solar cell: How to balance light absorption and recombination; Solar Energy 231, p. 1092 (2022)
- X. Zhao *et al.*; Elucidating the underlying physics in a two-terminal all-perovskite tandem solar cell: a guideline towards 30% power conversion efficiency; Solar Energy 231, p. 716 (2022)



Efficiency predictions for a 2-terminal perovskite-perovskite tandem solar cell by tuning the top perovskite charge carrier mobility, top and bottom perovskite trap-assisted recombination lifetimes, and charge-carrier surface recombination velocities. The magenta and black lines show the parameter combinations for the predicted 30.5% efficiency device and the baseline experimental device with an efficiency of 25.2%.

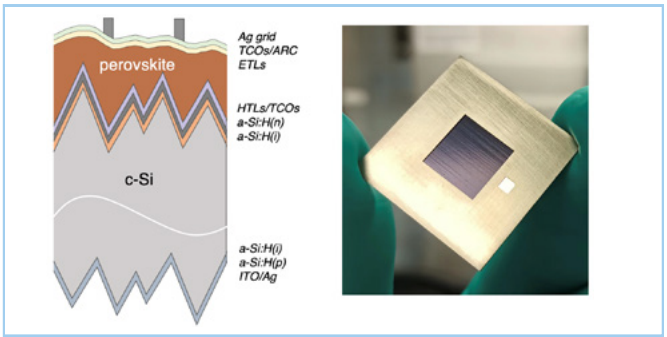
Perovskite-based Multijunction Solar Cells Group

The group's research efforts bridge broad chemistry, physics and engineering disciplines, and are primarily focused on materials, assembling, and device innovation for perovskite multi-junction solar cells. In 2022, our research directions consisted of three main thrusts:

1. Materials innovation: The core of this thrust is materials innovation for enabling new functionalities in devices. We focus on developing new wide-bandgap perovskite absorbers, interface materials, flexible electrodes, self-assembled monolayers, and metal oxides with the potential for efficient conversion of solar energy to electricity.
2. Emerging device structures and assembling processes: We explore new schemes of manipulating, processing, and assembling materials to create new and unexpected optical and electrical properties. We are targeting a set of reproducible, inexpensive and fast processing techniques that are compatible with large-scale and high-throughput fabrication in the solar industry.
3. Tandem solar cells: We integrate the learnings from the above thrusts into perovskite-based tandem solar cells with reliable, efficient, and inexpensive approaches. To harness solar energy more efficiently, we innovate different tandem architectures, new recombination junctions, electrical contacts, TCOs, passivating layers, and encapsulants in dual- and triple-junction solar cells.

Major achievements in 2022:

- Certified 23.4% efficient perovskite-organic tandem solar cell (0.055 cm^2)
- 24.0% perovskite single-junction solar cell (1 cm^2)
- 28.5% perovskite-silicon tandem solar cell (1 cm^2)



Cross-sectional schematic (left) and photo (right) of a 28.5% perovskite-silicon tandem solar cell. The grey cover in the photo is a 1-cm² shading mask used for 1-Sun I-V measurements.

Selected publications:

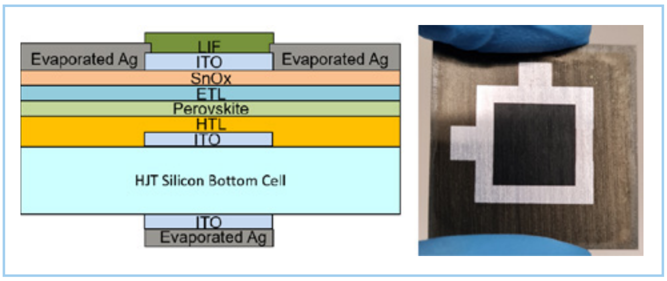
- K. Xiao *et al.*; Scalable processing for realising 21.7%-efficient all-perovskite tandem solar modules; Science 376, p. 762 (2022)
- F. Fu *et al.*; Monolithic perovskite-silicon tandem solar cells: From the lab to fab?; Advanced Materials 34, p. 2106540 (2022)
- W. Chen *et al.*; Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimised interconnecting layer; Nature Energy 7, p. 229 (2022)

Tandem Solar Cells Group

In 2022, this group focused on the research and development of cost-effective small-area high-efficiency (> 30%) perovskite-silicon tandem solar cells and mini-modules that can be upscaled to large-area devices with good long-term stability. It is dedicated to the optimisation and innovation of the materials, architectures and fabrication techniques for both crystalline silicon and perovskite solar cells, in order to develop reliable, reproducible and industrially viable low-cost solutions for perovskite-Si tandems. The group's research includes the development of perovskite solar cells and mini-modules suitable for either single-junction or tandem applications, specially designed & optimised silicon bottom cells and interconnection layers for tandem integration, as well as encapsulation, reliability and outdoor performance studies of perovskite and tandem solar cells and mini-modules.

Major achievements in 2022:

- 27.3% perovskite-silicon tandem solar cell (1 cm²) using industrial Si bottom cell
- Explored potential induced degradation (PID) of perovskite solar cells
- Developed a novel electron transport material applicable for both regular and inverted perovskite solar cells (> 22%, 0.1 cm²) with long-term stability using simple thermal evaporation
- Developed a novel passivation material for wide-bandgap (1.68 eV) perovskite solar cells with V_{oc} larger than 1.25 V.
- Developed low-temperature solution processed NiO_x as a hole transport material, compatible with tandem integration on HJT Si bottom cells



Cross-sectional schematic (left) and photo (right) of a 27.3% perovskite-silicon tandem solar cell with an active area of 1.0 cm².

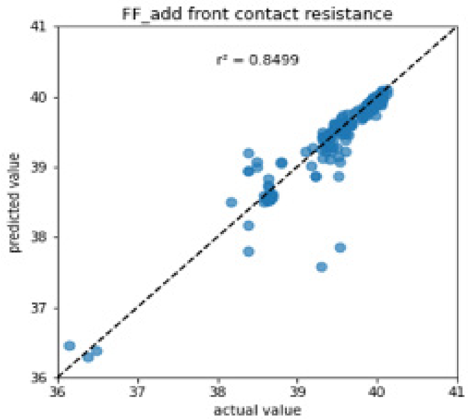
Selected publications:

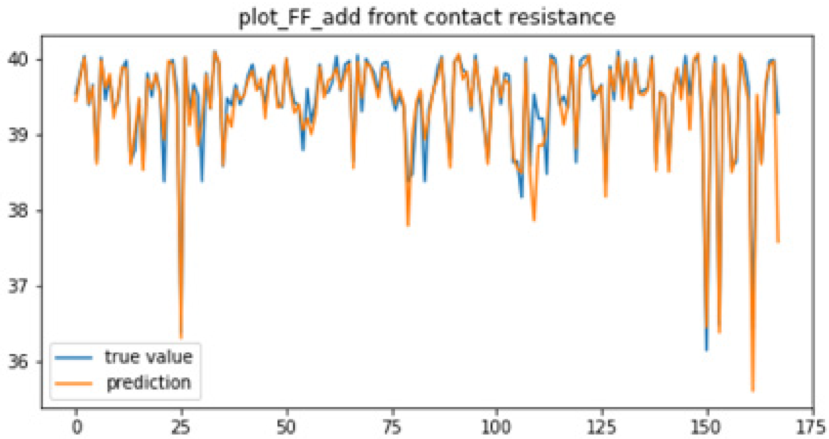
- Y. Cheng and F. Lin; Semitransparent Perovskites for Solar Cells and Smart Windows; Invited book chapter in "Perovskite Materials and Devices" Vol. 1, Wiley, pp. 349-377 (2022)
- X. Li *et al.*; Thermally Evaporated ZnSe for Efficient and Stable Regular/Inverted Perovskite Solar Cells by Enhanced Electron Extraction; Energy & Environmental Materials, e12439 (2022)
- G. Shen *et al.*; High-performance and Large-area Inverted Perovskite Solar Cells based on NiO_x Films Enabled with A Novel Microstructure-Control Technology; Energy & Environmental Materials, e12504 (2022)
- Y. Meng, X. Li *et al.*; Building-integrated photovoltaic smart window with energy generation and conservation; Applied Energy 324, p. 119676 (2022)

PV Devices Characterisation Group

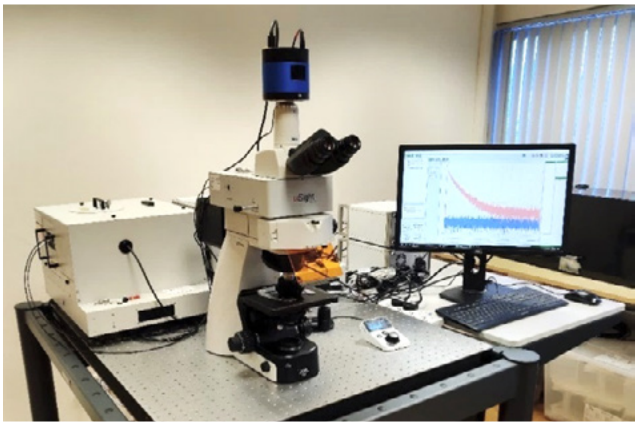
In 2022, this group focused on the research & development of innovative characterisation & analysis solutions for solar PV materials and devices. The group's activities involve disciplines of science and engineering, with applications covering the entire PV value chain. It is equipped with a raft of measurement, diagnostics and analysis tools. Selected R&D activities in 2022 were:

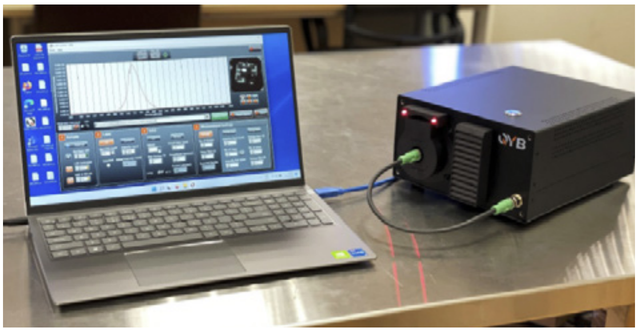
- Performing high-quality standard measurements (such as 1-Sun solar cell efficiencies) in accordance to established standards, e.g. IEC 60904.
- Advanced electrical, optical and electronic characterisations to uncover and understand PV material and device properties.
- Analysis into solar cell efficiency limiting factors. This encompasses mainstream (e.g. Si based) and emerging materials (e.g. perovskites), as well as novel concepts in photovoltaics.
- Development of novel characterisation/metrology methods, for both inline and offline applications.
- Advanced data analysis. When combined with strategic metrology, this can provide valuable insights for evaluating solar cell manufacturing processes.





Comparison of the results from a machine learning prediction model to the simulated values of 170 solar cells, for the FF loss related to the front contact resistance. The results are in good agreement with r^2 of about 0.85 (left) and with relatively good prediction trend (right). The model can assist solar cell manufacturing by performing fast in-line prediction of the cell performance.





(Top) Photo of upgraded time-resolved fluorescence spectrometer with added micro-luminescence characterisation capabilities. (Bottom) Photo of new characterisation tool for voltage loss analysis of perovskite solar cells, using the photoluminescence quantum yield technique.

Major achievements in 2022:

- Successful completion of Solar CRP project on "Future-ready solar cell manufacturing: Model driven process control to maximise efficiency and consistency" (2018 to 2022).
- Solar Cell Measurement Laboratory has successfully completed the assessment by Singapore Accreditation Council (SAC) for the ISO 17025:2017 SAC-SINGLAS accreditation. The lab's official accreditation status for the addition of two new test methods are expected to be awarded in 2023.

Selected publications:

- J.W. Ho *et al.*; Status review and future perspectives on mitigating light-induced degradation on silicon-based solar cells; Renewable and Sustainable Energy Reviews 159, p. 112223 (2022).
- K.S. Chan *et al.*; Application of non-contact quantum efficiency measurement for solar cell fabrication process insights; Solar Energy 233, p. 494 (2022).
- J.W. Ho *et al.*; Silicon Solar Cell Metallisation and Module Technology; Book chapter, IET, ISBN 978-1-83953-155-2 (2022).

2. Plans of NPVC Cluster for 2023

- Achieve > 30% efficiency for a perovskite-silicon tandem solar cell with active area of at least 1 cm^2.
- Achieve > 20% 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

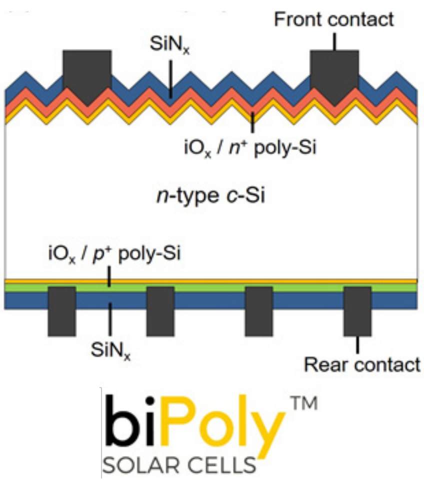
"We are developing and upscaling processes for the next generation of industrial solar cells and modules that provide superior performance and lower cost than incumbent technologies."

Research Focus/R&D portfolio of NISCM Cluster:
In 2022, the cluster's research focus remained on next-generation industrial solar cells and modules that provide superior performance at lower cost than today's market leading technologies. The experimental work in our solar cell 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 device areas larger than 200 cm^2. In addition, the cluster continued to conduct joint R&D collaborations with solar cell and module manufacturers from Singapore and abroad. These projects are of a confidential nature and thus no targets or results can be reported.

1. Major activities/achievements in 2022

Solar Cell Metallisation Group

The group develops advanced industrial metallisation solutions for both established and next-generation solar cell technologies. Its major activities in 2022 were the development of industrial low-cost metallisation solutions for advanced silicon solar cells based on SERIS' biPoly™ technology platform. The group also worked closely with other researchers in SERIS to develop next-generation metallisation solutions for heterojunction silicon solar cells and perovskite-silicon tandem cells. Furthermore, it collaborated with several solar cell companies and metal paste manufacturers.



biPoly™ silicon solar cell with an electron-selective passivating contact stack on the front and a hole-selective passivating contact stack at the rear. In the particular biPoly™ cell shown here, the metal contacts on the front and rear are formed by screen printing of metal pastes and subsequent "firing" through the silicon nitride antireflection coating at high temperature (> 700°C).

Major achievements in 2022:

- Development of an advanced metallisation process to contact doped poly-Si layers using aluminium pastes to achieve high open-circuit voltage and fill factor for large (~244 cm^2) biPoly™ solar cells
- Development of a metallisation process for contacting narrow (< 100 µm) doped 'finger' regions formed by a thin (< 100 nm) patterned polysilicon layer
- Development of next-generation low-temperature metal pastes compatible with industrial screen-printing technology for application on silicon heterojunction solar cells, jointly with metal paste manufacturers
- Filing of two Singapore Provisional Patent applications and one NUS Invention Disclosure related to biPoly™ cells.

Selected publication:

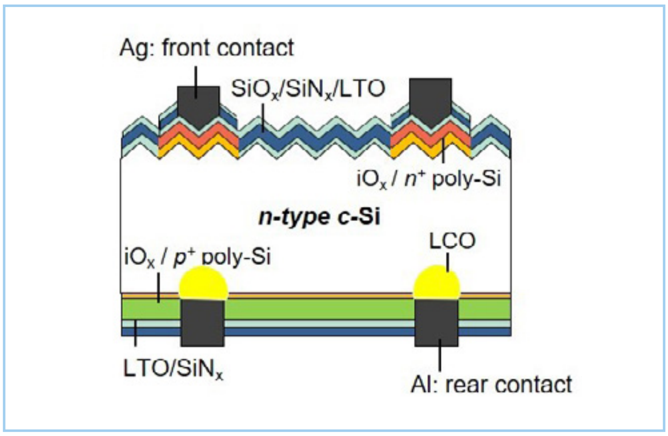
- P. Padhamnath, N. Nampalli *et al.*, Progress with passivation and screen-printed metallisation of boron-doped monoPoly™ layers; Solar Energy 231, p. 8 (2022).

Advanced Solar Cells Group

The group's major activities in 2022 were the further development of SERIS' bifacial biPoly™ passivated-contact silicon solar cell, implementing novel transparent metal oxides (TMOs) on silicon heterojunction cells, optimising wet and dry process capabilities for high-efficiency silicon solar cells (including bottom cells), and enhancing deposition capabilities for large (≥ 244 cm^2) perovskite cells on silicon bottom cells.

Major achievements in 2022:

- Demonstration of 22.7% efficiency for large (~244 cm^2) n-type biPoly™ cells
- Demonstration of full-wafer (> 244 cm^2) perovskite-silicon tandem solar cells
- Integration of alternative transparent conductive oxides (including using low-cost indium-free materials) and TMO/silicon based contacts for silicon heterojunction solar cells
- Development of laser-based crystallisation processes for silicon heterojunction and passivated-contact solar cells
- Filing of two Singapore Provisional Patent applications and one NUS Invention Disclosure related to biPoly™, silicon heterojunction and tandem solar cell technologies.



Schematic of the 22.7% biPoly™ bifacial silicon solar cell developed by SERIS. The electron-selective passivating contact stack at the front surface is limited to the regions of the front metal contact (screen-printed fire-through Ag paste). The metal contacts at the rear are formed by locally ablating the poly-Si/SiN_x layer stack with a laser and screen printing of an Al paste. The final process step is a short high-temperature (> 700°C) anneal during which the front electrode is fired through the underlying dielectric stack and the rear Al paste forms localised p^+ doped regions (shown in yellow) in the Si wafer via alloying.

Selected publications:

- N. Nandakumar *et al.*, Large-area monoPoly solar cells on 110 µm thin c-Si wafers with a rear n^+ poly-Si/SiO_x stack deposited by inline plasma-enhanced chemical vapour deposition; Progress in Photovoltaics, Special Issue, pip.3555 (2022).

2. Plans of NISCM Cluster for 2023

- Demonstration of >24% efficiency for heterojunction silicon solar cells
- Demonstration of alternative heterojunction contacts for advanced silicon solar cells
- Metallisation schemes for advanced solar cells
- Further improvements to device architecture and efficiency of n-mono silicon solar cells suitable for tandem applications
- Low-temperature metallisation processes for tandem solar cell structures, using polymer Ag pastes and electrically conductive adhesives (ECA)
- Further development and upscaling of perovskite-silicon tandem solar cells:
  - Demonstration of high-V_{oc} bottom cells
  - Process development for wide-bandgap perovskite cells on large (≥ 244 cm^2) silicon wafers
  - R&D on next-generation equipment for novel nanolayers and thin films

PVM Cluster Director's Foreword

Dr Mauro PRAVETTONI
Director, PV Modules for Urban Solar Cluster

" Innovation, reliability, and Peranakan modules! "

Research Focus / R&D portfolio of the PVM Cluster

In 2022, the Cluster's research focus remained on the following two main topics: (i) Reliability of PV modules, (ii) Integration of PV modules in heritage buildings. The first topic has been handled by the PV Module Characterisation & Reliability Group, which also runs SERIS' ISO/IEC 17025 accredited laboratory for PV module testing, while the other topic has been the focus of research of the BIPV Group.

1. Major activities/achievements in 2022

PV Module Characterisation & Reliability Group

The support of the local PV industry remained the focus activity of the group in 2022. In parallel to the well-established local collaborations with REC and Maxeon, the group has expanded its activities to the region. As a result, our support of the PV industry now combines both reference module (or "golden module") calibration and solar simulator classification. These activities have a strong influence on the quality of PV module manufacturing in Singapore and the region, and we are proud that the regional PV industry recognizes our group's competence when dealing with quality matters.

Our tireless efforts towards keeping the highest level of accuracy for our instrumentation and measurement systems led to an important study on the metastability of silicon heterojunction PV modules, which is currently taken into consideration for a dedicated, technology-specific reference to the appropriate module qualification standards.

A second important achievement of the pre-normative characterisation activities of the group has been the successful development of a new metrology technology for the measurement of the angular transmittance at the PV module level. The proposed method, whose preparatory research started in 2020, has now reached the required maturity and is now in consideration for implementation in the relevant standard IEC 61853-2.

With respect to PV module reliability studies, in 2022 the group completed a degradation analysis of a large number of 10-year-old PV modules decommissioned from the roof of the BCA Academy in Singapore. From the original analysis of soiling, the analysis was extended to a full reliability study and identification of the causes of the module failures. Presented at the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8, 26-30 Sep 2022) in Milan, the work attracted large attention due to the particular failures observed in the backsheets and the effects of corrosion.

Selected publications:

- M. Pravettoni, M. Mahesh, A. Singh Rajput, W. Li and S. Valliappan, "A study of module degradation from a 10-year installation in the urban tropical environment", *Proc. WCPEC-8, Milan*, 26-30 Sep 2022.
- M. Pravettoni and A. Singh Rajput, "On the metastability of silicon heterojunction solar photovoltaic modules", *MRS Bulletin*, in press

BIPV Group

In 2022, a major goal of this group was to introduce the SERIS-developed "Peranakan" BIPV module to the general public. Following the positive feedback received after its first description in the 2021 SERIS Annual Report, this product - which is inspired by Singapore and Malaysia's Peranakan culture - received a worldwide warm welcome at the WCPEC-8 conference in Milan, where it was the theme of the SERIS booth. For this particular occasion, the group also designed several special modules for a "Milan series": A PV module with the repeated pattern of the 16th century floor of the famous Milan Cathedral ("Duomo di Milano") and a "Leonardo module". The latter was the first sample designed with our novel "neo-pointillism" technique. Leonardo's self-portrait was made using a set of points of various shapes and sizes and the same algorithm as used for the Peranakan modules, to avoid current mismatch between the solar cells and minimise module efficiency losses due to the print patterns.

To provide the perfect background for the Peranakan modules, the SERIS booth was designed to replicate the atmosphere of a traditional Singapore shophouse, the NUS Baba House, a 3-storey house located in Singapore's historic district of Blair Plain. The house was built at the end of the 19th century and now is a museum of the Peranakan culture. A joint research initiative of SERIS and the NUS Centre for the Arts plans to install SERIS' Peranakan BIPV modules on a side façade of the Baba House, which could become a trailblazing example for the integration of PV in Singapore's heritage buildings.

Showcasing of Leonardo's module (front) and several "Peranakan" BIPV modules at the WCPEC-8 conference and exhibition at Milan, Italy.

The general appreciation of the beauty of these products has led to a growing interest in the deployment of BIPV that, in the years to come, could go beyond installations for testing purposes. These products are suggesting that PV can be seen as a decoration of the building, while at the same time generating clean electricity. This is a paradigm change with respect to previous concepts like the solar tile or PV modules that emulate conventional building materials (marble, bricks, etc). Instead of pursuing a camouflage approach, the group is now pursuing a "do not hide, but show" paradigm that could become a game changer in the BIPV community in the coming years.

One result in this direction has already been achieved: Other than at the NUS Baba House, three BIPV modules (the Milan series and a Peranakan module) are now part of the collection of the Museum of Science "Leonardo da Vinci" in Milan, where, with their beauty and inspiration, they will illustrate the potential of renewable energy (and of BIPV in particular) to the visitors for many years.

2. Plans of PVM Cluster for 2023

- Pre-normative reliability tests for off-shore floating PV applications. These tests will need to be newly designed based on the available evidence of module degradation from the field as well as from existing maritime ISO standards, which will need to be adapted to electrical testing of PV modules.
- A new reliability study for rooftop PV modules from the field after 10 years of installation in Singapore.
- Continuation of the development of a prototype of a Solar Testing Dome for the outdoor characterisation of high-efficiency and/or slow-response PV modules.
- Conduct R&D on advanced and novel BIPV modules and improve their performance.
- Develop PV modules suitable for urban applications in the tropics, such as noise barriers and urban farming ("Agrivoltaics").
- Redesign of BIPV modules for higher-level integration (e.g. plug & play PV, PV windows).
- Testbedding of light-weight PV modules for retrofitting of buildings.

SES Cluster Director's Foreword

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

> “We are supporting the solarisation of Singapore by driving innovations, technical standards, quality assurance, and policies tailored for the city-state's densely built-up urban environment to support both public and private sector players in their efforts to achieve the target of 1.5 GWp of installed PV capacity by 2025.”

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 Floating Solar 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 2022

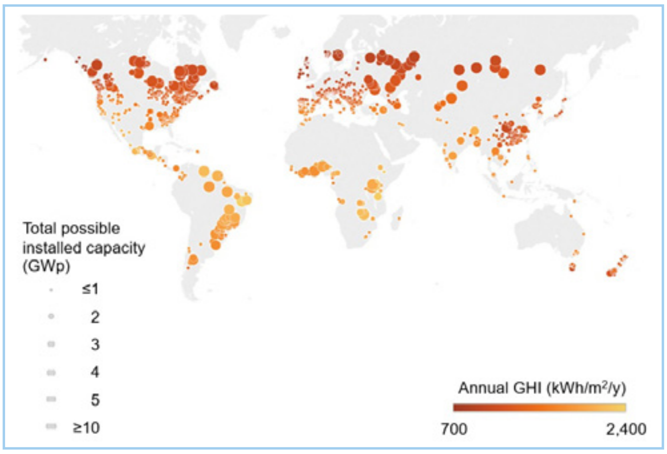
Solar System Technology Group

In 2022, the Solar System Technology 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) - led to an in-depth understanding of the challenges faced by floating PV installations in maritime conditions. Based on this, FOR takes a leading position as a project developer and future operator of large-scale near- and offshore FPV power production. In addition, novel and possibly ground-breaking technologies that enable such FPV systems are being developed.

SERIS has also signed a MoU with Keppel Infrastructure and the Energy Research Institute at NTU (ERI@N) for the development of utility-scale floating hybrid renewable energy systems, which are anticipated to consist of modular off-shore floating solar platforms with the flexibility to integrate other renewable energy technologies, such as ocean wave energy conversion systems, tidal energy turbines or paddles, as well as wind turbines. The study entails exploring the deployment of the system at a particular off-shore test site in Singapore waters, subject to the relevant regulatory approvals.

There was also substantial progress in the joint research project with EDPR Sunseap, funded under an EMA-KETEP grant, on the deployment of a near-shore floating PV testbed, in combination with energy storage systems.

The team was selected as partner in a range of technology transfer and consultancy projects in the area of Floating Solar funded by major grantors and lenders, such as the Asian Development Bank (ADB), the World Bank, the US Agency for International Development (USAID) and the Inter-American Development Bank (IADB). These projects often target existing hydropower stations for the combination with Floating PV, which has unique advantages such the utilisation of existing infrastructures (grid connection, transmission lines) and variability management of the solar resource by jointly operating the hydro and solar facilities. Together with an industry partner SERIS has carried out a global assessment of possible locations for FPV-hydropower hybrid systems, and also did selected deep-dives for the 12 most promising countries where detailed geo-referenced information about the hydropower station (location, reservoir size, turbine types) were combined with the feasibility studies on Floating Solar.



Summary of global assessment of hydropower reservoirs and their potential when covering 10% of their surface areas with Floating PV.

In the area of knowledge sharing, SERIS was the major driver of the newly published Technical Reference on Floating Solar under Singapore's standard-setting body, Enterprise-SG (TR100:2022). Furthermore, it is noteworthy that, as a major milestone, the previous SERIS reports on Floating Solar published together with the World Bank Group under the “*Where Sun Meets Water*” series, have surpassed 100,000 downloads from the World Bank website alone (they are also accessible via the SERIS homepage), which underlines the relevance of the reports and serves as an indication of their impact in the global Floating PV community.

Beyond floating solar, the group also expanded its capabilities in the area of field testing of PV technologies in real-world installations. The group signed a Research Collaboration Agreement with Sembcorp Solar on the installation and comparative testing of various PV system types in Singapore. There will be different PV module technologies (i.e. monofacial PERC, bifacial PERC, bifacial HJT), which will be installed both on fixed-tilt racks as well as horizontal single-axis trackers. This will allow to determine the optimum installation combination for Singapore, with the results being equally applicable to other low-latitude locations around the world.

The team also finalised the setup of a land-based urban farming testbed at the Singapore Discovery Centre (SDC) using two types of PV module technologies (opaque modules on a mobile structure to allow sunlight to reach the plant surfaces; and semi-transparent fixed installations). The combination of solar PV and crop growing on the same site is also referred to as "agrivoltaics". In addition, the team was awarded a testbed site at the upcoming Yuhua Agri-Solar Living Lab, where a HDB carpark rooftop is being converted into an urban farming setup. For this project the team will trial solar-powered soil-less farming, using both hydro- and aquaponics.

Photograph of the SERIS developed land-based agrivoltaics testbed at the Singapore Discovery Centre (SDC).

TruePower™ Alliance

The SST group also continued with its comparative research on PV module and system performance and energy yield across different climate zones, i.e., tropics (Singapore), desert (Australia) and two different temperate climates (Germany, China). The local TruePower™ site is at Marina Barrage, in close collaboration with PUB, Singapore's national water agency. In 2022, SERIS upgraded the system at Marina Barrage system in collaboration with Maxeon Solar Technologies, headquartered in Singapore, which installed its MAX3 series, one the most efficient commercially available PV modules in the market to date.

PV Quality Assurance Group

Feasibility studies, independent consultancy and testing & commissioning services

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. The projects range from ground-mounted to rooftop and floating PV systems, with a track record of ~2 GW_p in 6 countries. In 2022, the group was awarded a contract by the Housing and Development Board (HDB) to act as their representative overseeing the construction phase on HDB residential buildings in the SolarNova Phase 6 (SN6) project. The group won other Owner's Engineering contracts for both land-based solar installations under the JTC SolarLand programme as well as rooftop PV systems on government-owned buildings (also under SN6) and on industrial premises (by the private sector).

The group is also strongly involved in cross-group activities at SES, such as the "smart O&M" project, and acts as the interface to the PV DOCTOR™ spin-off (see also page 9 of this Annual Report).

Joint upgrading works by the SST and PVQA groups at the TruePower™ site at Marina Barrage, Singapore. The old solar modules will be tested and assessed in SERIS' PVM laboratories for their degradation mechanisms.

Digitisation of Energy Group

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

One of the key achievements in 2022 was the successful trial of a fully operational solar forecasting system at the Power System Operation Centre of Singapore's grid operator EMA (Energy Market Authority of Singapore). The Solar Forecasting tool allows EMA to anticipate the solar power output ahead of time and take pre-emptive actions to manage solar intermittency and balance the power grid. 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. More information on this project can be found on page 8 of this Annual Report.

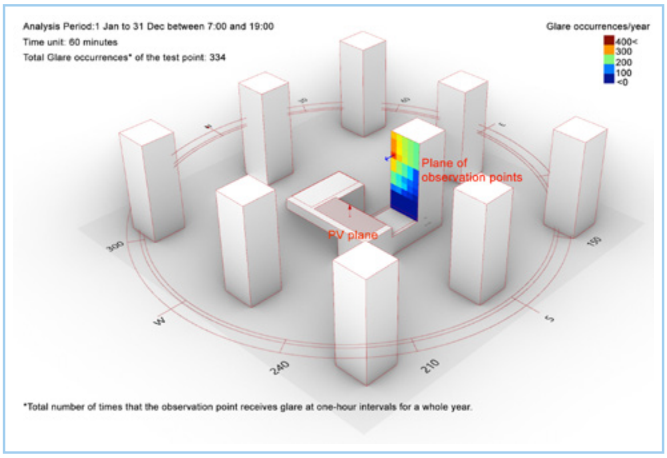
The group also carried out in-depth studies on the impacts of an increasing share of variable solar power on Singapore's electric power system. Based on different penetration scenarios, the project team derived and elaborated on possible mitigation measures for enhanced power system stability. A detailed techno-economic evaluation of the various mitigations measures was implemented, which ranged from smart inverters to grid enhancements and different storage options (e.g. central vs. sub-station level vs. decentralised).

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).

The group also expanded the research and implementation work for its proprietary solar asset management platform. While the SERIS "live" PV monitoring system has already been transferred to the cloud, new features and an API layer have been added. The new setup can accommodate parallel data transmissions with up to 1,000 parameters per logger. Currently, more than 100 remote monitoring stations (with multiple loggers per site) in 12 countries are in operation (both research and commercial projects). Gradually, also the solar forecasting and "smart O&M" tools are being added to the platform, which is designed for scalability and thus ready for future expansion and commercialisation.

The group 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 can also be used as a design tool to highlight areas that could cause glare and guide the optimum site selection for PV installations (in terms of maximised energy generation and avoidance of glare).

To enhance urban planning in the presence of PV installations on facades, the team has developed a software tool that allows to render a neighbourhood (e.g. starting from Google Streetview images) with a broad range of PV module colours on the facades and then evaluate the visual impact based on an objective assessment algorithm that uses delta saliency mapping. In a further expansion, areas with optimum irradiance conditions are automatically selected and economic parameters can be added, so that the final product, a 3-in-1 tool, allows to carry out comprehensive feasibility studies for PV retrofits on building facades based on publicly available input data. This allows urban planners, building designer and architects to make informed decisions at an early stage and with an easy-to-use tool.



Simplified visualisation of the glare assessment tool for urban environments with partial interruptions of the line-of-sight between the sun and the PV system and/or the PV system and the observation points.

2. Plans of SES Cluster for 2023

- 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.
- Design and test novel deployment options, e.g., for over-building existing infrastructures.
- Set up a real-world testbed for solar-powered urban rooftop farming in Singapore.
- Finalise the trial of the operational solar forecasting system 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 2022

SERIS Flagship Projects

SERIS has embarked 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. Boosting the efficiency of perovskite/organic tandem solar cells by a novel interconnecting layer design
2. Approaching 24% efficiency with large-area monoPoly solar cells with thin (110 μm) c-Si wafers
3. Making the Peranakan Module: the design principles
4. A study of PV module degradation from a 10-year-old installation in an urban tropical environment
5. Stability of silicon photovoltaic modules in intermediate precision conditions of measurement
6. Real-World assessment of different solar PV module types and structures for urban farming applications in Singapore
7. Planning and design tool for Building Integrated Photovoltaics (BIPV) in high-density urban environments
8. Effects of ‘invisible’ energy storage on power system operations
9. The TruePower™ Alliance: preliminary findings

SERIS Flagship Project
Thin-film on silicon tandem solar cells

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

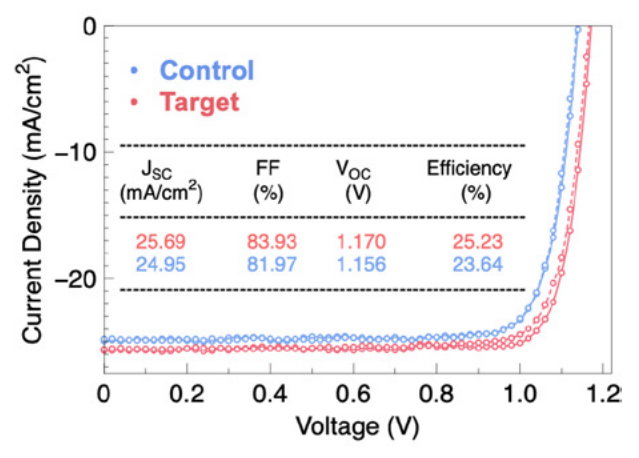
Introduction

Space is limited in Singapore and thus the solar PV systems installed here should have very high power conversion efficiencies to maximise the amount of generated PV electricity. While single-junction crystalline silicon solar cells have a fundamental theoretical efficiency limit of 29% under the standard solar spectrum (AM1.5G) and a practical efficiency limit of about 27%, much higher efficiencies can be achieved by stacking a second solar cell with different electronic properties (i.e., larger electronic bandgap) on top of the silicon cell, forming a so-called multijunction (or "tandem") solar cell. The fundamental theoretical efficiency limit of a silicon-based 2-junction tandem solar cell is 42.5% under the AM1.5G spectrum, whereby a practical cell efficiency limit of about 35% seems possible in future mass production (> 2030). Due to their excellent efficiency potential, tandem solar cells are of very high relevance for Singapore's solar sector, for both manufacturing and deployment.

In this flagship project, wide-bandgap thin-film materials - in particular organic-inorganic halide perovskites - are being investigated as the absorber layer of the top cell. In 2022, the project's research focus was on the development of perovskite/Si and perovskite/organic tandem solar cells, as well as further capability enhancements in the corresponding characterisation, modelling, simulation and reliability studies. Significant progress was made during the year in various sub-areas of the project.

Perovskite solar cells

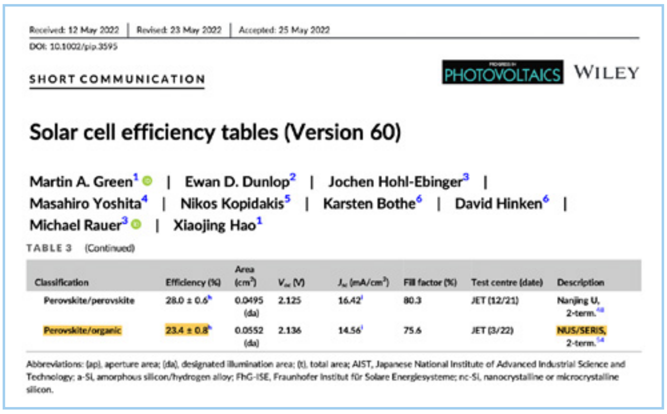
Currently, the most efficient single-junction perovskite solar cells are using an "n-i-p" configuration and have efficiencies of up to 25.8% for small areas. However, perovskite/Si tandem solar cells require a "p-i-n" configuration for optimal current matching between the top and bottom cells with minimised optical losses. In 2022, the Perovskite-based Multijunction Solar Cells Group made rapid progress with "p-i-n" perovskite solar cells, achieving efficiencies of up to 25.0%.



Measured J-V curves of solution-processed "p-i-n" perovskite solar cells (0.055 cm²).

Perovskite/organic tandem solar cells

We also focus on developing wider-bandgap perovskites with the potential for efficient, stable, solution-processed perovskite-based thin-film tandems, e.g., perovskite/perovskite and perovskite/organic tandems. A core element of these activities is how to innovate, control and understand the phase segregation in wide-bandgap perovskites. Via reduced recombination losses in both the bulk and the surfaces of the perovskite layer, our Perovskite-based Multijunction Solar Cells Group successfully demonstrated a 23.4% efficient perovskite/organic tandem solar cell with an area of 0.05 cm² (see figure below). This efficiency, measured by Japan's Electrical Safety and Environment Technology Laboratories (JET), is a new world record for perovskite/organic tandem solar cells. The result has been included in the latest Solar cell efficiency tables (version 60) of the journal Progress in Photovoltaics.


Received: 12 May 2022 | Revised: 23 May 2022 | Accepted: 25 May 2022
DOI: 10.1002/pip.3595

SHORT COMMUNICATION

PHOTOVOLTAICS WILEY

Solar cell efficiency tables (Version 60)

Martin A. Green[1] | Ewan D. Dunlop[2] | Jochen Hohl-Ebinger[3] | Masahiro Yoshita[4] | Nikos Kopidakis[5] | Karsten Bothe[6] | David Hinken[6] | Michael Rauer[3] | Xiaojing Hao[1]

TABLE 3 (Continued)

Classification	Efficiency (%)	Area (cm²)	V_{oc} (V)	J_{sc} (mA/cm²)	Fill factor (%)	Test centre (date)	Description
Perovskite/perovskite	28.0 ± 0.6[a]	0.0495 (da)	2.125	16.42[i]	80.3	JET (12/21)	Nanjing U, 2-term.[48]
Perovskite/organic	23.4 ± 0.8[a]	0.0552 (da)	2.136	14.56[i]	75.6	JET (3/22)	NUS/SERIS, 2-term.[54]

Abbreviations: (ap), aperture area; (da), designated illumination area; (t), total area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; a-Si, amorphous silicon/hydrogen alloy; FhG-ISE, Fraunhofer Institut für Solare Energiesysteme; nc-Si, nanocrystalline or microcrystalline silicon.

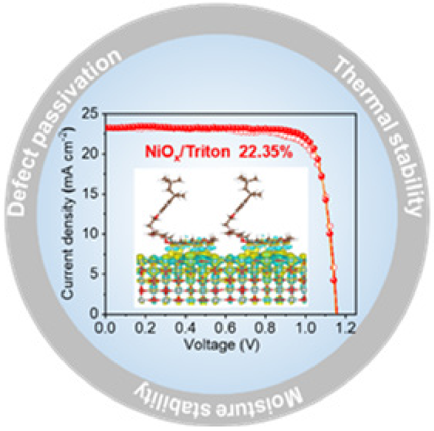
Certified efficiency of 23.4% of SERIS' perovskite/organic thin-film tandem solar cell included in the latest Solar cell efficiency tables (version 60) of Progress in Photovoltaics.

To compete commercially with standard silicon PV cells, perovskite multijunction solar cells must have a much higher conversion efficiency. In 2023, the team will continue to develop stable wide-bandgap perovskite materials, novel light management schemes, and customised thin-film fabrication processes.

Interface engineering for performance and stability improvement of perovskite solar cells

The detrimental reaction between the NiO_x hole transport layer and the perovskite components, and the moisture penetrating the NiO_x/perovskite interface extremely limit the long-term moisture and thermal stability of the corresponding perovskite solar cell devices. In 2022, our Tandem Solar Cells Group successfully demonstrated modified amphipathic molecules on the NiO_x surface. The hydrophilic chain of the molecule acting as a Lewis additive coordinates with the Ni^{3+} on the NiO_x surface, and hinder the detrimental chemical reaction at the NiO_x/perovskite interface. Meanwhile, the hydrophobic chain of the molecule points away from the NiO_x surface to prevent the moisture from penetrating into the NiO_x/perovskite interface.

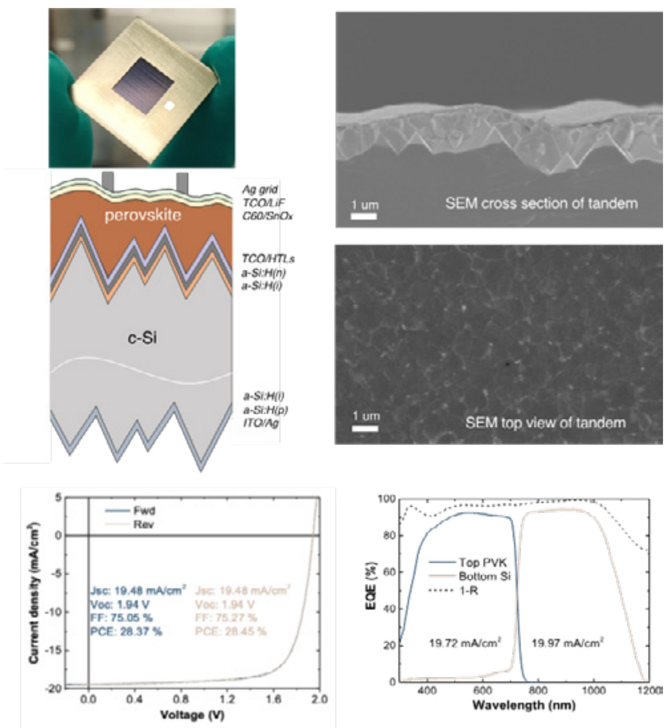
The modified NiO_x based perovskite solar cells with $Cs_{0.05}(MA_{0.15}FA_{0.85})_{0.95}Pb(I_{0.85}Br_{0.15})_3$ perovskite as the absorber layer (bandgap 1.6 eV) exhibit better moisture and thermal stability than the control devices, while achieving efficiencies of up to 22.35% and 20.46% for areas of 0.1 and 1.2 cm², respectively.



Measured J-V curves of a high-performance and highly stable wide-bandgap (1.6 eV) "p-i-n" perovskite solar cell (0.1 cm²) with modified NiO$_x$ interface.

Perovskite/Si 2T tandem cells on textured heterojunction Si bottom cells (Cz wafer)

Based on its efficient wide-bandgap perovskite single-junction devices, the Perovskite-based Multijunction Solar Cells Group made perovskite/silicon tandem solar cells using heterojunction silicon cells from an external collaborator. Cell area is 1.0 cm². We selected double-side textured n-type Cz Si wafers for these bottom cells. The structure of the resulting perovskite/Si tandem cell and a photograph of a finished tandem cell is shown in the figure below. Through process optimisation, we achieved to deposit high-quality 1.71-eV perovskite cells onto textured Si bottom cells using a fully solution-based processing method. As can be seen from the cross-sectional SEM image in the figure below, the perovskite cell fully covers the pyramid-textured silicon surface and has a large grain size.

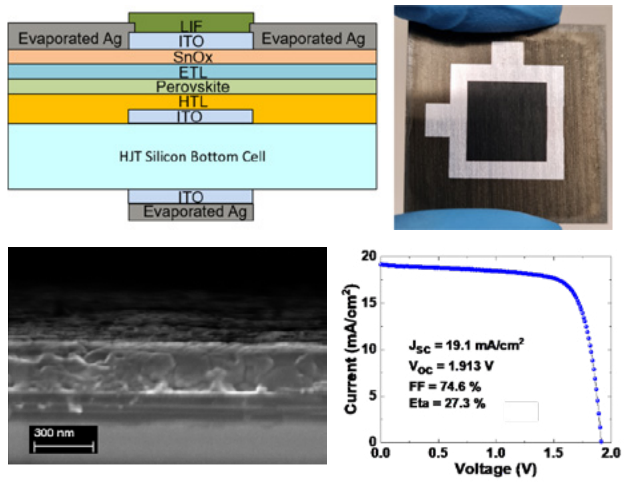


Schematic structure, cross-sectional SEM images, and measured J-V curves and EQE of a 28.5% efficient perovskite/Si 2T tandem solar cell (1 cm²) made in SERIS on a textured silicon surface.

Using this approach, we achieved perovskite/Si 2T tandem cells with efficiencies of up to 28.5% in 2022, whereby the cell area was 1.0 cm². The champion tandem cell showed a record V_{oc} of 1.94 V for such tandem devices. These learnings provide us a clear path towards 32% efficient perovskite/Si tandems.

Perovskite/Si 2T tandem cells on planar heterojunction Si bottom cells (Cz wafer)

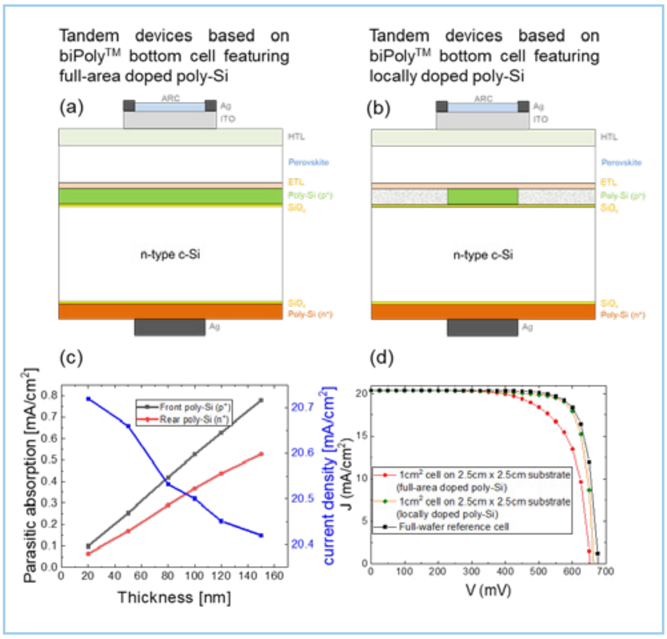
Applying the novel interface modifying technique for achieving high-performance and stable wide-bandgap perovskite solar cells, the Tandem Solar Cells Group demonstrated perovskite/silicon 2T tandem solar cells with an area of 1.0 cm² on *planar* (i.e., non-textured) heterojunction silicon bottom cells received from an external collaborator. By optimising the perovskite top cell and the interconnection layer, we demonstrated perovskite/Si 2T tandem cells with efficiencies of up to 27.3%. This achievement demonstrates a promising pathway towards highly efficient and industrially relevant stable perovskite/Si tandems via further optimising the current matching between the top and bottom cells.



Schematic structure, photo, cross-sectional SEM image, and measured J-V curve of a 27.3% efficient perovskite/Si 2T tandem solar cell (1 cm²) made in SERIS on a planar Cz silicon surface.

Optical and electrical engineering of perovskite/Si 2T tandem solar cells

In 2022, we continuously improved our perovskite/Si 2T tandem solar cells by detailed optical and electrical engineering. Optical models using optical data of in-house layers were established by the Tandem Solar Cells Group, calibrated with EQE measurements, and used to optimise light absorption and current matching of the tandem device. Parasitic absorption in the poly-Si layers capping the tunnel oxide in the biPoly™ bottom Si cell was evaluated. Compared to single-junction biPoly™ cells, the parasitic absorption in poly-Si layers in a perovskite/Si tandem device is less significant. By reducing the thickness of the poly-Si layers from 150 to 50 nm, the parasitic absorption in the two poly-Si layers can be reduced from 1.3 to 0.4 mA/cm². With detailed optical engineering, in-house perovskite/Si tandem devices are expected to achieve a current density of over 20.4 mA/cm². We also established a novel processing method to realise local contacts contacting well-defined locally doped poly-Si structures. Compared to full-area doped poly-Si structures, such locally doped structures can significantly improve the performance of the biPoly™ Si bottom cells, comparable to that of full-wafer reference cells under a perovskite-filtered spectrum. Correspondingly, the performance of the perovskite/Si tandem devices featuring such locally doped poly-Si structures were also significantly improved.



Schematic structures of perovskite/Si tandem devices based on a biPoly™ bottom cell featuring (a) full-area doped and (b) locally doped poly-Si structures. (c) Parasitic absorption in the front and rear poly-Si layers and predicted current density assuming different thicknesses of poly-Si layers. (d) Simulated J-V curves of biPoly™ Si bottom cells in perovskite/Si tandem devices featuring full-area doped and locally doped poly-Si structures plotted with full-wafer reference cell under perovskite-filtered spectrum.

Potential induced degradation studies on perovskite solar mini-modules

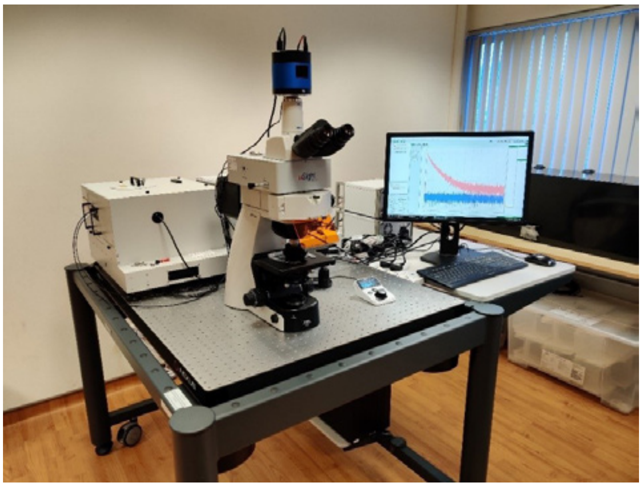
In 2022, the Tandem Solar Cells Group conducted comprehensive studies on potential induced degradation (PID) in perovskite mini-modules. PID is considered as one of the major reliability issues in commercial PV modules and can lead to catastrophic module failure in actual field applications. When multiple PV modules are interconnected in series, the voltage difference between the cell surface and the grounded glass pane can exceed 1000 V. Under such high voltage stress, Na^+ ions in the soda lime glass pane diffuse into the solar cells and cause corresponding degradations. PID for perovskite devices has so far not yet been well studied and understood.

We conducted comprehensive studies on PID in perovskite mini-modules under different polarities of high voltage bias as well as different temperature and humidity levels. We found that temperature and humidity are both critical factors affecting the amount of PID in perovskite devices. Advanced characterisations revealed the underlying mechanisms of PID in perovskite mini-modules. Meanwhile, PID recovery strategies were also explored and evaluated. In addition, based on the discovered underlying mechanisms, we explored PID mitigation strategies and demonstrated promising methods in preliminary studies. Detailed results will be provided in upcoming publications.

Advanced characterisations of perovskite and tandem solar cells

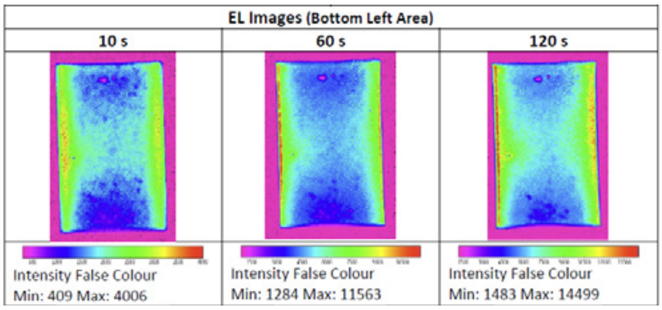
Being able to understand and measure the properties of thin films and related tandem solar cell materials is important for improving the solar cell device performance and reliability. SERIS is equipped with several advanced characterisation tools and will continue to develop new measurement and analysis techniques to provide deeper insights for device optimisation and process control.

In 2022, one of the highlights of our device characterisation work was the microscope upgrade to the time-resolved photoluminescence setup, which allows localised small-area measurements of the photoluminescence spectrum and the carrier lifetime of the device under test. Furthermore, with the selected LED wavelength illuminations and filter attachment to the microscope, it is able to perform photoluminescence imaging of the sample under the microscope.



Time-resolved photoluminescence setup with microscope upgrade, enabling lifetime measurements on a localised small area of the device. The upgrade also allows micro PL imaging, through the use of LED light sources.

In addition, the fine tuning of the works on the home-built perovskite luminescence imaging setup, luminescence quantum yield measurement, optical characterisation/simulation of thin film properties and other characterisation techniques, enables strongly improved understanding of the tandem devices fabricated at SERIS.



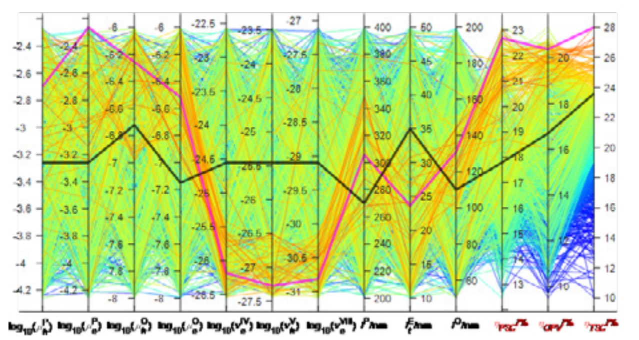
Electroluminescence (EL) images of a perovskite cell taken at different times of continuous illumination, using the home-built perovskite luminescence imaging setup. The increase in intensity of EL was observed at different time frame, which indicates that there may be some changes in recombination properties within the 120 s of illumination.

For more information on our characterisation capabilities, please refer to the sections "Photovoltaic Devices Characterisation Laboratories" and "Characterisation and Testing of PV Materials and Solar Cells" of the SERIS Annual Report 2022.

Modelling and simulation of perovskite solar cells and tandems

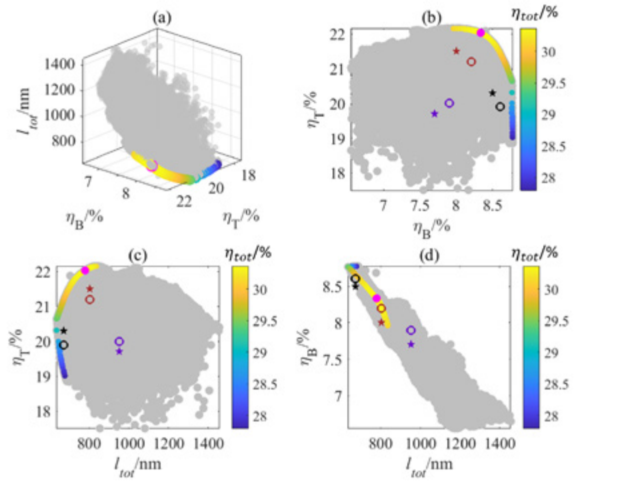
SERIS started the development of mathematical models for perovskite solar cells in 2016 and has since established a multiscale modelling framework that captures the morphology-performance relations, light propagation, and loss mechanisms in perovskite solar cells. These models have also informed and trained a range of in-house neural networks for fast and accurate predictions. We are now able to model single-junction perovskite solar cells as well as tandem solar cells with perovskite as the top cell.

In 2022, the Thin Film Modelling Team in SERIS developed comprehensive, experimentally validated optoelectronic and opto-electric-electronic models for perovskite top cells on perovskite, organic and CIS bottom cells. For the all-perovskite two-terminal (2T) tandem device, pathways towards 30.5% efficiency and 35.1% efficiency under bifacial operation were identified; for the perovskite-organic 2T tandem device, pathways to increase the efficiency from the in-house fabricated cell at 23.6% to 28% were identified; and for the perovskite-CIS four-terminal tandem device, the optimal design and fabrication space in terms of efficiencies for the two subcells as well as material cost were established as a pareto front.



Optimisation of the power conversion efficiency, η, for a 2T perovskite-organic tandem solar cell by tweaking the charge carrier mobilities, μ, reducing the net interfacial recombination velocities, v, and by adjusting layer thicknesses, l, to improve current matching.

We are currently extending our work towards multi-objective mixed-integer optimisation to further improve our tools to predict and optimise the device performance.



Multi-objective optimisation of a perovskite-CIS 4T tandem device: pareto fronts (colored, filled circles); experimental measurements for devices with perovskite layer thicknesses of 420 nm (★) 550 nm (★) and 700 nm (★) with the respective predictions from a neural network (○); the highest predicted tandem cell efficiency (●); and the search space for the pareto optimisation (●).

Plans for 2023

In 2023, SERIS will further strengthen its fabrication, characterisation, modelling, simulation and reliability study capabilities for perovskite solar cells and tandem solar cells, as well as perovskite and tandem mini-modules. We aim to improve the efficiency of our small-area perovskite/Si tandem solar cells beyond 30% and demonstrate perovskite/Si tandem mini-modules with efficiency beyond 25%. Both internal and external collaborations will be further enhanced to develop industrially relevant advanced technology solutions for upscaling the device area and improving the long-term stability of perovskite/Si tandem solar cells and mini-modules.

SERIS Flagship Project
Building Integrated Photovoltaics (BIPV)

Dr LEOW Shin Woei, SAW Min Hsian, Gavin Prasetyo RAHARJO, LIANG Tian Shen

Introduction

Singapore has set ambitious goals towards reducing carbon emissions, with clean energy forming a key pillar in the SG Green Plan 2030. With limited renewable energy options, solar photovoltaic (PV) energy remains the most viable solution that can be locally deployed. According to the "Solar PV Roadmap for Singapore", there is potential to install up to 8.6 Gigawatt-peak (GWp) of solar PV spread across 36 km^2 of net deployable area. While roof tops account for 35.9% of the net total area, facades (BIPV) offer a significant untapped resource contributing 9.8 km^2 (26.6%) of potential space. The deployment of BIPV in Singapore has so far been slow, for reasons such as additional regulations as a building material or structural component, longer financial payback time of BIPV vs. rooftop PV, and the limited aesthetic capability of PV modules to fulfil architecture design concepts. Integration complexity and unfamiliarity of BIPV's use as functional building components present additional hurdles towards wider acceptance and deployment.

Aesthetic PV modules

Improving the visual appeal of PV modules is crucial in pushing for the adoption of PV beyond typical rooftop installations, and into areas with high visual impact such as facades, glass railings and sloped roofs. To create aesthetic PV panels, several techniques can be used such as coloured films and spectrally selective filters. However, digital printing remains one of the most versatile in creating striking patterns and is widely used in the building industry for decorative glass.

When ceramic inks or colour pigments are printed onto the front glass pane of PV modules some light is obscured, reducing the PV power output. The loss is dependent on colour, ink density and other parameters. Without deliberate design, current mismatch and hot spots could occur and may lead to malfunction or early degradation of PV modules. This issue is exacerbated in high-resolution prints used to create vivid patterns. Inspired by traditional Peranakan motifs found in this Southeast Asian culture, we applied our understanding of the ink's optical properties and module design, to produce a series of visually stunning PV panels dubbed the "Peranakan Module".

Figure 1. Peranakan inspired PV modules developed by SERIS.

Tuned print properties and a repeated pattern ensure equal light transmission to each solar cell in a PV panel under the AM1.5 spectrum. This mitigates current mismatches, and lab tests have shown them to be free of hot spots.

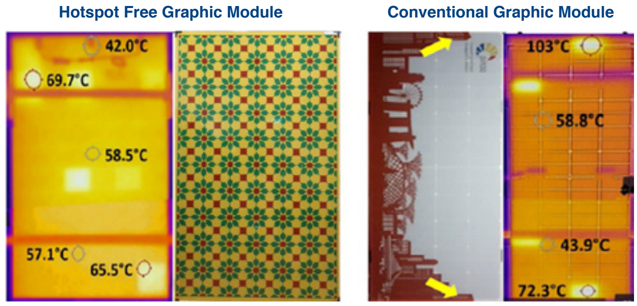


Figure 2. Absences and Formation of hotspots in Peranakan and conventional printed PV modules.

Under standard test conditions, the prototype Peranakan modules exhibit a relative efficiency loss of 7% (single colour black/white), 23% (blue/white), and 43% (yellow/green/red). A provisional patent (PCT/SG2022/050737) has been filed for this work.

Though attractive, solid digital prints tend to produce strong levels of optical loss. Conversely, spectrally selective filters such as interference coatings or photonic structures, produce intense single colours with 10-15% absorption, but lack pattern flexibility. Combining the features of both techniques, sparsely printed glass was superimposed onto a background created by single-colour filters to create a more complex visual pattern, as shown in Figure 3.

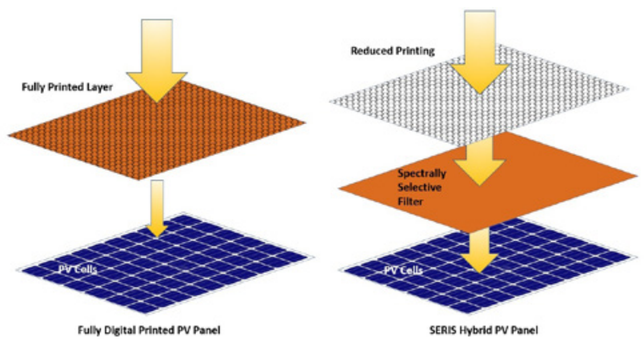


Figure 3. Creating patterns by superimposing layers

Coined the "SERIS-hybrid", the flexibility of digital printing is retained while minimising optical losses with the reduced absorption from lower ink coverage and high transmission films. Figure 4 shows PV modules produced by this method that emulate building materials. Terracotta tiles have black lines overlaid on a red reflective film, with the granite and marble patterns similarly designed. National patents have been filed in Singapore (11202251769V) and China (number pending).

Figure 4. SERIS-hybrid PV mini-modules

PV-Integrated building components

Aesthetic panels provide a way for designers to harmonise PV panels to the architectural concept of a building, and are a step towards enabling higher levels of PV integration. Such designs can be used in façade claddings, spandrel panels in a curtain wall, or guardrails for buildings. However, unfamiliarity with BIPV in construction and how such systems are implemented present barriers towards their use in the field. We had previously demonstrated a PV curtain wall prototype and a "Solar Artwork" balustrade to serve as learning examples and references for industry.

To explore the concept of building integration further, we partnered JCEC Concrete Sdn Bhd, a company producing concrete prefabricated prefinished volumetric construction (PPVC) units. On four units, PV modules were incorporated into the roof, windows, cladding, sunshade, and wall. Microinverters, power optimisers and solar tracking sunshades were also employed. The purpose was to evaluate the feasibility of PV and installed technologies on urban residential buildings. Performance data has been collected for the past year and is still being monitored. Analysis indicates that the high component of diffuse sunlight in the tropics negates the advantage of solar trackers. As expected, panels with microinverters had comparable performance to power optimisers with string inverters setups and could prove advantageous when considering cable routing. Other statistics are still being processed and we welcome any stakeholders who are interested in such systems to approach us for further information exchanges.

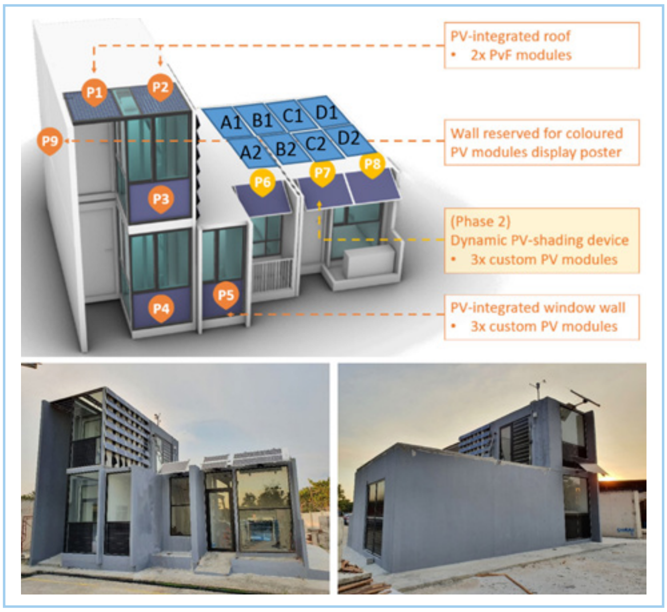


Figure 5. Concrete PPVC units with installed BIPV/BAPV

Retrofit vs Ground up design:

The most cost-effective and easiest way to deploy BIPV is to integrate the modules during initial design and construction. While retrofitting of existing structures is possible, the regulations imposed on BIPV represent a challenge, as the new requirements were not conceptualised in the original design. For example, PV facades tend to be heavier due to the thick glass covers needed for fire safety and structural provisions. This could pose a weight challenge to existing mounting structures designed for lighter claddings. As we learned from the concrete PPVC experiment, ease of installation, component placement and cable routing can also hamper retrofitting efforts. Going forward, we look to extend the current site's experimental setup to explore design changes for higher levels of PV integration. We also intend to look at possible changes to concrete PPVC design that can facilitate BIPV installation from the construction phase. Industry participation will be essential, and we welcome any feedback or opportunities to collaborate.

Another form of PPVC is the use of light steel frames for structure, to which prefabricated unitsed walls are attached to form the building skin. The interlocking joint design enables fast installation and guarantees the structure conforms to air and water tightness requirements. The system's modularity enables a PV incorporated wall to be pre-wired and assembled off-site, allowing for workers without electrical experience to handle the onsite installation. Wall pieces are hoisted in place while installation is performed by workers from the interior. Without the need for scaffolding, the pre-fabricated unitised BIPV wall (PUBW) can be installed onto tall buildings faster than building attached PV on the exterior. A mock-up structure, dubbed the "Modular Pod", was constructed by Lightrus, and is currently hosted by City Development Limited (CDL) at the top level of the Central Mall carpark.

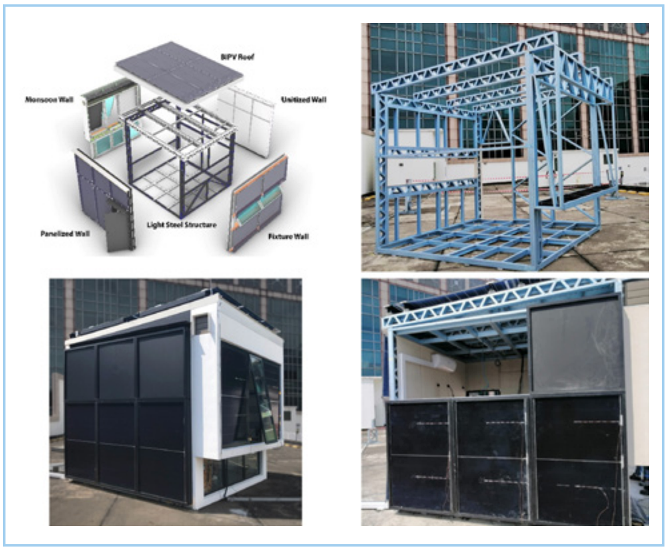


Figure 6. Modular Pod design concept and construction

Several BIPV cooling concepts were tested including PV monsoon windows and ventilated PUBW. By design, monsoon windows create a perpetual cross ventilation effect which was redirected to cool the PV panels. During the hottest hours, panel surface temperatures can be reduced by up to 2.5ºC which translates into power gains.

Ventilated PUBW take advantage of the wind tunnel effect in the cavity behind the PV module, which helps dissipate heat. This could reduce daily maximum panel temperatures by about 10ºC.

The steel structure was also filled with insulation to test its thermal performance. While air-insulated PUBW had lower interior wall temperatures by several degrees, the use of rock wool or similar insulating materials is necessary for noise proofing purposes.

This study serves as a showcase for a plug and play BIPV system applicable to tall facades with large opaque surfaces. The modular system is easy to install and provides architects with a level of design flexibility.

SERIS Flagship Project
Floating Solar Systems

Dr Carlos RODRÍGUEZ, Dr Thomas REINDL

Floating PV (FPV) offers great opportunities, particularly for countries with land constraints and available water bodies, like Singapore, Korea, Taiwan, Japan or the Netherlands. Despite the COVID-19 pandemic, Floating Solar has continued its expansion, mainly in Asia and Europe. As of end of 2021, the cumulative installed global capacity surpassed 3 GW_p (see Figure 1).

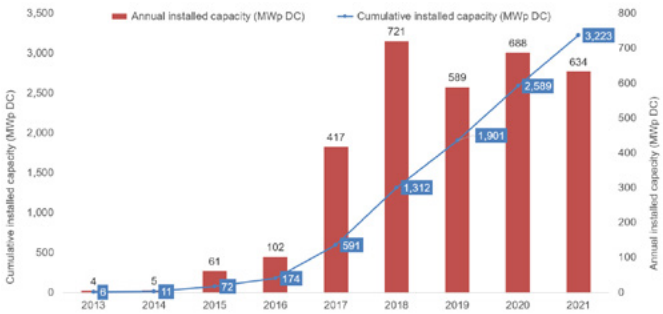


Figure 1. Globally installed FPV capacity

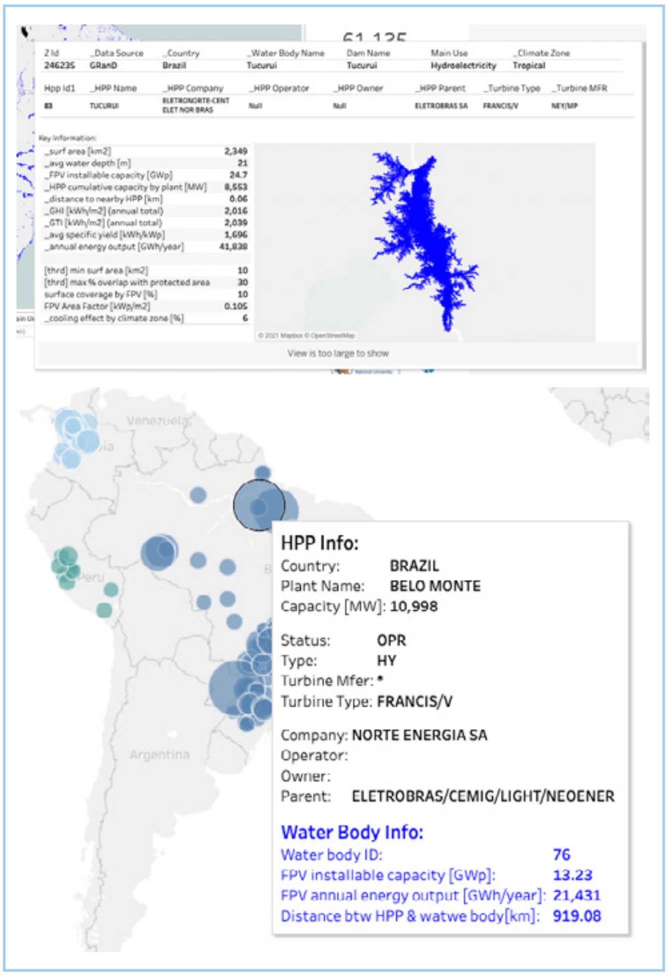


Figure 2. Example from the detailed SERIS database on hydropower stations that are suitable for hybridisation with Floating PV (here: sample from Brazil)

In order to better understand the potential of FPV, SERIS compiled a database of all reservoirs worldwide and overlaid it with the available solar resource data. As a result, it was shown that by only covering 10% of the surface areas with FPV systems, a total capacity of ~23 TW_p could be reached with 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 floating PV in the future.

A very promising segment in this market is the combination of Floating Solar with existing hydropower stations, whereby the reservoirs can be used as storage systems which help to optimise the combined output ("hybrid" mode). This not only for the diurnal cycle (utilising mostly solar power during the day and hydro power at night), but possibly also for buffering the short-term variability of the PV output and for compensating seasonal fluctuations (dry/wet seasons). Starting from the global assessment of reservoirs, SERIS carried out a detailed study of the 12 most promising countries for FPV-hydropower hybrid plants and created a database which not only describes the FPV potential but also lists relevant data from the hydropower station such a installed capacity and turbine type (which is a critical parameter for assessing the technical possibility of a hybridised operation). Figure 2 shows an example for a hydropower reservoir in Brazil. There is also a large potential for such hybrid systems in the ASEAN region, especially in Indonesia, Thailand, Vietnam, Laos, and Myanmar.

SERIS has been leading the Floating Solar research in Singapore and worldwide in recent years, leveraging the technical expertise gained from the 1-MW_p Floating PV testbed at Singapore's Tengeh water reservoir which has been operational since 2016 (see Figure 3). SERIS - in close collaboration with Singapore's national water agency PUB and the Singapore Economic Development Board (EDB) - has 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 2022, downloads of these reports from the World Bank sharing website (ESMAP) have surpassed the 100,000 mark. This underlines the high relevance of these reports for the solar industry.

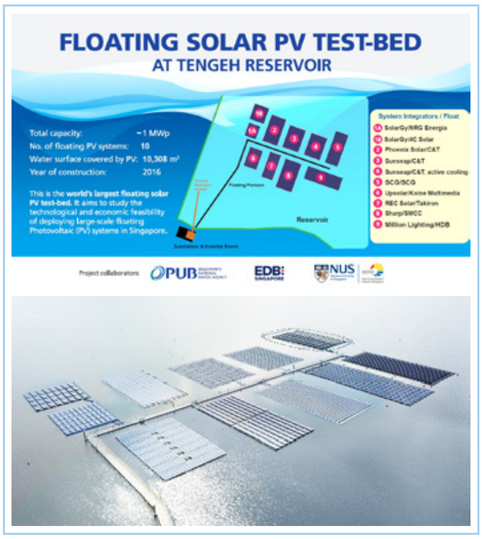


Figure 3. (Top) Schematic of the FPV testbed at Tengeh reservoir with project partners. (Bottom) Photograph (aerial view) of the testbed.

SERIS' Floating Solar flagship project has adopted a holistic approach towards driving various aspects of the FPV industry, which is summarised in Figure 4 and further explained in detail in the following sections.

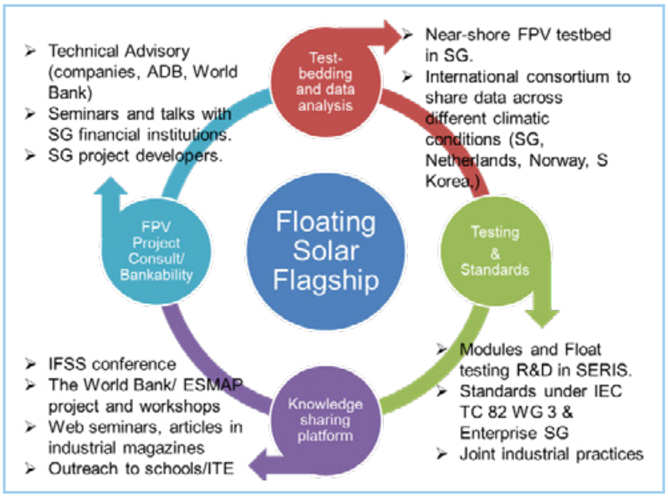


Figure 4. Thrust areas of the Floating Solar flagship project.

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, 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.

2. 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). This new 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.

3. Near-shore and off-shore FPV test-bedding

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 very 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. On national level, SERIS is involved in a consortium with leading solar developer Sunseap to develop a system that combines floating PV with a floating energy storage system (ESS). A testbed located in deep-water sea conditions in Singapore is under preparation. On 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.

During this year's Singapore International Energy Week (SIEW 2022), SERIS signed a Memorandum of Understanding (MOU) with Keppel Infrastructure and the Energy Research Institute at NTU (ERI@N), see Figure 5) to explore and conduct feasibility studies and research in hybrid ocean renewable energy systems, i.e. hybridising offshore floating solar with alternative renewable energy sources like ocean waves energy conversion systems, tidal energy systems such as turbines and paddles, wind energy systems, and/or any other viable energy source(s).

Figure 5. MOU signing ceremony between Keppel Infrastructure, SERIS and ERI@N at SIEW 2022 (image credit: Keppel)

4. Plans for 2023

SERIS will continue to drive scientific excellence and innovation in the area of Floating Solar. Apart from the plans to set up a Floating Solar testbed in marine conditions, SERIS is also exploring the multi-purpose uses of space in near- and off-shore applications. These uses aim to "solve more than one problem for Singapore", for example additional generation of fresh produce (e.g., by combining FPV with fish farming and/or crop growing), fresh water (e.g., by combining FPV with desalination) or green hydrogen (e.g., by combining FPV with electrolysers).

Selected R&D Project

Boosting the efficiency of perovskite/organic tandem solar cells by a novel interconnecting layer design

Dr CHEN Wei, LIANG Haoming, Dr LIU Shunchang, Asst Prof HOU Yi

1. Background

The potential of exceeding the single-junction Shockley-Queisser solar cell efficiency limit has stimulated intense interest in developing low-cost tandem solar cells (TSCs).[1] Perovskite materials have broad bandgap tunability (~1.17-3.10 eV), which makes them an ideal choice as both the top and bottom sub-cell in a TSC.[2] Thin-film based tandems (e.g. perovskite/perovskite, perovskite/CIGS (copper indium gallium selenide) and perovskite/organic) have great potential for cost-effective production of flexible and lightweight TSCs, and thus are promising for urban-integrated photovoltaic applications.[3]

Perovskite/organic TSCs have received increasing interest due to the recent improvement of the efficiency of organic photovoltaic (OPV) devices via the extension of the spectral response beyond 1000 nm using narrow-bandgap non-fullerene acceptors.[4] Perovskite/organic TSCs have the advantage of using orthogonal solvents for the perovskite and organic absorbers, potentially reducing the large-area solution-processing challenges related to perovskite/perovskite TSCs.[5] Compared to other bottom cell absorbers, organic materials have a larger chemical space and broader bandgap tunability, offering more bottom absorber options for perovskite-based TSCs.[6] However, the efficiency of perovskite/organic TSCs[7] is still much lower than that of their counterparts, such as perovskite/perovskite and perovskite/CIGS[8] tandems.

The low efficiency of perovskite/organic TSCs mainly originated from the optical and electrical losses in the interconnecting layer (ICL). An ideal ICL must be chemically inert, electrically conductive, optically transparent, and provide enough recombination sites between the top and bottom sub-cells.[9] In state-of-the-art perovskite/organic TSCs, the ICLs are commonly nanometre-thick evaporated metal films which enhance charge carrier recombination. However, the thin metal film likely results in a large optical loss,[10] which limits the short-circuit current density (J_{sc}) of the bottom cell and hence the efficiency of the TSC. Thus, the optimisation of the ICL to maintain efficient recombination while minimising optical losses remains a major challenge in developing high-efficiency perovskite/organic TSCs.

2. Scope of project & objectives

We demonstrate a high-performance ICL consisting of a sputtered 4 nm thick indium zinc oxide (IZO) film sandwiched between a bathocuproine (BCP) layer and a molybdenum oxide (MoO_x) layer, resulting in a large efficiency improvement compared to the ICL using 'BCP/Ag/MoO_x'. The very thin IZO film forms quasi-ohmic contacts with both sub-cells and provides effective charge carrier recombination. IZO-based ICLs show excellent near-infrared (NIR) optical transmittance, which minimises the current losses of the organic bottom sub-cell. The developed ICL enables perovskite/organic TSCs with an open-circuit voltage (V_{oc}) of 2.06 V, a J_{sc} of 14.2 mA/cm^2 and a 1-Sun efficiency of 22.9% for small-area devices (0.08 cm^2). This efficiency is significantly higher than that of previous perovskite/organic record TSCs, and approaches the record efficiencies of perovskite/perovskite and perovskite/CIGS TSCs.

3. Results & Discussion

Figure 1 shows the architecture of the fabricated perovskite/organic TSC, where the C_{60}/BCP/carrier recombination layer (CRL)/MoO_x are ICLs. There are several CRLs reported in the literature for perovskite/organic TSCs. One commonly used CRL is a thermally evaporated thin metal film, for example 1 nm of Ag or Au. Another possible alternative is a transparent conductive oxide (TCO) layer, e.g. indium zinc oxide (IZO) or ITO (10-100 nm), which have been used as CRLs in perovskite-based TSCs. To examine these different CRLs in perovskite/organic TSCs, we integrated them into tandem devices and compared their performances.

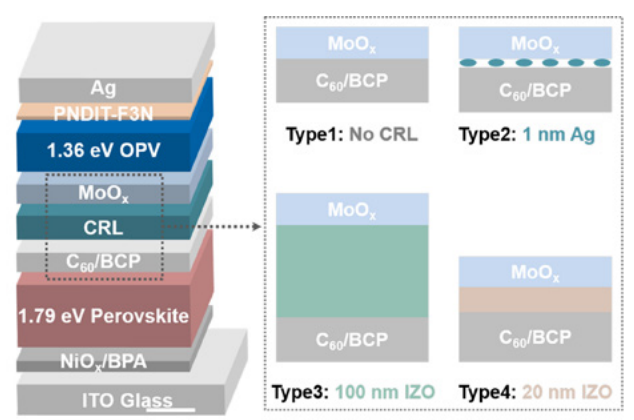


Figure 1. Schematic diagram of the fabricated p-i-n perovskite/organic tandem solar cells. The sunlight enters through the glass pane at the bottom. The dashed black frame on the left side shows the interconnecting layers (ICLs) region, which electrically series connects the perovskite top cell and the organic bottom cell. CRL: Carrier recombination layer. The designs of the ICLs with four different types of CRLs are depicted on the right side of the graph.
(Reprinted by permission from Springer Nature Customer Service Centre GmbH, Springer Nature, Nature Energy, Chen, W., Zhu, Y., Xiu, J. et al. Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimised interconnecting layer. Nat Energy 7, 229–237 (2022). Copyright: Springer Nature, 2022)

Figure 2(a) clearly shows that the TSCs without any CRL exhibit the lowest efficiency, with an S-shaped I-V curve due to the Schottky barriers between the BCP and MoO_x, which hinder charge carrier transport and thus result in inefficient interface recombination. TSCs based on a 100-nm IZO CRL suffer from a high leakage current, which also results in low PV efficiency. In contrast, TSCs with a 1-nm Ag CRL demonstrate a reasonable PCE of 18.6%, which is comparable to that of previously reported perovskite/organic TSCs. When we further reduced the IZO thickness down to 20 nm, the fill factor (FF) and the V_{oc} both increased, but the efficiency remained below that of the device having a 1-nm Ag ICL. Ideally, the ICL needs to exhibit maximum 'vertical conductivity' (maximum carrier recombination), maximum 'horizontal resistance' (minimum current leakage) and high NIR transmittance, which will combine to high J_{sc}, V_{oc} and FF in one device (Fig. 2(b)). The 'horizontal resistances' (i.e., sheet resistances) of both the 20 nm and 100 nm thick IZO layers are much smaller than that of the 1-nm Ag film, causing higher leakage current and low FF (Fig. 2(c)).

Moreover, among these commonly used ICLs, we found that the 1-nm Ag ICL has the lowest NIR transmittance (Fig. 2(d)). This optical loss further increases the current loss of the organic bottom cell and leads to a current mismatch in the perovskite/ organic TSCs. According to these results, we concluded that none of the ICLs proposed in Figure 1 gives both excellent optical and electrical properties.

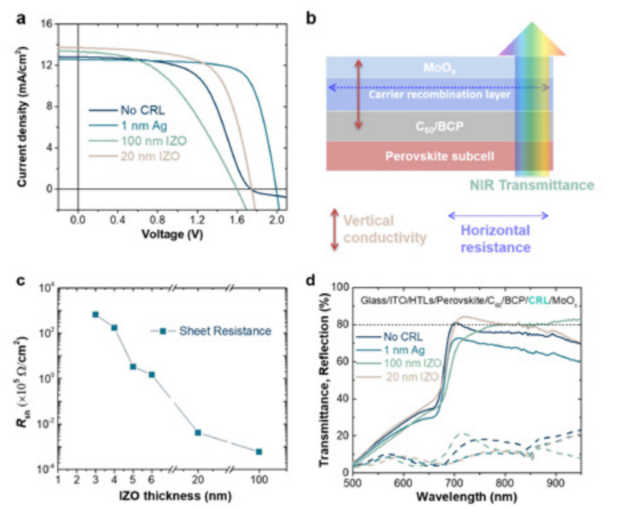


Figure 2. a) J-V curves of the perovskite-organic TSCs with different ICLs under 1-Sun illumination (AM1.5G, 100 mW/cm²) and reverse scans. b) Schematic diagram of the interconnection layers and meaning of the three parameters mentioned in the text. c) Comparison of the sheet resistance (R_{sh}) of IZO films with different thicknesses on glass substrates. d) Transmittance spectra of the perovskite sub-cells with four types of CRLs.
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Since IZO gives much higher NIR transmittance than Ag, we continued by focusing on the optimisation of IZO based ICLs by reducing the thickness of the IZO. To investigate the impact of the IZO thickness on the efficiency of the TSCs, we deposited thin IZO layers with a thickness in the range of 2 to 6 nm. As shown in Figure 3(a), the 4-nm IZO-based ICL exhibited much higher NIR transmittance than the 1-nm Ag-based ICL. Figure 3(b) shows the measured J-V characteristics of perovskite/ organic TSCs with IZO thickness of 2 nm to 6 nm. There was noticeable S-shaped J-V curves for the TSCs with an IZO thickness below 4 nm, which is mainly attributed to the inefficient carrier recombination in the ICLs. When the IZO thickness was increased to 4 nm, the S-shaped J-V curve disappeared. However, when the IZO thickness was further increased to 6 nm, the J-V curve started to show a higher current leakage and a reduced FF. Figure 3(c) shows a comparison of the J-V curves of the TSCs with IZO and Ag-based ICLs. By replacing Ag with a thin IZO, the tandem devices showed a clear efficiency improvement from 19.5% to 22.9%. This is largely driven by the enhancement of the J_{sc}. EQE measurements highlighted the advantage of switching from a thin metal-based ICL to a thin IZO-based ICL. Optical losses occurring in the thin metal-based ICL induced more current loss in the 700-900 nm range, resulting in a clear J_{sc} increase of 1.46 mA/cm² (Fig. 3(d)). These results of perovskite/organic TSCs with IZOs and Ag-based ICLs solidly confirm the advantages of the 4-nm IZO based ICLs.

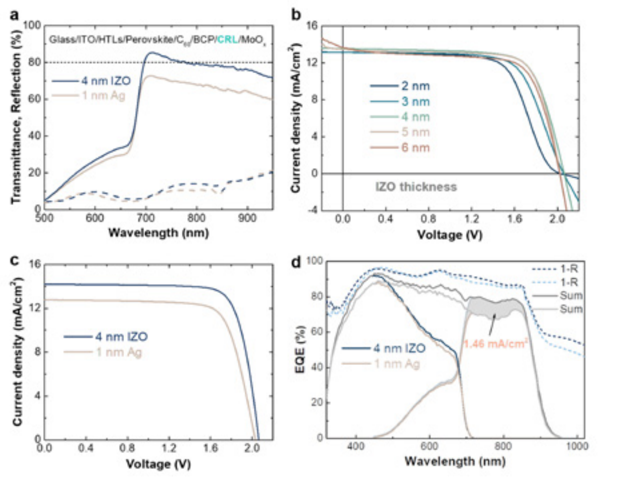

Figure 3. a) Transmittance spectra of the perovskite sub-cells with 4 nm IZO and 1 nm Ag-based ICLs. b) One-Sun J-V curves of the perovskite/organic TSCs using IZO-based ICLs with different thickness. c) One-Sun J-V curves of the perovskite/ organic TSCs with IZO and Ag-based CRLs. d) External quantum efficiency (EQE) spectra of the TSCs with IZO and Ag-based ICLs. The integrated J_{sc} of the organic bottom cell with IZO-based ICLs demonstrates an improvement of 1.46 mA/cm² compared to the Ag-based ICLs.
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4. Conclusion

In this work, we demonstrated that a sputtered 4 nm thick IZO interconnecting layer (ICL) in perovskite/organic tandem solar cells provides both excellent electrical and optical properties. This finding enabled us to fabricate small-area (0.08 cm²) perovskite/organic tandem cells with 1-Sun efficiencies of up to 22.9%. Our approach confirms the effectiveness of the strategy of reducing optical losses by avoiding a metal film as ICL, and provides an important design guideline for ICLs in perovskite-based tandem solar cells.

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Selected R&D Project

Approaching 24% efficiency with large-area monoPoly solar cells with thin (110 μm) c-Si wafers

Dr Naomi NANDAKUMAR, Dr John RODRIGUEZ, Dr Pradeep PADHAMNATH, Dr Nitin NAMPALLI, Prof Armin G. ABERLE, Dr Shubham DUTTAGUPTA

1. Background

In recent years, passivating contact stacks have increasingly been investigated by the silicon photovoltaic (PV) sector, looking for solar cell efficiencies of > 24% in production. These contacts are characterised by very low contact recombination combined with a low contact resistance, which is challenging to achieve with conventional diffused silicon layers. MonoPoly cell technology developed at SERIS consisting of a polycrystalline silicon (poly-Si) layer on an interfacial silicon oxide (SiO_x) offers an attractive means of achieving this goal. However, the large-scale adoption of such passivating contacts in solar cell manufacturing requires the use of cost-effective materials and a lean process flow that is compatible with mainstream production lines. The first step to significantly reduce the manufacturing cost for crystalline silicon (c-Si) wafer solar cells would be to reduce the thickness of the silicon wafers. A general rule of thumb in today's PV industry is that for every 10 µm reduction in wafer thickness, the $/W$_p$ cost of the solar cell is reduced by 3%. Hence, reducing the thickness offers a large advantage from a cost perspective, particularly for advanced technologies such as passivating contacts. In this report we describe our recent work regarding the impact of reduced silicon wafer thickness on SERIS' monoPoly silicon solar cell technology. This research was supported by the Singapore Economic Development Board (EDB) under a Solar Competitive Research Programme grant (S18-1179-SCRP).

2. Scope of project & objectives

This work investigates monoPoly solar cells fabricated on thin (~ 110 µm) Czochralski silicon (Cz-Si) wafers with a rear n^+ poly-Si/SiO_x stack. Despite the cost benefit of reduced wafer thickness, one of the main challenges preventing the widespread adoption of thin silicon wafers in production is the reduced wafer yield due to increased wafer breakage. To overcome this challenge, it is necessary to modify and adapt production tools for improved handling of thinner wafers. SERIS' monoPoly process uses an industrial inline plasma-enhanced chemical vapour deposition (PECVD) tool that enables the single-sided deposition of in-situ doped poly-Si and SiO_x stacks with high deposition rates (~ 90 nm/min) and low wafer breakage. Another challenge with thin c-Si wafer solar cells is the reduced absorption of solar photons, especially those in the 900-1100 nm wavelength range. As a result, the short-circuit current density (J_{SC}) is typically reduced. The loss in J_{SC} can be countered with an increase in open-circuit voltage (V_{oc}). and fill factor (FF) if the surface passivation (and surface recombination current density, J_0) is sufficiently improved. This can be achieved with next-generation device architectures using passivated contacts, such as monoPoly. To compensate for the J_{SC} loss due to the reduced silicon wafer thickness, two separate homogeneous p^+ emitters are evaluated on the thinner wafers and on standard thickness wafers for reference. A detailed breakdown of the different voltage loss mechanisms is presented.

3. Significance and impact of project

There are several economic benefits of thin wafers in terms of poly-Si feedstock to module manufacturing cost, and levelised cost of electricity (LCOE) for utility-scale PV systems. For advanced device concepts such as monoPoly which feature relatively good surface passivation, reducing the wafer thickness down to 50 µm (from the standard 150 µm) could potentially reduce manufacturing capex by 48%, module cost ($/W$_p$) by 28% and LCOE ($/kWh) by 24%.

4. Methodology & Results

This work was conducted on M2-size (244.4 cm^2) n-type, 190 µm thick (0.8 Ωcm) and 140 µm thick (1 Ωcm) Cz-Si as-cut wafers. The wafers were saw-damage etched (SDE) in a potassium hydroxide (KOH) solution followed by alkaline texturing on both sides. All samples were then subjected to a standard Radio Corporation of America (RCA) clean before boron (p^+) diffusion in a commercial tube furnace (Quantum, Tempress). Two separate diffusion recipes for a heavily doped and lightly doped homogenous p^+ emitter with corresponding sheet resistances (R_{sheet}) of 70 and 150 Ω/sq were used. After boron diffusion, the samples underwent an inline single-side etch that removes the boron-silicate glass while simultaneously etching the rear surface to remove any wrap-around p^+ doping and to polish the rear. A rear-side SiO_x and n^+ a-Si layer stack was deposited using a single-side inline PECVD tool (custom-MAiA, Meyer Burger) using PH_3 as the dopant source. All samples were then annealed at 850ºC for 30 minutes. The front p^+ surface was passivated with a stack of 8 nm AlO_x, 60 nm SiN_x and 90 nm SiO_x, while the rear n^+ poly-Si/SiO_x was capped with 75 nm SiN_x, all deposited by inline PECVD (FABiA, Meyer Burger). The measured wafer thickness of the cell precursors at this stage was 160 µm ('thick') and 110 µm ('thin'), respectively, measured across 45 points (MX 6012, E+H system). The solar cells were metallised on an industrial screen printing line (Eclipse, DEK-ASM) using commercially available Ag-Al paste for the front and Ag paste for the rear, before co-firing the cells in an inline belt firing furnace (Sinterra, BTU-Amtech) at a peak temperature of 745ºC. All cells were printed with a busbarless ("0BB") contact grid. Full-area I–V measurements were conducted using a multi-wire busbarless LED tester (SINUS-220, Wavelabs) on a reflective and conductive brass chuck. The tester was calibrated with a reference cell from ISFH CalTec, Germany. In addition, selected solar cells were sent for external verification to ISFH CalTec. For each wafer type, two sub-groups are evaluated to test a heavily doped (70 Ω/sq) and a lightly doped (150 Ω/sq) front p^+ emitter. A summary of the measured p^+ emitter characteristics is given in Table 1 for each group.

Table 1: Measured properties of the boron emitter and silicon wafer.

Groups	Rsheet (Ω/sq)	Peak dopant conc (cm^{-3})	Final cell thickness (µm)
G1: Thin70	68 ± 3	1.5 x 10^{19}	109 ± 3
G2: Thick70			157 ± 2
G3: Thin150	152 ± 3	9 x 10^{18}	109 ± 3
G4: Thick150			157 ± 2

The finished cell I-V parameters show outstanding cell V_{oc} of > 705 mV for the 'thin' wafers, corresponding to a peak cell efficiency of 23.2% (Figure 1) and a batch median of 23.0% (Figure 2). The groups with a thinner bulk Si wafer show a boost in V_{oc} of +2 mV and in FF of +8%$_{abs}$ when compared to the reference groups on standard wafers (Fig. 2). Overall, the gain in V_{oc} and FF overcompensates the corresponding loss in J_{SC} of 0.3 mA/cm^2 due to the reduced wafer thickness, resulting in a 0.2 - 0.3 %$_{abs}$ gain in median cell efficiency. An evaluation of the FF losses shows that the largest FF loss is from series resistance (2.9%$_{abs}$ for 70 Ω/sq and 4.0%$_{abs}$ for 150 Ω/sq) followed by J_{02} recombination (1.0%$_{abs}$) with negligible loss due to shunt resistance (<0.1%$_{abs}$). Despite a drop in FF of > 1.0%$_{abs}$ from the increased contact resistance and lateral resistance of the higher R_{sheet} p^+ emitter (150 Ω/sq), these groups result in an improved cell performance due to an increase in V_{oc} and J_{SC} irrespective of the wafer thickness.

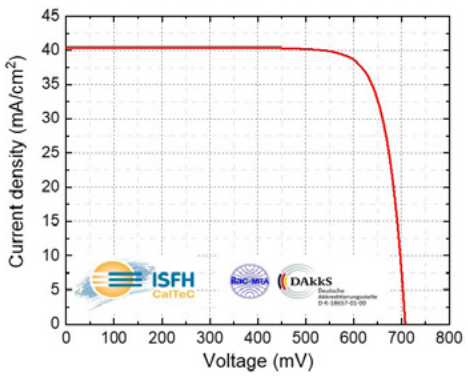


Figure 1. Current-voltage (I–V) curve of the champion n-type 'thin' wafer (110 µm) solar cell from G3 (Thin_150) with a rear PECVD n^+ poly-Si/SiO_x stack, as verified by ISFH CalTec, Germany.

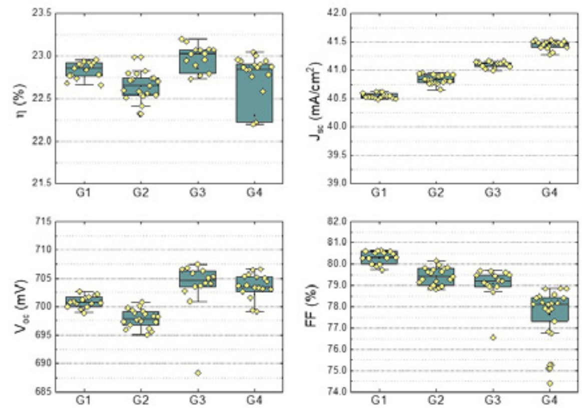


Figure 2. Batch I-V characteristics of n-type bifacial solar cells on 'thin' and 'thick' Cz-Si wafers with 70 and 150 Ω/sq p^+ front emitters. All cells have a 100 nm thick rear n^+ poly-Si/SiO_x passivating contact stack fabricated by inline PECVD with screen-printed front and rear contacts. The box and whiskers correspond to the 5th, 25th, 50th (median), 75th and 95th percentile of each split.

The unmetallised cell precursors with a 70 Ω/sq emitter, measured after firing, showed a lower median iV_{oc} of 709 mV (thin wafer) and 706 mV (thick wafer) compared to 716 mV (thin wafer) and 718 mV (thick wafer) for those with a 150 Ω/sq emitter. After metallisation, the corresponding median cell V_{oc} values are 701 mV (thin wafer), 698 mV (thick wafer) for the 70 Ω/sq splits and 705 mV (thin wafer), 703 mV (thick wafer) for the 150 Ω/sq splits. These final cell V_{oc} results (including the champion V_{oc} of 707 mV) are state-of-the-art for large-area c-Si solar cells with high-temperature screen-printed and fired metal contacts.

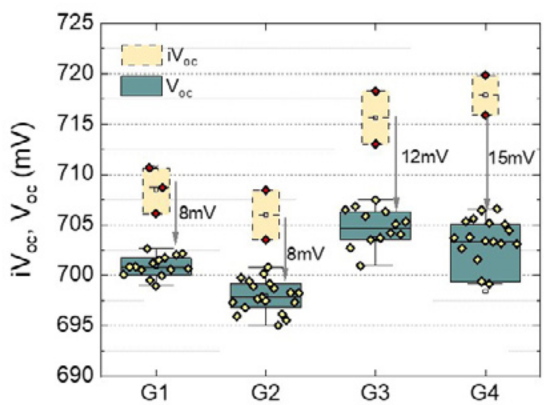


Figure 3. 1-Sun iV_{oc} for unmetallised cell precursors measured by QSS-PC post-firing and final cell V_{oc} obtained from I-V measurements of the metallised solar cells from each group. Each data point corresponds to a unique sample. The box and whiskers correspond to the 5th, 25th, 50th (median), 75th and 95th percentile of each split

When comparing the iV_{oc}-to-V_{oc} difference in this study (Fig. 2), a larger drop of 12 - 15 mV is observed for the 150 Ω/sq emitter compared to an 8 mV drop for the 70 Ω/sq emitter. This is due to the expected increase in J_0 recombination (J_{0metal}) to the lowly doped regions for the 150 Ω/sq emitter. Despite a higher V_{oc} loss at the metal contacts, the 150 Ω/sq emitter showed a higher final cell V_{oc} because of a much higher (+10 mV) unmetallised iV_{oc}. It is observed that the J_{0bulk} for the thinner wafers is lower than the thicker wafers for both emitter groups, and the same trend is reflected in the measured implied FF (iFF) for these cell precursors. More significantly, the lowly doped 150 Ω/sq emitter shows a lower total J_{0surf} of 25 - 30 fA/cm^2, whereas it increases to ≈40 fA/cm^2 for the heavily doped 70 Ω/sq emitter. Because of this difference in J_{0surf} of 10 - 15 fA/cm^2 between the two emitters, despite the increase in J_{0metal} (calculated to be +5 fA/cm^2), the lowly doped emitter shows an overall gain in final cell V_{oc}.

5. Conclusions

As the PV industry moves towards incorporating advanced technologies such as passivating contacts in their device design, cost considerations play an increasingly important role. The first step towards reducing costs would be to reduce the silicon wafer thickness for technologies with excellent surface passivation. In this work, a comparison of large-area monoPoly cells on 'thin' and 'thick' wafers with lowly doped and highly doped p^+ emitters was performed, whereby the cells were fabricated with a rear passivating contact stack of n^+ doped poly-Si/SiO_x deposited by inline PECVD. An efficiency of 23.2% and a V_{oc} of 707 mV were achieved for front and rear screen-printed and fired metallisation. The lowly doped p^+ emitter (150 Ω/sq) gives an overall gain in V_{oc} as well as J_{sc} compensating for the losses experienced by the same 'thin' wafers using a conventional heavily doped p^+ emitter (70 Ω/sq). Lastly, we presented the recent progress of the monoPoly technology and an outlook for rear-junction cell structures with a selective n^+ poly-Si stack at the front and a p^+ poly-Si emitter at the rear.

**** This article is the extract of a more comprehensive work published in Progress in Photovoltaics Res Appl. 2022; 1–9, as Nandakumar et alia, "Large-area monoPoly solar cells on 110 µm thin c-Si wafers with a rear n^+poly-Si/SiO_x stack deposited by inline plasma enhanced chemical vapour deposition", with permission from the publisher John Wiley & Sons, Ltd.***

Selected R&D Project
Making the Peranakan Module: the design principles

SAW Min Hsian, Gavin P. RAHARJO, Srinath NALLURI, Dr LEOW Shin Woei, Dr Mauro PRAVETTONI

1. Background

Conservation of heritage buildings in the high density urban context of Singapore is shifting its paradigm from purely physical preservation to making them functionally relevant through constant redevelopment and repurposing. This opens opportunities for the adoption of modern and innovative technological solutions, such as building-integrated photovoltaics (BIPV), with a novel approach to value-add these living artefacts: transforming them from energy consumers to clean energy providers.

An important feature of integrating PV modules into heritage buildings is respecting their aesthetics, while harvesting as much energy as possible from its limited available surface to meet the energy demand. Without an innovative solution in terms of aesthetics and colour, PV integration on conserved buildings can only be relegated to the areas out of the public eye.

In fact, for better aesthetic integration, colourful PV modules are gaining interest in the public. However, it comes with a compromise on PV performance: the ink and frit pigments will absorb and reflect the solar spectrum in particular wavelengths to achieve the desired colour. The light transmittance differs for different colours, and this can cause two issues: i) mismatch losses and ii) potential formation of hot-spots during operation of the PV module.

The Peranakan module [1], designed in 2021 and unveiled at the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8, Milan, 26-30 Sep 2022), aims at addressing these issues, with a novel design principle that has been filed as a patent application for its innovative solution with the Singapore Patent Registry.

2. Design principles

A comprehensive study has been conducted to investigate the impact of colours and printing parameters on the light transmittance to the solar cells and the modules' electrical efficiency [2]. Building upon this extensive work, two design principles are proposed:

- Colour science: It relates to the selection of colours (two or more), and the appropriate printing parameters for each colour such that the different colour areas have the same amount of optical transmittance and electrical efficiency (i.e. short-circuit current).
- Pattern coverage area/ratio: It relates to creating the same amount of pattern coverage area for each solar cell in the PV module, e.g. with repeated patterns covering the solar cells throughout the entire PV module.

Adopting these two principles, multi-coloured and patterned PV modules with improved aesthetics and mitigated current mismatch and hot spot formation risk can be created. The repeated design also brings a sense of unity, consistency, and cohesiveness to the viewers.

3. Significance and impact of project

The new design concepts behind the Peranakan module address both functional and aesthetic aspects. First, the design principles circumvent the challenges posed by multi-coloured PV modules, lifting the constraint of considering only monochromatic PV modules for building applications. Diminishing the risk of hot-spot formation is particularly crucial for integration of solar PV into buildings where fire safety is of utmost importance. Such multi-coloured PV modules do not only serve to generate energy, but could also serve as decorative elements, preserving or adding aesthetical value to the heritage buildings. An assortment of patterns or heritage features can be used jointly with combination of colours, offering architects and designers high design flexibilities. As a result, this encourages a wider adoption of BIPV not only in modern buildings but also in preserved heritage buildings which form the fundamental societal identity and root and serve as the link to the past. There are about 6500 heritage houses in Singapore [3]. By tailoring PV modules that harmonise well into these buildings, they contribute to the sustainability movement pledged by the Singapore Green Plan 2030 [4].

4. Methodology & Results

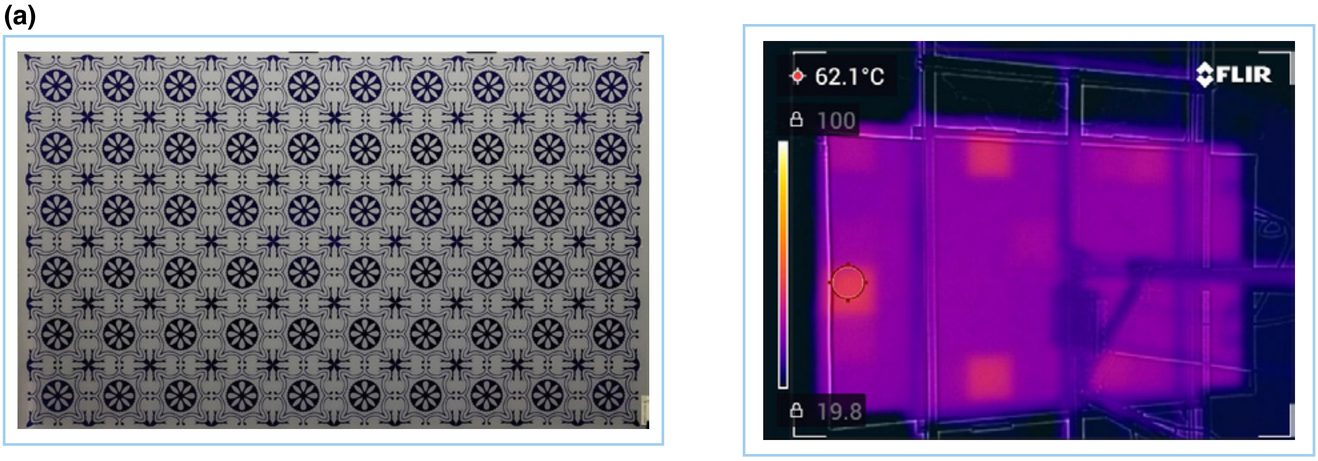
Highlighting the connection with the local environment and traditions, we demonstrate the proposed design principles on colourful PV modules with repeated patterns which are inspired by the Peranakan culture uniquely to Singapore and Malaysia. Peranakan houses are often decorated with colourful tiles with floral motifs, geometrical patterns etc. Two examples of multi-colour and pattern designs with Peranakan elements that we created for the modules, coined as "Peranakan PV", are shown in Figure 1: (a) blue-white Peranakan PV —these two colours symbolise peace, purity, and serenity and are commonly used in the porcelain and dinnerware of Peranakan families; (b) Peranakan PV with red and green — these bright colours are often seen in the objects of the daily life, ornaments and fashion of the Peranakan people.

The tile designs were first created in an imaging software, then printed onto glass with digital printing technology and subsequently fabricated into 60-cell PV modules with our in-house R&D pilot line. To highlight the importance of our proposed design principles and demonstrate contradistinction, apart from the Peranakan PV modules, the results of a patterned PV module (coined as "Singapore landscape module") is also presented: this module was designed with little attention paid to non-uniform shading and hot-spot reliability concerns (Figure 1c). The modules were then characterised for their electrical performance at Standard Test Conditions (STC) with spectral mismatch corrections.

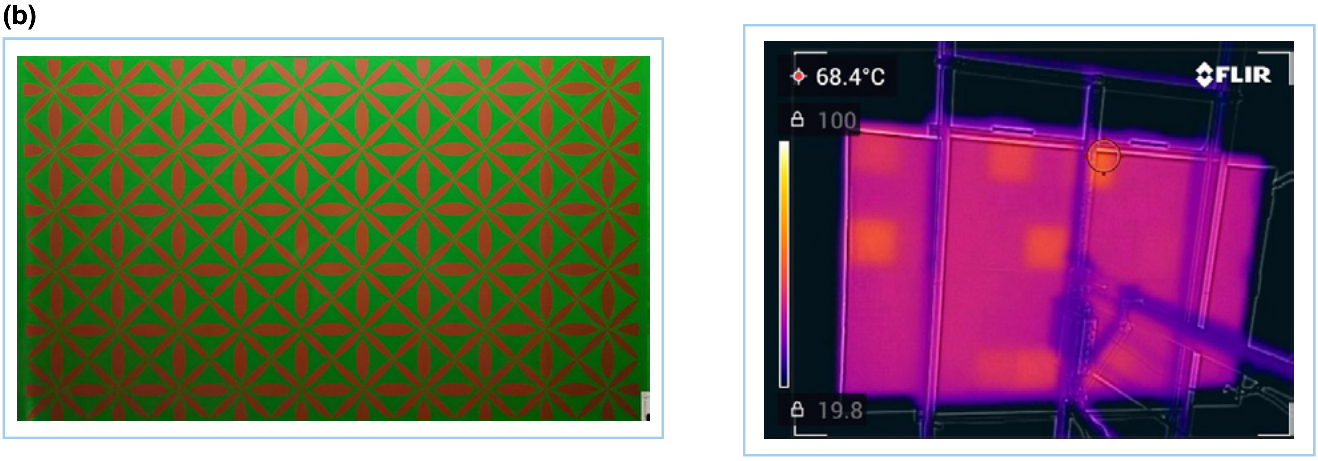
Furthermore, to validate the mitigation of hot-spots, we conducted outdoor hotspot endurance tests and mapped the surface temperature distribution of the solar cells in the modules with infrared thermography (IR). The IR images of the 3 modules are illustrated in Figure 1. The pictures on the left show the front view of the modules: for the Peranakan modules in (a) and (b), they are reflected vertically to match the perspective of the IR images; while for the Singapore landscape module, the image is reflected horizontally. As seen from the IR images, two solar cells in the Singapore landscape PV module (indicated by the arrows in the corresponding image) exhibit temperatures exceeding 100°C, due to the larger shading of these two cells compared to other cells connected in the same string. This suggests potential of localised heating and hot-spot development for them. In contrast, despite also having colour and pattern printings on the front glass, solar cells in a Peranakan PV module show homogeneous temperature distribution (ranging from 50°C to 70°C, in the same exposure conditions). Higher cell temperature observed in the Peranakan modules is caused by internal factors, e.g. micro-cracks in cells.

Figure 2 shows the measured I-V and P-V curves of the modules. Essentially, there is no mismatch effect observed for the Peranakan PV modules, implying uniform light transmittance to all solar cells. In contrast, the Singapore landscape module shows the activation of bypass diodes in both I-V and P-V, caused by current mismatch between the strings.

(a)



(b)



(c)

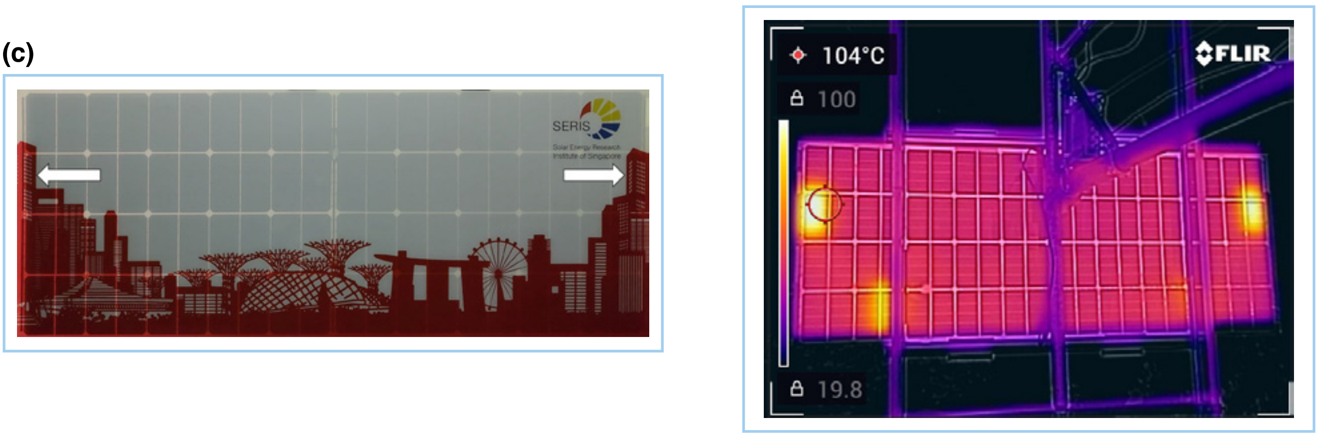


Figure 1. Infrared (IR) thermography images (right) and corresponding photographs (left, reflected vertically for the Peranakan modules, and reflected horizontally for the Singapore landscape module, to represent the same perspective of the IR thermographies) of the Peranakan modules and Singapore-landscape module, respectively. The IR images were captured during an outdoor hotspot endurance test under the same exposure conditions, whereby the arrow indicates the hot-spot cells in the Singapore landscape module.

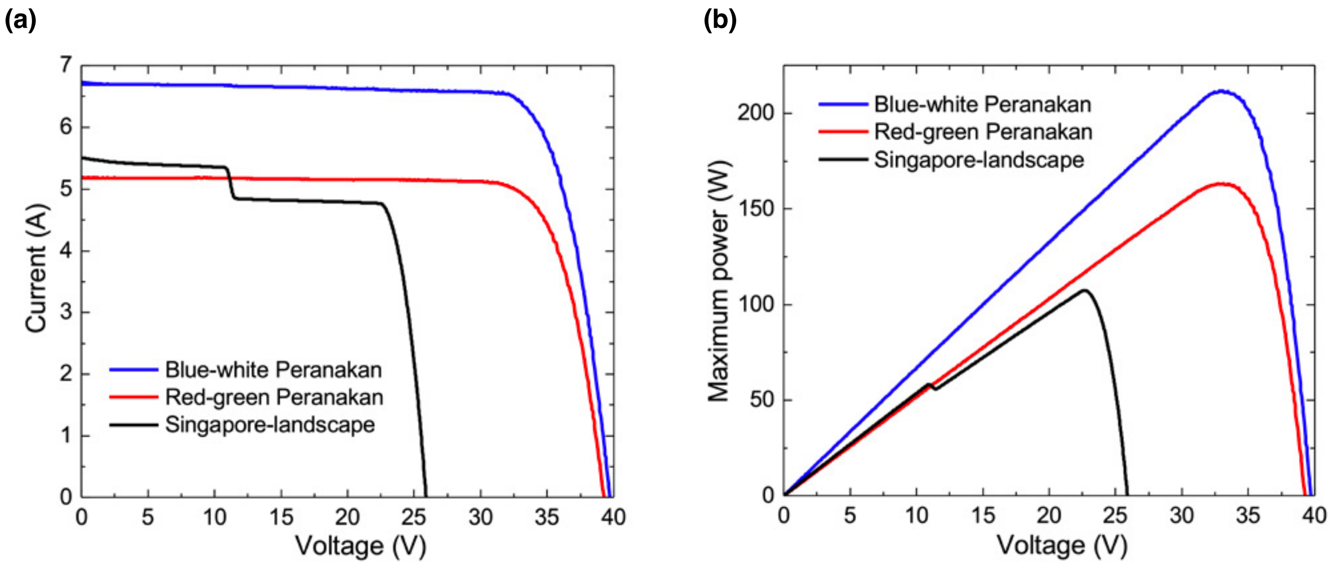


Figure 2. (a) I-V curve; and (b) P-V curve of the Peranakan PV modules and Singapore landscape module

Table 1. I-V parameters of the Peranakan PV modules at Standard Test Conditions (STC): 1000 W/m², 25°C module temperature, AM1.5g

Technical specifications	Blue-white Peranakan PV	Red-green Peranakan PV
Short-circuit current, I_{SC} (A)	6.79	5.33
Open-circuit voltage, V_{OC} (V)	39.7	39.3
Maximum power, P_{MAX} (W)	21.4	167

5. Conclusions

We have successfully demonstrated the feasibility of our two design principles in creating colourful and patterned PV modules that are free from current mismatch and hot spots. The Peranakan modules obtained are based on our colour science algorithm and the adoption of repeated patterns. With this innovative technology, we simultaneously enrich the visual appearance of coloured PV modules for building applications and address the associated technical challenges. This eliminates the constraint of using monochromatic modules for BIPV applications, providing more design flexibilities and better integration into both heritage and modern buildings. Moving forward, a research collaboration project between SERIS, NUS Baba House and the NUS Department of Architecture to integrate the Peranakan PV modules into the vertical façade of NUS Baba House is under discussion. This opens up the opportunity to a wider BIPV adoption, with particular interest in heritage buildings.

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Selected R&D Project
A study of PV module degradation from a 10-year-old installation in an urban tropical environment[†]

Dr Mauro PRAVETTONI, Mike Mahesh S/O SUNDAR DAS, Dr Amit Singh RAJPUT, Wan LI, Selvam VALLIAPPAN

1. Background

The solar photovoltaic (PV) installation capacity is growing widely in South-East Asia and at the fastest pace among all renewables. Solar PV accounts for about 60% of the regional installed capacity of non-hydro renewable electricity, the areas that receive the strongest solar intensity being located in Thailand, Myanmar, Cambodia, and Vietnam. But the whole region offers a variety of installation potentials, from the conventional rooftop and utility-scale plants, to building-integrated PV (BIPV), floating PV (both on reservoirs and offshore), agrivoltaics, and in the future also likely vehicle integrated PV (VIPV). However, reliability concerns arise from the hot and humid tropical climate in large parts of the region and from soiling, of either natural or anthropic origin [1].

Today's PV market requires module performance warranties that last for more than 20 years [2]. Recently, Maxeon Solar (the Singapore head-quartered spin-off of SunPower) announced that it will offer a world-record 40-year performance warranty for its Interdigitated Back Contact (IBC) product line. However, recent works have shown how midlife failures may be worryingly frequent in tropical regions [3]. Most of the reliability studies in the literature focused so far on continental climate, while data and statistics from the hot and humid tropical climates are still poorly available.

2. Scope of project & objectives

Studying the performance and history of degradation mechanisms in the most aggressive environmental conditions for PV performance is becoming essential to allow achieving outstanding reliability targets. This work aims at representing one of the first comprehensive reliability studies of a statistically relevant sampling of PV modules after 10 years of installation in the tropical region. The observed degradation modes are listed and analysed, and their occurrence is correlated to the power degradation.

3. Significance and impact of project

The combination of tropical climate and the urban environment of Southeast Asian megacities is the best testbed for challenging a performance warranty of more than 20 years of operation. This research addresses the effort of the PV industry towards an improvement in the selection of the bill of materials (BoM) to manufacture efficient and reliable panels. It also assists the standardisation community, via SERIS' participation in the International PV Quality Assurance Task Force (PVQAT, particularly through the work of Task Group 5 "UV, Temperature and Humidity") and through SERIS' liaison with the International Electrotechnical Commission (IEC, Technical Committee 82), towards the improvements of standards for module qualification and type approval. It indirectly contributes also to the Singapore Green Plan, with more know-how on the severe environmental challenges that the PV modules must address for a successful and long-lasting deployment nationwide.

[†]This is an extract of a work presented at the 8th World Conference of Photovoltaic Energy Conversion (WCPEC-8), Milan, 26-30 September 2022

4. Methodology

The PV modules analysed in this work belong to a system of 750 modules decommissioned from the roof of the Zero Energy Building (ZEB, [4]) of the Building and Construction Authority (BCA) Academy in Singapore (Fig. 1a, total capacity: 142.5 kW_p; Module type: multi-crystalline silicon; year of installation: 2009).

(a)

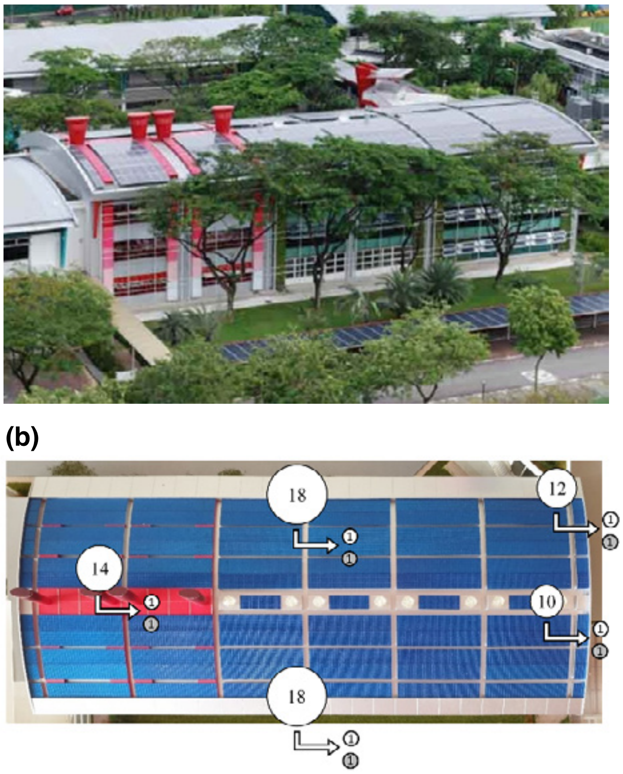

Figure 1. (a) The case study - the roof of the Zero Energy Building (ZEB) of the Building and Construction Authority (BCA) Academy in Singapore [4]. (b) Sampling of 72 modules from 5 locations (the circles indicate the number of modules sampled in each location; the small circles indicate the subsampling of 2 modules, the visually cleanest and dirtiest, per location).

A total of 72 PV modules were sampled based on the string performance from the decommissioned original plant of 750 modules. Figure 1b indicates the location and number of the 72 sampled modules; five different locations were selected to map the best, the worst and the average performing strings, with different tilts and orientations. Two modules per location where subsampled (the cleanest and the dirtiest at visual inspection, respectively): these were analysed in detail for performance degradation due to soiling and reported in [1].

The modules were manufactured by one of the top-10 manufacturers of polycrystalline silicon (poly-Si) modules at that time (2009). They have an area of 1658 × 834 mm, 50 cells in series (M0 wafer size), and a PET backsheet. The nominal performance is as follows: maximum power: P_{max} = 190 W;

short-circuit current: I_{SC} = 8.23 A; open-circuit current: V_{OC} = 30.8 V; fill factor: FF =75.0%. From the technical information available at the time of commercialisation, it is reported "unknown potential induced degradation (PID)" risk.

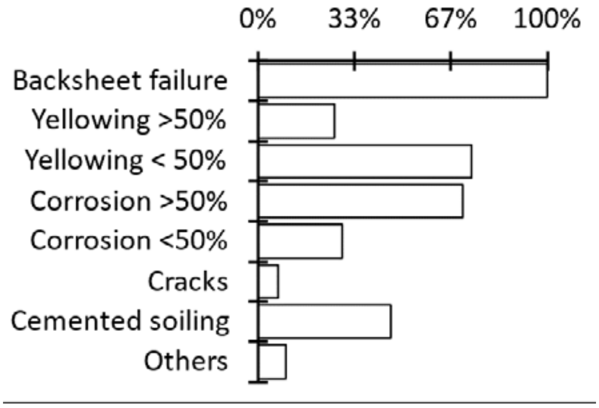

Figure 2. Results of visual inspection: frequency of occurrence of the various degradation mechanisms observed.

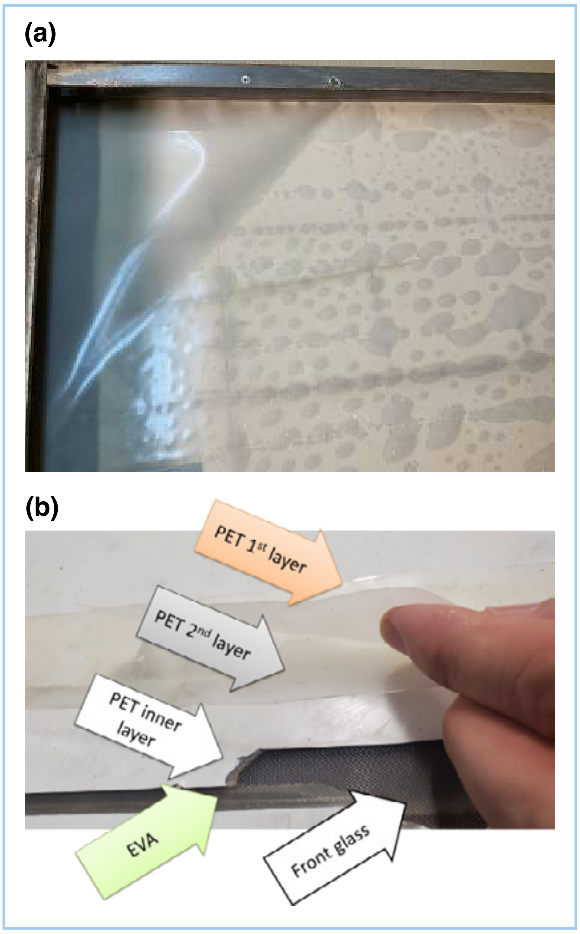

Figure 3. (a) Backsheet failure, commonly found on all the sampled modules; b) The subsequent delamination of the three layers of PET.

5. Results

Figure 2 lists the frequency of occurrence of the most important degradation mechanisms observed on the tested modules.

Backsheet failures occurred in all 72 modules in form of delamination of the backsheet (Fig. 3a), with formation of bubbles and in most cases with severe detachment of the 1st layer of PET (Fig. 3b). These failures are the possible cause of moisture ingress [5], which caused extensive corrosion of the metallisation in all modules (in 71% of the cases, distributed over the entire module). Yellowing is clearly visible in all modules: in some modules (26%) the backsheet and encapsulant are yellowed almost over the entire front surface, while the remaining modules have only portions that are visually yellowed. Yellowing was shown to cause up to 16% transmittance losses on average.

Soiling was the largest cause of transmittance loss, and it has been analysed in detail in a subsampling of 10 modules and reported in [1]. There, it was observed that tropical storms were generally only able to partially remove soiling in the dirtiest cases (up to 5% recovery in I_{SC}), while manual cleaning with detergents can achieve up to 10% I_{SC} recovery. Cemented soiling was overall observed in nearly half of the cases (46%). The presence of metals (Fe, Al, Zr, etc.), alongside carbon, silicon and oxygen was observed: these are elements that are commonly present in soil [6-7]. The absence of nitrogen and low presence of sulphur is remarkable, suggesting that transport related pollution is well confined in the urban environment of Singapore.

Cracks and microcracks causing the electrical isolation of parts of the cells were observed in a few modules (7%). Other observed failures include the delamination of the front encapsulant with the formation of bubbles, junction box and connector failures. The electrical performance of the 72 sampled modules was measured via current-voltage (I-V) characterisation at Standard Test Conditions (STC). Measurements were performed in SERIS' ISO/IEC 17025 accredited laboratory for PV module testing. Each module was gently cleaned to remove the dust before the measurements, but no additional detergent was used to remove more persistent soiling, apart from the ten-subsampling analysis of [1].

The best performing module showed a remarkably low (-4%) relative loss in I_{SC}, with no change in V_{OC} and a -18% relative loss in FF, for a total -22% relative power loss, corresponding to a degradation rate of -2.2%/yr. The worst performing module showed the most severe degradation in FF (-58% rel.) and I_{SC} (-52% rel.), a marginal degradation in V_{OC} (-3% rel.) and a huge -81% relative power degradation (-8.1%/yr).

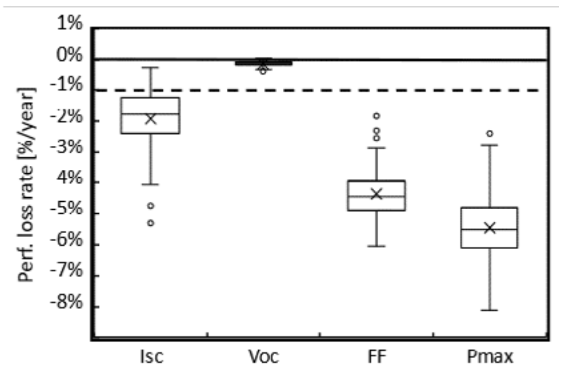

Figure 4. Performance loss rate (in %/year) for I_{SC}, V_{OC}, FF and P_{max}.

In general (Fig. 4), the relative performance degradation of all electrical parameters is in good approximation normally distributed, with an average degradation rate of approximately -2%/yr in I_{SC}, negligible degradation in V_{OC}, ~ -4.5%/yr degradation in FF, and -5.5%/yr maximum power loss. The severe power degradation can mainly be attributed to corrosion and partly to yellowing and soiling losses.

None of the 72 sampled modules satisfies the threshold of 10% maximum degradation after 10 years of operation (corresponding to -1%/yr, in linear approximation).

6. Conclusions

A sampling of modules decommissioned after 10 years of installation in the central district of Singapore showed severe soiling and corrosion as the main causes of premature failure.

No V_{OC} degradation occurred, suggesting that the modules did not suffer PID, which is confirmed by the EL analysis (not discussed in this article).

While the frequent tropical storms have shown to remove soiling only up to 5%, manual cleaning with detergents can achieve up to 10% short-circuit current increase in the dirtiest cases. The presence of metals (like Fe, Al, Zr, etc.), alongside carbon, silicon and oxygen, was reported. The absence of nitrogen and only traces of sulphur indicates that transport and industrial pollution cannot be considered among the main causes of soiling in Singapore.

Together with yellowing (both glass and EVA), soiling caused severe transmittance losses. Severe failures of the PET backsheet likely caused moisture ingress that accelerated the power degradation well beyond the warranty threshold of -1%/yr.

This abnormal behaviour cannot be generalised and should be carefully addressed case-by-case in other PV installations of similar age (~10 years). In this case, it was likely caused by the poor quality of the backsheet selection in a historical period (the decade 2000-2010) were a capacity shortage of established technology (e.g. Tedlar) pushed manufacturers towards using new and cheaper materials, like PET and PA, with little field experience, and no experience from hot and humid climates.

The result highlights the importance of reliability studies, in the path towards the decarbonisation of the regional energy systems and the ambitious targets of solar PV adoption.

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Selected R&D Project

Stability of silicon photovoltaic modules in intermediate precision conditions of measurement†

Dr Mauro PRAVETTONI, Dr Amit Singh RAJPUT

1. Background

Silicon heterojunction (SHJ) technology gained strong interest from solar photovoltaic (PV) module manufacturers and in the global PV market due to its remarkable efficiency potential [1]. However, the presence of an amorphous silicon layer in SHJ solar cells may raise concerns about its stability under light exposure [2-9].

When stored in a controlled indoor ("dark") environment, crystalline silicon (Si) PV devices are generally considered more stable than thin-film devices, which are subject to *metastability*. With this term we refer to the change of the electrical performance to a status with lower (or higher) stable maximum power (P_{max}) when the module is stored in the dark for a prolonged period. The phenomenon is reversible, as PV devices affected by metastability can revert to their original status via light soaking.

Hydrogenated amorphous silicon (a-Si:H) is well known to suffer a form of reversible light-induced degradation (LID) - called the "Staebler-Wronski effect" [2] - which is caused by the recombination-induced breaking of weak Si-Si bonds by optically excited carriers after thermalisation. The effect shows P_{max} degradations of the order of ~10%, and is reversible, as a-Si:H modules slowly recover their original metastable status of higher P_{max} when kept in the dark for a long time (order of months).

The thin-film PV modules of the II-VI group, cadmium telluride (CdTe) and copper indium (gallium) selenide (CIS or CIGS), usually show the opposite light-induced effect than a-Si:H: light soaking is beneficial and increases the performance of CdTe and CIS (or CIGS) modules, while in the dark these PV modules quickly (within a few weeks) relax to a metastable status with lower P_{max}. For CdTe, the metastable status can be ~15% lower than the stabilised P_{max} [10], and this has been explained via various mechanisms, for example copper atoms from the back contact which diffuse across the CdTe layer or the anneal process used in the preparation of the CdTe absorber layer. Some CIS and CIGS modules also benefit from light soaking [11-12], although the metastability effect in these II-VI compounds is highly product dependent. Various possible explanations have been proposed, including the creation and/or neutralisation of metastable defects and the reversible migration of ions under bias during device operation.

2. Scope of project & objectives

In this work, we compare the stability of SHJ modules to the stability of *p*-type and *n*-type homojunction monocrystalline Si PV modules and of a few thin-film PV technologies. The analysis is performed in *intermediate precision conditions of measurement* [13], where the same modules are measured indoors with the same measurement procedure, the same location and equipment, and over an extended period of time, during which the modules are kept in the store and not exposed to light. The results from all tested SHJ modules, which were also confirmed in reproducibility conditions, will show a slow exponential degradation in the dark, which is fully recovered when the module is subsequently light-soaked. With this behaviour, SHJ PV modules shows a metastability that is qualitatively similar to CdTe and CIS (or CIGS).

3. Significance and impact of project

The growing solar PV share in future electricity generation is unquestionable, and all energy outlooks now report PV as a key player in the next decades for the transition towards a zero-fossil-fuel energy system (see for example [14]). When transferred into the manufacturing and deployment phase, the ambitious targets meet, among others, the challenge of accurate and reliable power rating of the PV modules, for which differences of a fraction of a percent mean significant investment gains or losses for the manufacturers, investors, and buyers.

With the excellent passivation properties of a-Si:H, SHJ is considered as one of the most promising PV technologies and is expected to be the fastest growing in terms of world market share [1]. Therefore, understanding its metastability is now urgent for the future of this technology, to understand the potential challenges it poses to the production and qualification of products and to its long-term performance in the field.

4. Methodology

We study the metastability of four commercial SHJ PV modules that have been on the market for the last 10 years and compare it with the known stability of monocrystalline Si homojunction (two *p*-type and one *n*-type) modules and with the known metastability of three thin-film modules (a 2-junction a-Si, a CdTe and a CIS panel): all tested modules are (or were) on the market at the time of production.

The metastability of PV modules can be described with the following exponential function:

$$y(t) = y_{ms}\,[1 - e^{-t/\tau}] \qquad (1)$$

where y(t) is the relative power deviation from the initial stabilised P_{max} value measured at STC, y_{ms} is the maximum relative deviation (positive for regeneration, or negative for degradation) at the metastable status from the stabilised P_{max} and τ is a time constant. The *half-life time* $t_{1/2}$ (i.e. the time required to reach half the metastable status) can be obtained from τ by the known relation:

$$t_{1/2} = \tau \ln 2. \qquad (2)$$

From the literature, we know that CdTe modules and some CIS/CIGS modules generally degrade in the dark to a metastable status, while a-Si:H modules regenerate in the dark (the already cited "Staebler-Wronski effect"). The two *p*-type Si samples of this study (labelled as p-type 1 and p-type 2) and the three thin-film modules (CdTe, CIS and a-Si) were stabilised at the beginning of the study, according to IEC 61215 and technology specific subparts. Initial stabilisation was also performed on

†An extended version of this work is under review for publication in the MRS Bulletin, with the title "On the metastability of silicon heterojunction solar photovoltaic modules".

two SHJ modules (SHJ 3 and SHJ 4, manufactured in 2018 and 2020, respectively), while the older SHJ samples (labelled as SHJ 1 and SHJ 2), have been in store without significant light exposure since their arrival in the laboratory in 2009 and 2017, respectively. (The *n*-type sample was also not stabilised, as this technology is generally considered stable against LID).

5. Results

Figure 1 shows the relative deviations from the initial measurements of P_{max} at STC for the 4 SHJ modules, compared with the other Si samples. The dashed black lines indicate the ±0.75% threshold for the stability of P_{max} in intermediate precision conditions of measurement at STC at SERIS. During the 2-year exercise, the homojunction samples p-type 1, p-type 2 (blue markers) and n-type (green marker) showed random variations that were well within the intermediate-precision threshold. The two initially stabilised SHJ samples (SHJ 3 and SHJ 4, in yellow full dots), instead, showed an exponential drift in relative deviations from the stabilised P_{max}. In contrast, SHJ 1 and SHJ 2 (also in yellow empty dots, and whose data are normalised to the stabilised P_{max} values measured after approximately 260 days), did not show a significant drift (i.e., beyond the threshold of intermediate precision conditions) in the first ~260 days.

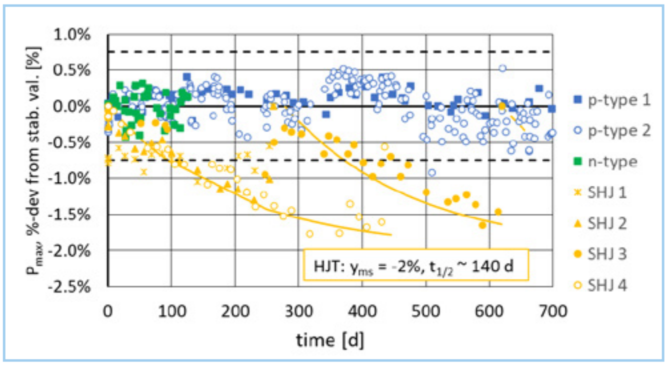

Figure 1. Metastability of commercial SHJ modules (yellow markers) compared to the stability of p-type Si (in blue) and n-type (in green) commercial Si module. The analysis was performed in intermediate precision conditions of measurements; the yellow lines indicate the exponential degradation according to function (1) from the stable to the metastable status.

Two light-soaking cycles of approximately 20 kWh/m^2 were then conducted (one after approximately 260 days for samples SHJ 1, SHJ 2 and SHJ 3, the other after 430 days for SHJ 4). After light soaking, all modules showed the quick power regeneration to the initial stable status. Afterwards, in the dark, the modules restarted their exponential degradation trend (SHJ 3 was further light-soaked for approximately 20 kWh/m^2 after 620 days toward the end of the reporting period). The yellow line of Fig. 1 indicates the exponential degradation model of eq. (1) for P_{max} from the light-stabilised status to the metastable status in the dark, with y_{ms} ~ 2% and $t_{1/2}$~140 days.

In Fig. 2 the observed drift of SHJ samples is compared to the known drift of the metastable thin-film samples CdTe, CIS and a-Si. The red lines indicate the degradation trends according to eq. (1) to the metastable status in the dark for the tested CIS sample (y_{ms}~ -9%, with $t_{1/2}$ ~ 90 days) and for the CdTe sample (y_{ms}~ -13%, with $t_{1/2}$ ~ 21 days), and the regeneration trend in the dark to the metastable status for the a-Si sample (y_{ms}~+4%, with $t_{1/2}$ ~ 70 days). Figure 2 highlights how small the metastability drift of SHJ modules is in comparison to the investigated thin-film PV modules.

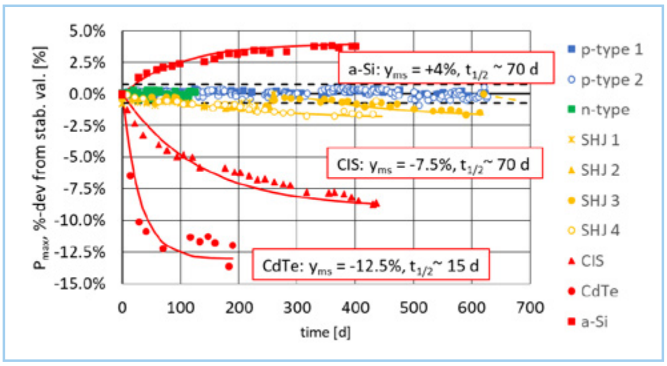

Figure 2. Comparison between the observed metastability of SHJ modules and the known metastability of thin-film PV modules. The continuous lines indicate the interpolation according to the exponential function of eq. (1).

6. Conclusions

In this work we analysed the metastability of SHJ PV modules when stored in the dark for long periods of time. We compared it to both the stability of homojunction Si modules and the well-known metastability of thin-film PV modules (CdTe, CIS, a-Si) for the same period. The analysis was performed in intermediate precision conditions of measurement. The results showed that the relative deviations from the initial measurements of P_{max} at STC exceed the acceptable limits of stability for Si modules in intermediate conditions of measurement, indicating a metastable status. However, these deviations are shown to quickly recover after light soaking to the initial values of P_{max} at STC, reshaping the behaviour of thin-film PV technologies like CdTe and CIS, but with less severity and at a slower rate. As such, the observed metastability of SHJ modules benefits from light exposure and thus does not represent a concern for the stability of their outdoor operation in the field. However, care should be taken in the quality processes of the SHJ module production lines and in qualification and type approval tests, as both require stable reference or control modules that are usually kept in the laboratory for many months.

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Selected R&D Project

Real-world assessment of different solar PV module types and structures for Urban Farming applications in Singapore

Haresh PANDIAN, Dr Thomas REINDL

1. Background

As a city-state with limited land resources, Singapore is largely dependent on other countries for its food supplies. The recent pandemic has further shown the constraints of global supply chains, which also affected food deliveries to Singapore. Therefore, to make its food supply more resilient, policies have been rolled out to support more home-grown food sources, with the overall aim to achieve 30% of nutritional crops grown locally by 2030 ("30-by-30" programme), as documented in the SG Green Plan (https://www.greenplan.gov.sg/). In parallel, Singapore also wants to become more sustainable in its energy supply. As a densely built-up city-state in the tropics, solar photovoltaics (PV) is the most viable form of renewable energy generation. The SG Green Plan also sets out ambitious local solar deployment targets of 1.5 GW_p by 2025 and at least 2 GW_p by 2030. With both agriculture and solar PV deployment requiring large areas (be it land or rooftops), this project focuses on the combined use of the same areas for crop growing and renewable energy generation. This is also known as "agrivoltaics".

Innovative ways for agrivoltaics structures have been proposed in the literature and implemented around the world. Those range from over-arching crops with semi-transparent PV modules (typically using crystalline silicon solar cells that are spaced apart from each other to allow sunlight to go through the cell gap regions of the glass-glass laminates and thus reach the plants) to solar-powered greenhouses and vertical structures in-between rows of crops.

To support Singapore's 30-by-30 programme and maximise land use, agrivoltaics also has come to the forefront of innovation here. Several groups at universities, institutes, and polytechnics in Singapore are working on novel approaches to conjointly optimise crop harvest and solar energy yield, with applications targeting both land-based as well as soil-less urban rooftop farming.

2. Scope of project & objectives

SERIS has been working on the combination of solar PV with agriculture since 2019, initially by powering a container-based farming testbed at the National Junior College (NJC) with solar PV. Recently, SERIS has teamed up with the Singapore Discovery Centre (SDC) to implement a land-based agrivoltaics testbed on SDC's premises.

The testbed features two different PV module types and structural set-ups. One set-up uses standard crystalline Si modules (opaque) which are mounted on a rack that is designed in a way so that the solar roof can be shifted by up to approximately 1 m apart, which then allows to test the plant growth under various sunlight conditions, e.g., purely diffuse light (when the roof is closed) and various degrees of direct & diffuse light (when the roof structure is opened more and more). The other section of the testbed uses a fixed roof structure, however with semi-transparent glass-glass modules that provide a permanent 50% sunlight transmission.

The testbed also aims to understand in what form the transpiration of crops creates a microclimate, and whether that could potentially lead to a cooling effect for the PV modules, which in turn would lead to a higher annual energy yield.

3. Significance and impact of project

The aim of the research is to compare the crop harvest results under different growth conditions and for various types of crops, which in turn will allow relevant stakeholders to make informed decisions on which would be the best approaches for investments into agrivoltaics in Singapore.

4. Methodology & Results

The agrivoltaics testbed was designed to have six individual aluminium structures for each PV module type. All modules are installed in a north-south orientation (in parallel with the existing plant rows of the earlier farming set-up) with a tilt angle of 10° and a ground clearance of 3 metres at the lower edges.

The opaque monocrystalline silicon PV modules (REC Alpha Series, REC355AA with 355 W_p) are installed on structures that can be opened horizontally to allow direct sunlight reach the crops and to manage environmental effects such as rain and heat on the ground. The opening distance can be varied from 0 m to 1 m.

In contrast, the structures for the semi-transparent PV modules (Xiamen Optimum Sun Energy Co., #PSG160 with 160 W_p) are fixed. The modules are made of multicrystalline silicon solar cells in a glass-glass configuration whereby the distances between the individual solar cells were chosen to provide a transparency of 50%.

As an initial experiment, temperature measurements were collected over a period of time (6 April to 9 May 2022) to determine the operating conditions of the PV modules under shaded and non-shaded conditions arising from nearby trees.

SketchUp modelling and sun-path analysis was used to simulate the irradiance conditions on the solar modules. As can be seen in Figure 1, there is significant shading from the trees surrounding the existing farming set-up.

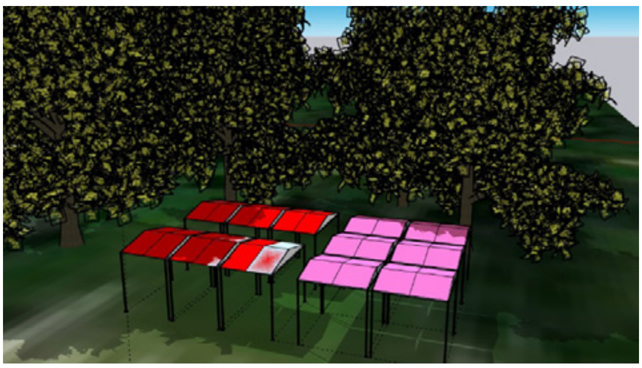

Figure 1. Sketch-up model of the agrivoltaics testbed at SDC, showing the shading effect from the surrounding trees during the measurement period (example here: 3 pm on 3 May). The moveable opaque modules are coloured in red, while the pink ones are the semi-transparent fixed modules.

The data show that under non-shaded conditions the temperatures of the opaque PV modules reach 50.4°C (see Figure 2), while the temperatures of the semi-transparent glass-glass modules even reach 60°C (see Figure 3). Under shaded conditions, both types of PV modules operate at ~40°C, i.e. ~10°C and ~20°C cooler than for the non-shaded conditions. The assessment of the impact of the different module temperatures on their energy yields is ongoing.

5. Conclusions

The newly established agrivoltaics testbed at the Singapore Discovery Centre (SDC) tries to better understand the impact on the crop growth when installing solar PV modules over agriculture land. This would greatly enhance the knowledge about the possible applications in Singapore. The overall aim is to concurrently support two goals of the SG Green Plan: sustainable locally grown food and green electricity generation on the same plot of land. The agrivoltaics testbed is affected by shading from the surrounding trees, due to the previously existing farming layout. This shading reduces the amount of sunlight that reaches the PV modules and the crops, but it also significantly reduces the operating temperatures of the PV modules. This external shading effect also dominates any potential cooling effect from the evapotranspiration of plants on the PV modules.

A number of experiments are ongoing, and the results will also influence the design and implementation of SERIS' next agrivoltaics testbed, which will follow a soil-less concept as part of the Yuhua Agri-Solar Living Lab that is being established on the open top-floor of a Housing Development Board (HDB) carpark.

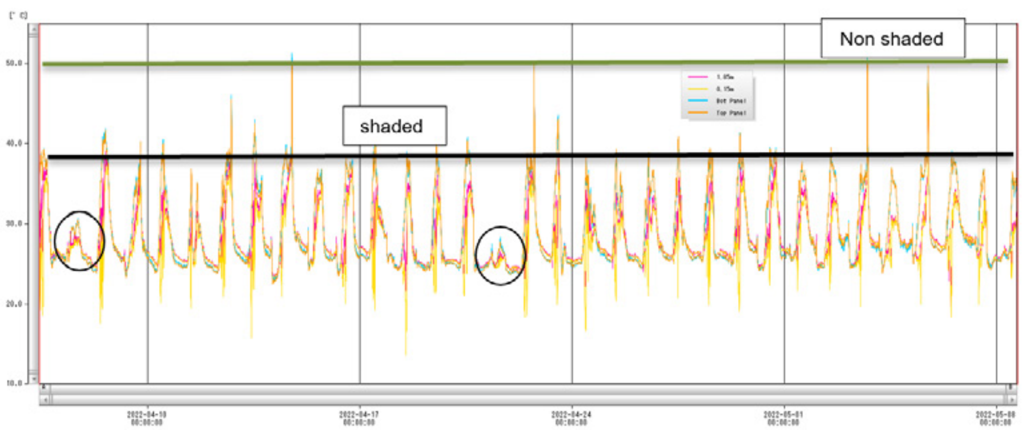

Figure 2. Temperatures of the opaque PV modules from 06 April to 09 May 2022. Black circles represent the temperature during heavy rain, the black and green solid lines indicate typical temperature values for shaded and non-shaded conditions, respectively.

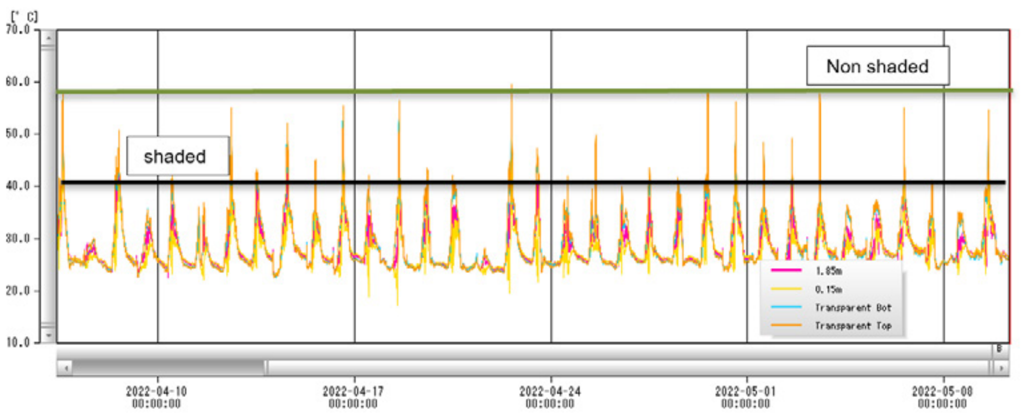

Figure 3. Temperatures of the semi-transparent PV modules from 06 April to 09 May 2022. The black and green solid lines indicate typical temperature values for shaded and non-shaded conditions, respectively.

Selected R&D Project

Planning and design tool for building integrated photovoltaics (BIPV) in high-density urban environments

Dr SUN Huixuan, Dr Thomas REINDL, Prof HENG Chye Kiang

1. Background

In Singapore, a densely built-up city-state in the tropics, solar photovoltaics (PV) is the only viable form of renewable energy generation. As part of its SG Green Plan, the government has therefore set ambitious deployment targets of 1.5 GW_p by 2025 and at least 2 GW_p by 2030 [1]. Given the scarce land resources and the high degree of urbanisation, building integrated photovoltaics (BIPV) on the envelopes of buildings is a very promising option to increase the deployment areas for PV. The 2020 Update of the Solar Roadmap for Singapore identified 9.8 km^2 net usable façade areas for BIPV deployment [2]. However, in contrast to rooftop installations (which are hardly seen from the street level), façade-integrated PV systems need to be visually appealing in order to gain social acceptance. Therefore, besides optimal energy generation, the visual impact of PV installations on façades also has to be assessed to enable architects and urban planners to make informed decisions both on building- and neighbourhood levels.

While standard PV modules often come with a negative visual connotation, novel BIPV technologies that are available in different colours, designs and shapes ('aesthetic BIPV') are not only able to preserve the existing appearance of building facades (e.g. by mimicking traditional construction materials such as marble, bricks or wood) but can even be used as design elements to create a positive visual impact or enhance the appearance of the building or neighbourhood. In this work, we develop an *objective* and quantifiable methodology for the visual impact assessment (VIA) using computer vision techniques to substitute the conventional, time-consuming *subjective* VIA methods that are largely based on questionnaires and surveys.

This research is supported by the National Research Foundation, Singapore and the Singapore Economic Development Board (EDB) under its "Holistic LCOE reduction for distributed solar PV systems in Singapore" project grant (NRF2015EWT-EIRP003-007).

2. Scope of project & objectives

This work aims to develop a BIPV planning and design tool that is able to: a) assess the feasibility of BIPV on building façades with the two key criteria of energy yield and visual impact; b) objectively quantify the visual impact of BIPV using computer vision techniques; and c) propose optimal BIPV design strategies.

3. Significance and impact of project

The BIPV planning and design tool developed in this research can provide guidance for architects, urban planners, and PV experts at the preliminary design stage. The proposed objective visual impact methodology is expected to lead to higher social acceptance of BIPV deployment on building facades. It also greatly reduces the time and labour costs of the design process, which in turn should further increase the likelihood of BIPV adoption.

4. Methodology & Results

A comprehensive mapping tool is proposed to evaluate the feasibility of BIPV applications, by introducing a quantitative visual impact assessment, in addition to the traditional energy yield projections.

First, a solar irradiation analysis of the building envelope is conducted, based on which qualified building surfaces for BIPV deployment are identified. For the case of Singapore, the following minimum thresholds for the annual solar irradiation were used: 1,500 kWh/m^2 for rooftops and 500 kWh/m^2 for façades [2]. The visibility analysis of each building surface is conducted from the viewpoints of simulated pedestrians at the street level based on line-of-sight. Subsequently, the visibility assessment is overlaid on the 3D solar irradiation map to identify and visualise the most suitable building surfaces for BIPV applications. In parallel, an objective VIA approach is developed based on saliency mapping, a computer vision technique predicting human visual attention to identify the visual impact of hypothetical coloured BIPV retrofits (classified as positive, neutral, or negative).

Orchard Road, the main commercial boulevard in Singapore was selected to represent a modern urban context in Southeast Asia. Both rooftop and vertical facade areas were assessed in this study.

The solar irradiation simulation of building surfaces is conducted with the software tool Grasshopper using two environmental plug-ins, namely, Ladybug for importing EnergyPlus weather files and providing 3D interactive graphics, and Honeybee for enabling parametric simulation and results visualisation by linking Radiance to Grasshopper. Based on the modelling of blocks and vegetation, building surfaces of the developments along Orchard Road are determined as target surfaces, which are subdivided into 3 m x 3 m grids. Annual solar irradiation is simulated based on the cumulative sky matrix.

Visibility analysis is conducted in Grasshopper with 400 viewpoints evenly distributed along the sidewalk boundaries at a viewing height of 1.5 metres. Given no upper limits to the field of view and viewing distance, a binary result is obtained for each viewpoint which determines whether a target surface is visible or not. For each target surface, the visibility is calculated as the frequency of being observed by the defined viewpoints:

$$(1) \qquad Visibility_{building\ surface} = \frac{A_{visible}}{Total\ number\ of\ viewpoints}$$

A mapping tool is generated by combining the above-mentioned visualisation results. The results of overlaying the visibility mapping onto the solar irradiation mapping are shown in Fig. 1.

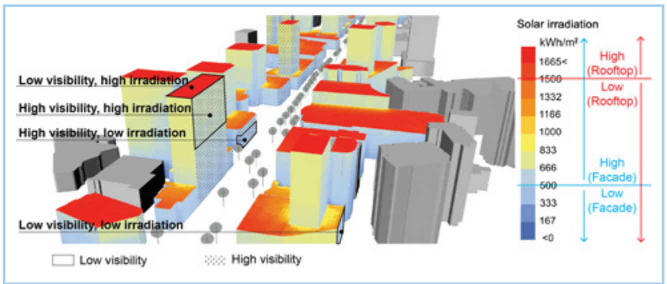

Figure 1. Multi-layer mapping tool assessing visibility and annual solar irradiance of building rooftops and facades [3]

Furthermore, the objective VIA methodology using saliency mapping is applied to predict the visual impact of coloured BIPV. In the pre-processing stage, for a target building frontage, street views from different viewpoint locations (same side, opposite side, street corners) can be obtained from Google Street Views, a publicly accessible online source. Processed images with hypothetical coloured BIPV can then be generated for each original street view.

In the processing stage, the visual impact is assessed as the visual attention change resulting from the introduction of coloured BIPV. For each original and processed street view, saliency maps are computed with each pixel indicating its conspicuousness within the human view on a scale of 0 to 1. Saliency change, the difference in saliency values between the original street view and the corresponding processed image, is computed for each pixel. A delta saliency map can then be generated by highlighting the pixels in white, which has a saliency change higher than 0.1 (Fig. 2). The objective metric, 'S value' is calculated to measure the strength of the visual impact of BIPV:

$$(2) \qquad S = 1000 \times ST_{t=20\%} \times ST_{t=10\%} \times Max_{delta\ map}$$

where $ST_{t=10\%}$ = the threshold for the top 10% saliency changes, $ST_{t=20\%}$ = the threshold for the top 20% saliency changes, $Max_{delta\ map}$ = the maximum of saliency changes.

Image Signature [4], a bottom-up saliency model with colour as one visual feature is applied for the objective VIA, the prediction results of which have been validated by a subjective visual impact assessment. The validation results indicated coloured BIPV with a higher S value tends to result in negative visual impact, and 30 can be applied as the threshold of the S value to classify negative and positive visual impact. Furthermore, the optimal colour options can be determined whenever coloured BIPV produces a positive visual impact in all selected street views (see Fig. 3).

Taking a building located at a street corner as an example, the process of the objective VIA is described in Figure 4. First, four street views captured from different viewpoints are selected for analysis. Second, processed images are generated by overlaying a coloured translucent layer on the curtain wall area. Third, Delta saliency maps and objective metrics are computed as the results of the objective VIA. Fourth, the visual impact of BIPV in each street view is classified by comparing the S value with the threshold. Lastly, the determination of the optimal colour option is completed.

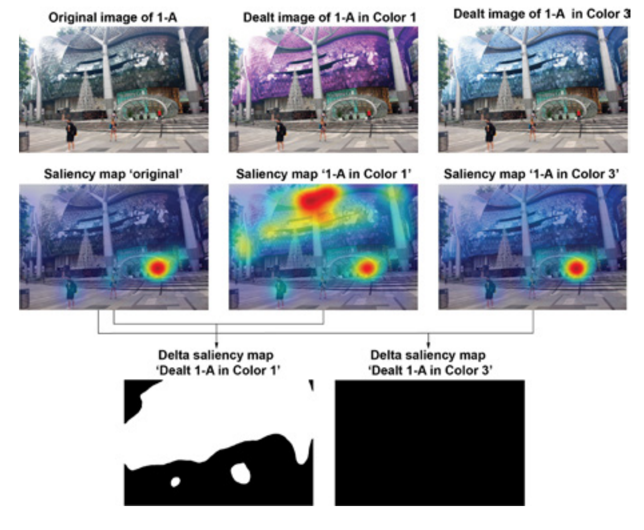

Figure 2. Delta saliency map as the visualisation result of the objective VIA [5]

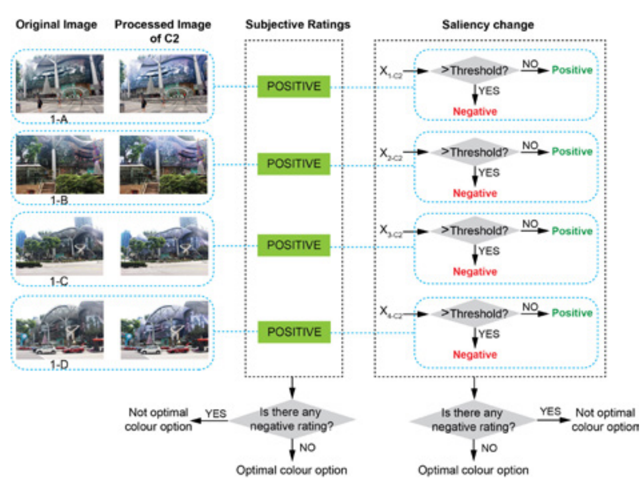

Figure 3. Determination of optimal colour options through the proposed objective visual impact assessment (VIA) that is validated through a subjective VIA [5]

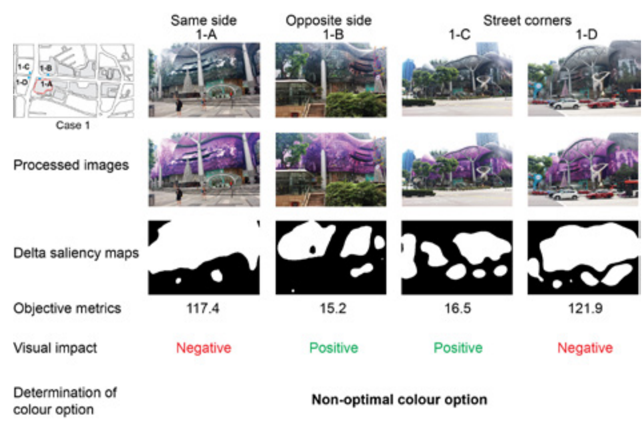

Figure 4. Process of objective VIA using saliency mapping

5. Conclusions

In view of the promising prospects of 'aesthetic BIPV' on building facades in densely built-up urban environments, this research proposes to assess the feasibility of BIPV applications with the criterion of visual impact in addition to energy yield. Saliency mapping, a prevailing computer vision technique that predicts human visual attention, is applied in the proposed objective approach as an alternative to the traditional subjective visual impact assessment. The quantitative feasibility assessment process developed in this research could be instrumental for enabling an objective, yet fast and efficient evaluation of design options for architects and urban planners in their strive to make buildings and neighbourhoods more sustainable.

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Selected R&D Project
Effects of ‘invisible’ energy storage on power system operations

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

1. Background

Energy storage systems (ESSs) are becoming more common across the world, largely due to their rapidly declining prices, and the benefits they can bring to power system operators (as part of grid management) and asset owners for grid support services, or for variability management when combined with renewable energy generators such as wind and photovoltaic (PV) systems. Many works have investigated the impacts of coordinated (utility-scale) ESSs on power system operations and electricity markets. At the same time, benefits of distributed ESSs for consumers through reducing demand charges and electricity bills, as well as increasing consumers’ self-sufficiency have been well documented.

However, the impacts of ‘invisible’ behind-the-metre ESSs on the transmission system operations and electricity markets are still largely unknown. PV and ESSs are considered invisible when they are installed behind the metre and are not registered with the power system operator (PSO). By definition, they are not curtailable or dispatchable. The PV and ESS outputs are netted out with the on-site loads and hence the PSO can only “see” the resulting net effects.

This research is 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” (grant NRF2017EWT-EP002-004).

2. Scope of project & objectives

In this project, the impacts of “invisible” ESSs on transmission system operations and electricity markets are analysed in detail. In particular, this project sheds light on the impacts of invisible ESSs on net demand, generation compositions, ESS owners’ electricity bill, energy generation and reserve costs, and electricity price.

3. Significance and impact of project

Studying the impacts of invisible ESSs is of critical importance for PSOs since they are becoming more and more prevalent in countries like Australia and Germany, In 2019, the International Renewable Energy Agency (IRENA) predicted behind-the-metre ESSs to make up more than half of the globally installed ESS capacity in 2030.

Similar to how the “duck curve” phenomenon occurred faster than predicted due to rapidly rising PV penetration, the invisible ESS impacts analysed here may also be closer than anticipated, and PSOs may not realise the presence of invisible ESSs until too late.

To the best of the authors’ knowledge, this study is the first to investigate the impacts of invisible ESSs on the transmission system operations. The results of the study can help regulators make informed decisions about policies related to ESSs and their combination with PV systems. Moreover, the proposed optimisation method can be used by PSOs to investigate the impacts of invisible ESSs on their respective networks, especially since the impacts depend heavily on the power system characteristics.

4. Methodology & Results

Two levels of optimisation were investigated for their impacts of invisible ESSs. The upper level adopts the perspective of the PSO who aims to minimise energy generation and reserve provision cost through unit commitment and economic dispatch (UCED) optimisation. The lower level adopts the perspective of the end-consumers who have PV and ESSs and aim to minimise their electricity bill by optimising the ESS (dis)charging schedule according to their net load profile, and the prevailing electricity price or tariffs. While the PSO is optimising the whole power system centrally, each consumer is minimising their own electricity bill independently of other customers.

Different ESS and PV penetrations, from 0 to 100% in steps of 20%, were simulated. The PV and ESS penetration levels were calculated by dividing the PV and ESS installed capacity, in [MW_p] and [MWh] respectively, by the peak load [MW] without PV and ESS. The optimisations were formulated and analysed using the software tool GAMS 28.2.0, employing a 24-bus IEEE reliability test system, Singapore real weather data measured by SERIS, and Singapore electricity price data.

There are four main insights from this project:

1. Invisible ESSs substantially increase the volatility of net demand, ramp rate requirement, and electricity price.
2. Main contributors to the increased volatility are customers who have access to wholesale electricity price (with multiple price peaks and nadirs for ESS energy arbitrage).
3. The costs that invisible ESSs incur to the transmission system can be greater than the benefits they bring to the ESS owners.
4. Without mitigating measures, invisible ESSs have the potential to increase the share of fossil fuels in the electricity mix.

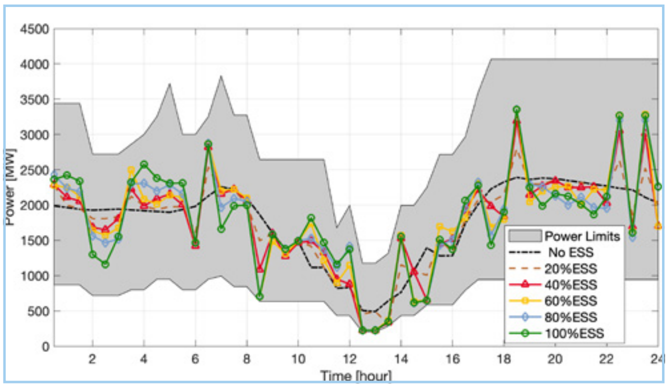


Figure 1. Total net demand at 100% PV penetration

The results are illustrated in Figs. 1 to 3. Figure 1 shows the net demand of the system at 100% PV penetration for different ESS penetration levels. It can be observed that the higher the ESS penetration, the further away the net demand is from the original net demand without ESS, and the closer the net demand is to the power limits of the committed generators. The ramp rate requirement is also increased with increasing ESS penetration, rendering the system more vulnerable to sudden disturbances or contingencies.

The net demand volatility is mainly caused by the industrial consumers (with access to wholesale electricity price) performing energy arbitrage. As a result, the benefits (in the form of electricity bill reductions) are mostly reaped by the industrial customers. Unlike the benefits, the costs of invisible ESSs to the power system do not always increase with increasing ESS penetration. And although the benefits only increase somewhat linearly, the costs are rising exponentially as depicted in Fig. 2, highlighting the complexity of invisible ESS impact and the criticality of the issue.

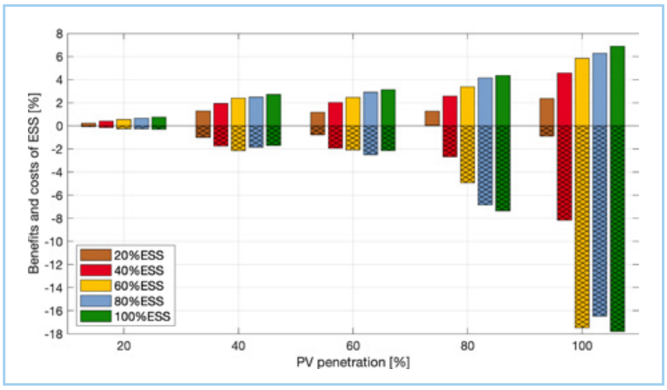


Figure 2. Benefits and costs of ESSs at different PV penetration levels. The benefits are in the form of electricity bill savings by ESS owners, represented by the solid bars. The costs are in the form of increased system energy and reserve costs, represented by the cross-hatched bars.

As the net demand of the system changes, so does the generation composition fulfilling the net demand. Figure 3 shows the evolution of the generation composition for the different PV and ESS penetrations. From the figure, it is evident that as ESS penetration increases (across all PV penetration levels), the shares of hydro and flexible thermal power generation decrease, while those of coal and oil increase. The decrease in hydro and flexible thermal occurs because of (1) increased flexibility requirement and they are the generators with the most flexible up and down time, and (2) hydro and flexible thermal are the most cost-effective electricity sources in the system, so they are already producing at maximum power for all periods when there are no ESSs. Therefore, their power outputs can only decrease when there is a reduction in net demand. Yet, when the net demand increases because of ESSs, the increase is fulfilled by coal and oil generators which are still not operating at maximum power yet. Since hydro and flexible thermal are the cheapest electricity sources in the system, a reduction in their market share leads to an increase in power system operation costs, as shown in Fig. 2.

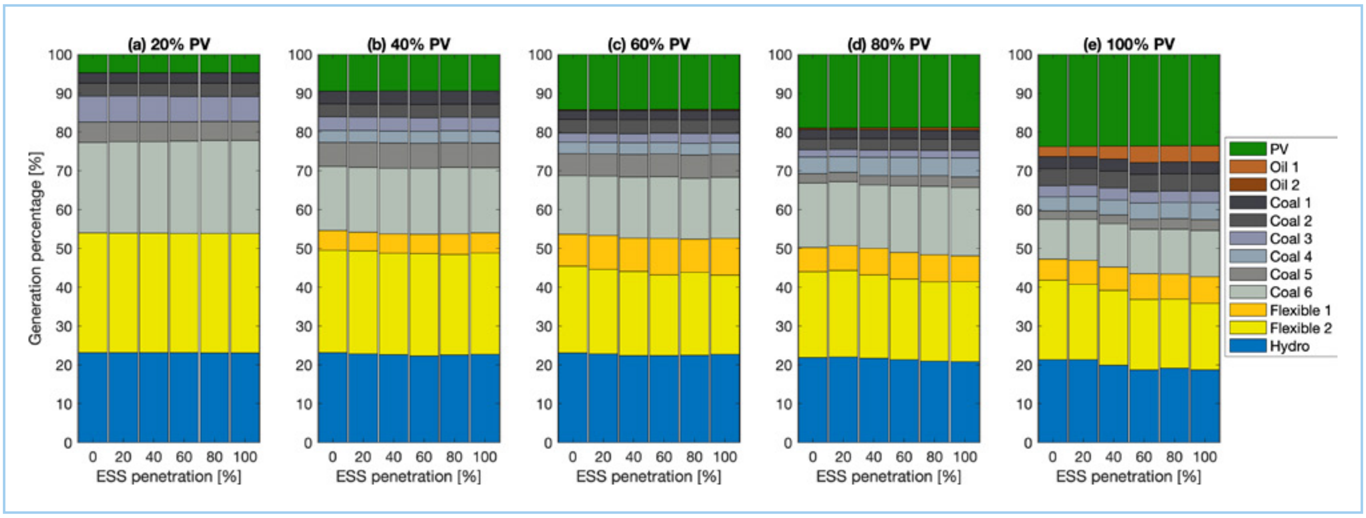


Figure 3. Generation composition for different PV and ESS penetration levels

5. Conclusions

Behind-the-metre ESSs, which are invisible to the PSO, have been growing rapidly in many parts of the world and will continue to do so as the prices for ESSs keep falling. The rise of invisible ESSs has the potential to make power system net demand more volatile and increase the ramping requirement. Consequently, power system generation cost may rise with increasing invisible ESS penetration, even more than the benefits experienced by the ESS owners. Extreme electricity prices also become much more common with increasing PV and ESS penetration.

In light of these findings, regulators and PSO should prepare for the inevitable rise in invisible ESSs and formulate measures to mitigate the negative impacts while enhancing the positive ones, for instance by imposing peak demand charge to prevent extreme hikes in demand and incentivising a smoother demand curve.

Selected R&D Project
The TruePower™ Alliance: preliminary findings

Dr Carlos RODRÍGUEZ, Dr Thomas REINDL

1. Background

The TruePower™ Alliance is a multi-stakeholder project led by the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) to assess the uncertainties associated with predicting the electrical performance of photovoltaic (PV) modules and systems in different climate zones. Varying climate and weather conditions - such as temperature, humidity, irradiance, spectrum and direct-diffuse ratio - as encountered in different regions of the world can influence the electrical performance of commercial PV module technologies in different ways.

2. Scope of project & objectives

Standard Testing Conditions (STC) define a single set of values for irradiance level, device temperature and spectrum to determine the nominal electrical performance data of PV devices. However, the real-world conditions experienced by PV modules and systems in various climate zones can vary considerably from STC, and hence the standard tests provide only a rough estimate of how the various PV technologies will perform in actual field conditions. Thus, as a part of the TruePower™ Alliance, we aim to measure the electrical performance of PV modules supplied by our project partners on both module and system level with highest possible precision. SERIS operates four outdoor test sites where the exact same PV technologies and installation designs (with the exception of the optimum PV orientation and tilt angle, which is dependent on the location) have been applied to enable an equal-to-equal comparison of the same PV technology across different climates. The climates and locations of the testbeds (see also Figure 1) are:

- Desert climate: Australia
- Temperate I climate: Germany
- Temperate II climate: China
- Tropical climate: Singapore

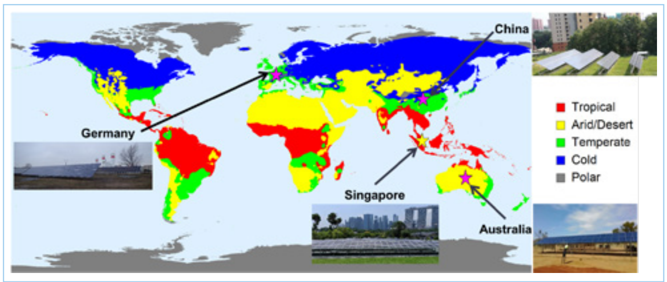


Figure 1. Location of the 4 TruePower™ sites

From the range of different solar cell (various c-Si technologies, CIGS, CdTe) and module types (e.g., glass-backsheet, glass-glass packaging), in this work we will focus on one selected Si-based PV technology (the manufacturers cannot be named here due to confidentiality reasons).

3. PV system performance

As a first step, we discuss the daily average peak sun-hours (defined as the equivalent number of hours assuming an irradiance of 1000 W/m²) reaching the tilted PV module surface at each site (see Figure 2).

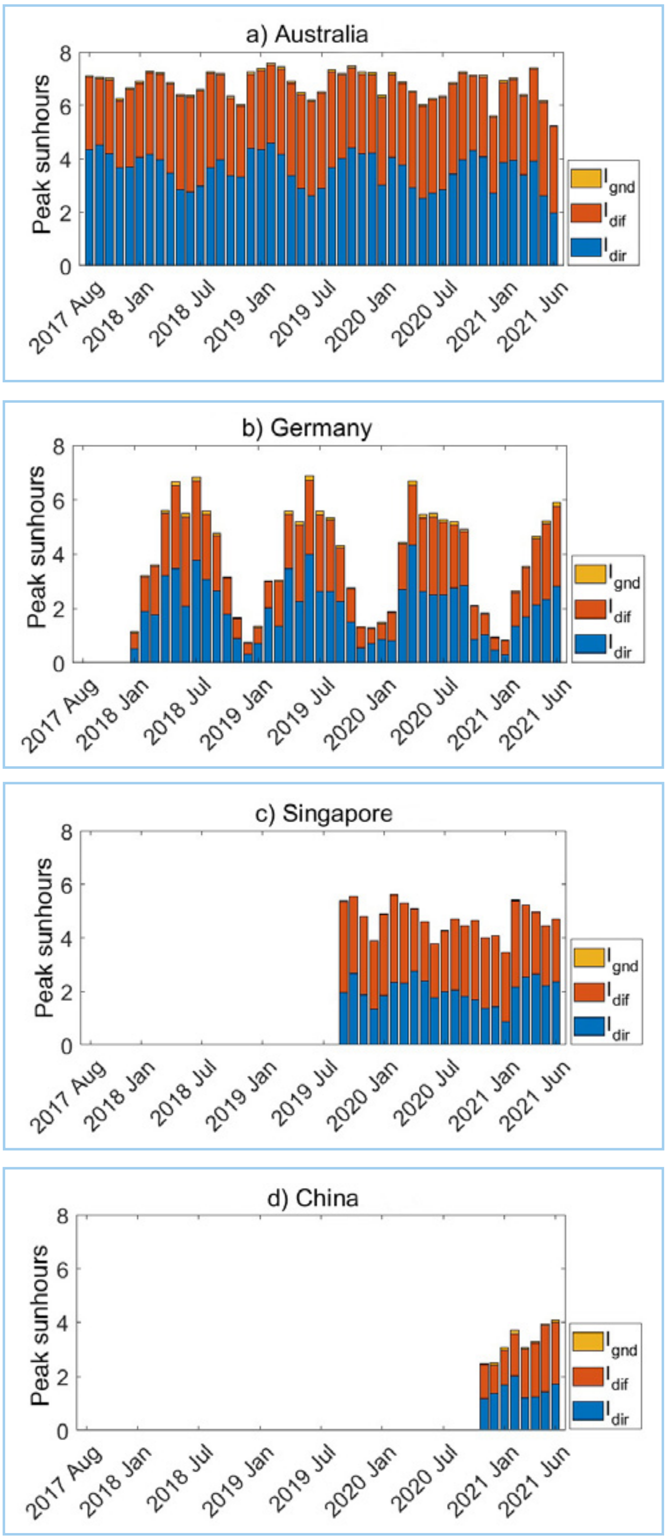


Figure 2. Irradiance characteristics of the 4 test sites.

This is split into the 3 components direct irradiance (I_{dir}), diffuse irradiance (I_{dif}), and ground irradiance (I_{gnd}). It can be seen that the Australian site receives the largest total irradiance and also has the highest share of direct irradiance (with an average of 52%), while Singapore shows the highest share of diffuse irradiance (with an average of 57%). In the case of the Germany site, considerable monthly variations in the sun-hours reflect the higher degree of seasonality (with clear winter and summer seasons). The China site was only commissioned in late 2020 and thus far shows lower irradiance values compared to the other locations. The following will discuss how the different environmental conditions affect the PV performance in each site.

With respect to the electrical performance, in this work we present the average daily specific energy yield for the selected crystalline silicon PV module technology, whereby we measure their properties at two different levels:

- Module level: Single panels individually connected to a MPPT tool that is also used for SERIS' outdoor module testing (OMT) services.
- System level: A group of panels forming PV strings connected to a grid-tied inverter where we measure the DC input power injected into the inverter (referred as "DC system") as well as the AC output power ejected from this same inverter (referred as "AC system").

The results (see Figure 3) show a similar trend between the module and system levels. It can also be seen that the Australian site reaches the highest values throughout the year with a daily average of 5.5 Wh/W_p (equivalent to an annual specific yield of 2,008 kWh/kW_p), with little seasonality.

In the case of the German site, as expected, there are considerable variations in energy yield between summer and winter (with a factor of 6 between highest and lowest months). While top values are similar to Australia, in winter the daily yield can be as low as ~1 Wh/W_p. Annual average for the daily yield on that particular site in Germany is 3.3 Wh/W_p (equivalent to an annual specific yield of 1,205 kWh/kW_p). For the case of Singapore, there is little seasonality and the average daily yield is 3.6 Wh/W_p (equivalent to an annual specific yield of 1,314 kWh/kW_p). It is noted here that the share of the diffuse irradiance in Singapore is quite high due to the tropical climate conditions. The testbed in China showed thus far (less than 12 months) the lowest energy yield among the four test sites (2.8 Wh/W_p) and analyses regarding the most influential weather parameters there are ongoing. The data of all sites are still being further analysed and cross-referenced.

4. Conclusions

This brief report provides an initial discussion of the measured data from our four TruePower™ test sites. Key aspects on the prevailing weather conditions in each location and how these affect the electrical performance of a standard c-Si PV technology are presented. The team is currently preparing a detailed manuscript for a journal publication which will include further discussions on the different weather parameters as well as a detailed investigation on the long-term PV performance of several PV module technologies, including factors such as energy yield loss analysis and PV power degradation.

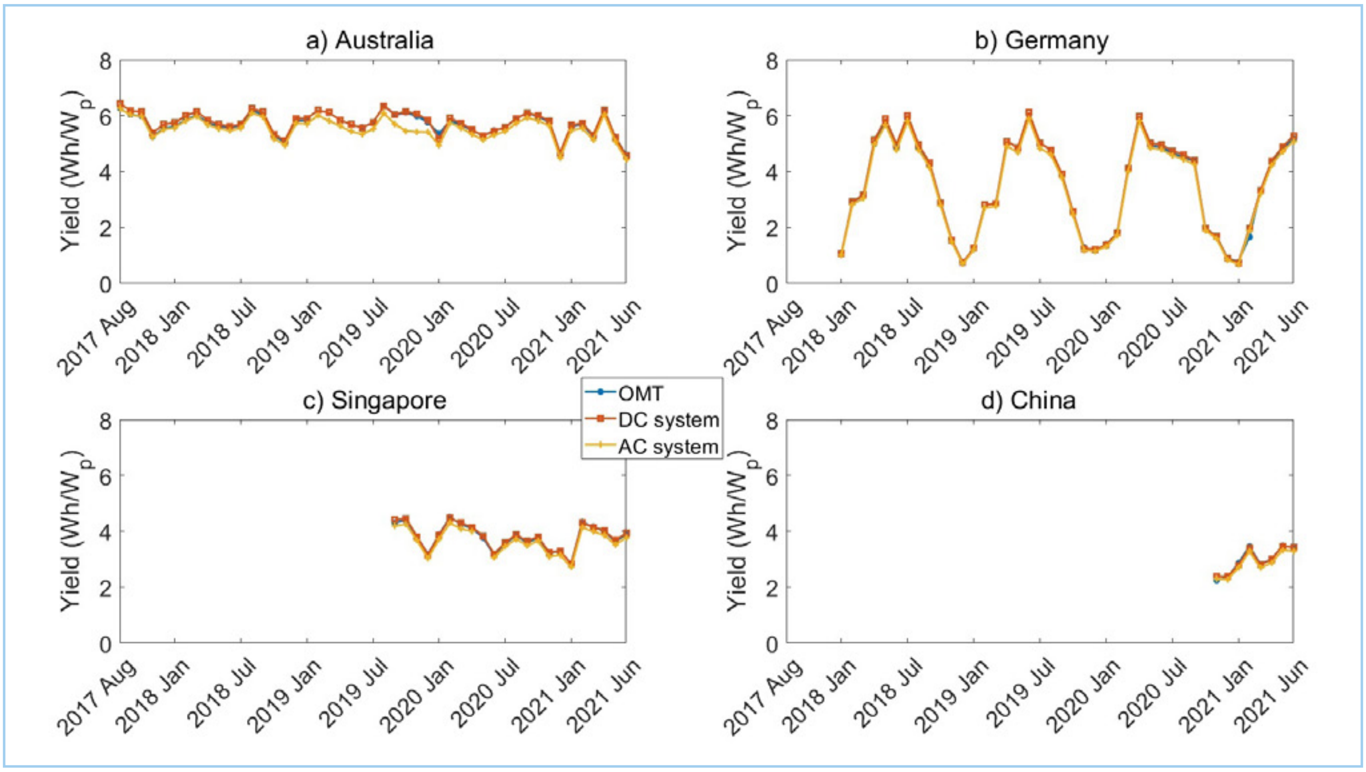


Figure 3. Daily average specific energy yield of one selected c-Si PV technology in the 4 TruePower™ test sites

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.

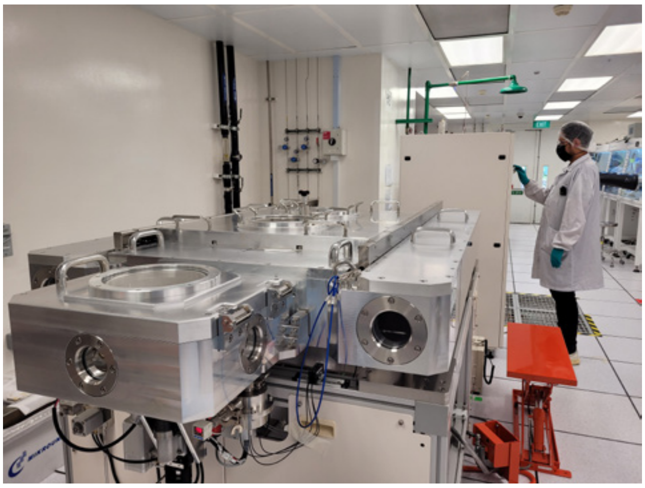
Several compartmental gloveboxes in the Perovskite Laboratory dedicated to various processes such as synthesis, deposition, metallisation and characterisation of perovskite materials and solar cells.

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 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. Two additional units of gloveboxes are dedicated to specific processes -

i. sample preparation for the thermal evaporation system,
ii. encapsulating and testing of samples - and house equipment such as a solar cell I-V tester and a UV curing encapsulation system.

Thermal Evaporation System (Angstrom Engineering)
This thermal evaporator is used for the deposition of metallic, organic and other functional thin films (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 (RADAK 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 cryogenic pump (high vacuum stage, < 10^{-6} Torr). Furthermore, the vacuum chamber has a rotating substrate holder and uniformity shutters 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 program, capable of running automated (PID-controlled) and finely-tuned processes from the PC setup or remote access.

Low-Damage Low-Temperature Sputtering System
This sputtering system is designed with low-temperature processing capabilities, which enables the deposition of high-quality thin films (ITO, TiO_x, NiO_x) with minimal damage to the sample's surface. The tool is able to process various substrates (glass, silicon) with sizes up to 166 mm x 166 mm.



Other equipment for processing and device integration:
- X-Ray diffraction bench-top unit (Malvern P.)
- Semi-automated wafer bonding system (EVG)
- Chamber furnace (Protherm)
- UVO Cleaner (Jelight)
- Fume hoods
- Humidity chamber for sample testing (Memmert)
- Inert encapsulation system

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

SILICON SOLAR CELL LABORATORY

The silicon solar cell research laboratories at SERIS are located on levels 1 and 2 of the E3A building, NUS campus. Industrial tools with high throughput ranging from 100 to 3600 wafers per hour are used to enable industry-relevant solar cell R&D using monocrystalline silicon wafers with a size of up to M4 (i.e. 161.7 mm x 161.7 mm).

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 with M2 and M4 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 M6 wafer size). 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 M6 size). 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 various chemical vapour deposition tools that can deposit thin films of several different materials with thicknesses ranging from a few atoms thick to several hundred nanometres.

APCVD (5K6-BSG-PSG-SI/ Schmid Thermal Systems, USA)
Atmospheric pressure chemical vapour deposition (APCVD) is an inline method for depositing SiO_x, phosphorus-doped SiO_x (PSG), and boron-doped SiO_x (BSG) layers onto Si wafers in a single-sided process.

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, Germany 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 (350-550ºC). The machine can deposit silicon nitride, silicon oxide and aluminium oxide layers on large silicon wafers (M2 - G12).

Spatial ALD tool (InPassion LAB / SoLayTec, Netherlands)
The InPassion LAB ALD tool from SoLayTec is a pioneering R&D system developed for the deposition of Al_2O_3 films using spatial atomic layer deposition (ALD) technology, where precursors are separated in space rather than in time. The deposition of Al_2O_3 films aims to improve surface passivation of Si solar cells to boost cell efficiencies as well as pave the way for new and advanced solar cell concepts. Further, SERIS and SoLayTec are jointly implementing an upgrade of this tool to include the deposition of intrinsic ZnO, Ga-doped ZnO, Al-doped ZnO and SnO thin films by spatial ALD for the development of transparent conductive oxides or transparent metal oxide applications in high-efficiency, large-area perovskite-silicon tandem solar cells.

Versatile Tube furnace #2 (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, as well as annealing of ion implanted samples.

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 both single-junction silicon solar cells and tandem devices with silicon bottom cells.

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 the PV sector. 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 cell applications, including contact opening, selective mask processing or edge/junction isolation, wafer drilling, wafer cutting, and laser marking for tracking purposes.

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.

Solar Cell Metallisation Lab 2B:

> This laboratory is aptly named as it facilitates the metallisation of different types of solar cells. It has multiple tools for different metallisation processes, suited for both high-temperature and low-temperature applications.

Inline Plating Tool (DPL-CPL 110 / Meco Equipment Engineers, Netherlands)

The Meco inline plating tool is a versatile system for pilot-scale R&D on plated metallisation of solar cells. It is equipped with a vertical wafer transport mechanism and process channels for nickel, copper, tin and silver plating. Plating of nickel and copper may be carried out in either the light-induced plating (LIP) mode or the electroplating mode. A novel contact flipping mechanism enables an inline transition between LIP and electro-plating. Additionally, by exploiting the vertical wafer transport, the tool can be used for simultaneously plating both surfaces of bifacial solar cells.

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 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 was recently added to the lab to facilitate uniform mixing of the metal paste. The lab is also equipped with a viscometer to determine the paste's viscosity.

Fast firing furnace (SinTerra / BTU, USA)

The SinTerra is an automated fast firing furnace from BTU/ AMTECH Systems. The furnace is equipped with automated cassette loading and unloading. It has 6 zones with infrared lamps for heating Si wafers 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 functional thin films (Al, Ag, etc) onto various substrates (wafers, glass sheets, etc). 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 500ºC. 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 M4-size wafers per run can be processed at temperatures of up to 200ºC. The tool is also used for deposition of Cu and other metal seed layers onto wafers for subsequent plating.

Contact person:
Dr Pradeep PADHAMNATH (pradeep_p@nus.edu.sg)

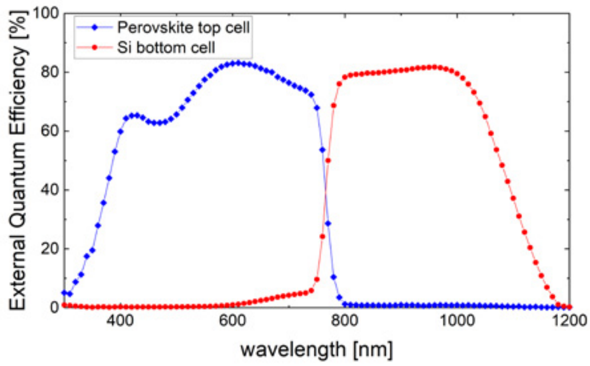
PHOTOVOLTAIC DEVICES CHARACTERISATION LABORATORIES

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 metallisations 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



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.

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.

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.

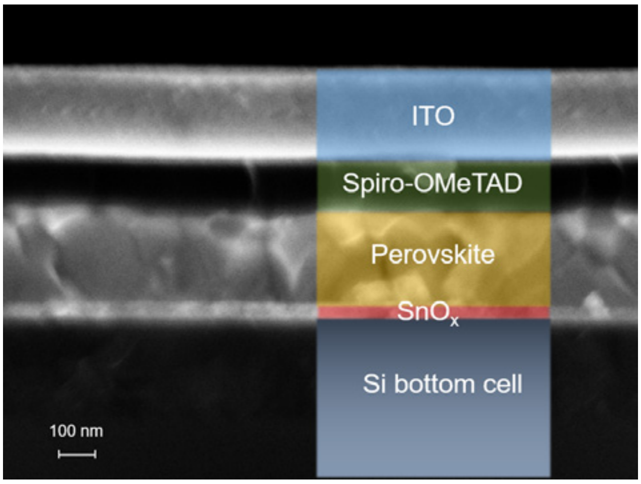
Solar cell metal line and contact resistance measurement (IVT)
The transmission line method (TLM) enables metal-semiconductor contact resistance measurements down to 1 mΩ-cm^2. Different probe heads are available for a wide range of metallisation finger pitches, for measuring both screen-printed solar 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.

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 (sample provided by the Tandem Solar Cells Group)

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 high-precision I-V 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.

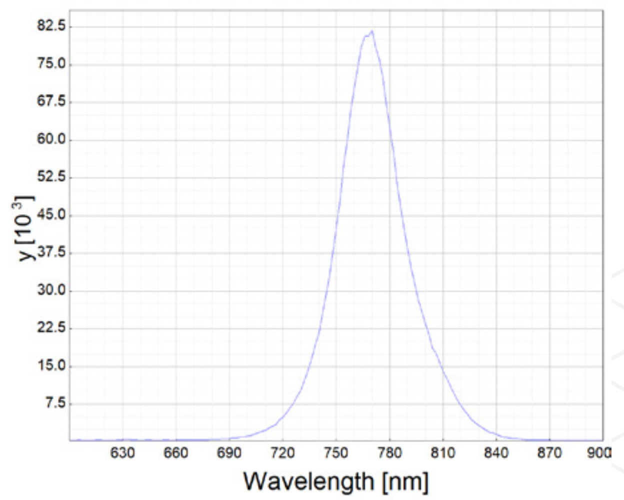
Large-area spectral response analyser (Enlitech, SR-156)
This system projects a large monochromatic beam which overfills the solar cell area for differential spectral response measurement up to 1 Sun bias light intensity. The external quantum efficiency (EQE) extracted from the measured spectral response curve enables the determination of the spectral mismatch correction factor.

Advanced Characterisation Laboratory

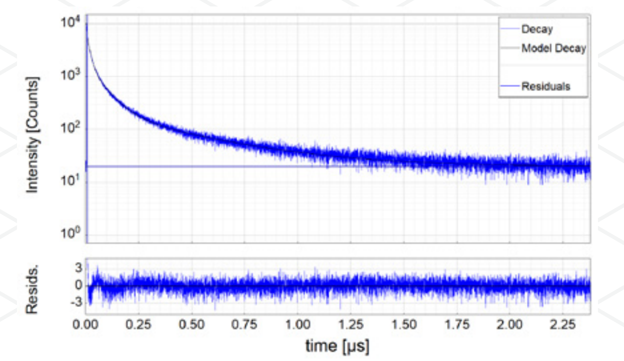
> The Advanced Characterisation Laboratory houses cutting-edge commercial characterisation tools as well as tools that are currently being developed by SERIS. It contains a time-resolved photoluminescence tool, which is used to measure the luminescence spectrum of perovskite materials and their effective 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)

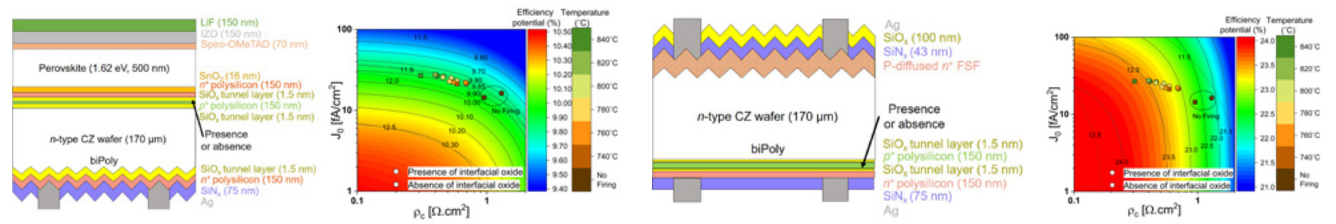
The Zeta optical profiler is a 3D true colour imaging tool that can image large areas of a sample surface and provide accurate topography information contactlessly. It allows measurements of lateral dimensions, step heights and wall angles, and is ideally suited to obtain high-resolution 3D shapes of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

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

PV DEVICE MODELLING AND SIMULATION

SERIS is operating a simulation infrastructure which can assist in solar cell optimisation. Various 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 of measurements, 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 tandems
• Metrology simulation	I-V, EQE/IQE, carrier lifetime, EL/PL imaging
• Energy yield simulation	PV modules and systems
• Optical simulations	Transfer matrix, ray tracing, path tracing
• Loss analysis	Solar cells (silicon, perovskite), PV modules and systems
• Web based solar cell simulation platform	XSolarAI



Left: Structure and simulated 1-Sun efficiency potential of biPoly silicon solar cells using a front-side poly-Si tunnel junction for subsequent 2-terminal tandem device integration (the "add-on" efficiency of the biPoly bottom cell is simulated as a function of the passivation quality (j_0) and the contact resistance (ρ_c) of the tunnel junction, superimposed with corresponding measurements for different peak firing temperatures, deploying/not deploying an additional interfacial oxide). Right: Structure and simulated 1-Sun efficiency potential of a corresponding biPoly stand-alone cell (i.e., not tandem integrated), with a rear-side poly-Si tunnel junction enabling conventional screen printed metallisation.

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 as well as contact-passivated silicon solar cells (monoPoly, biPoly, abcPoly). 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.

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").

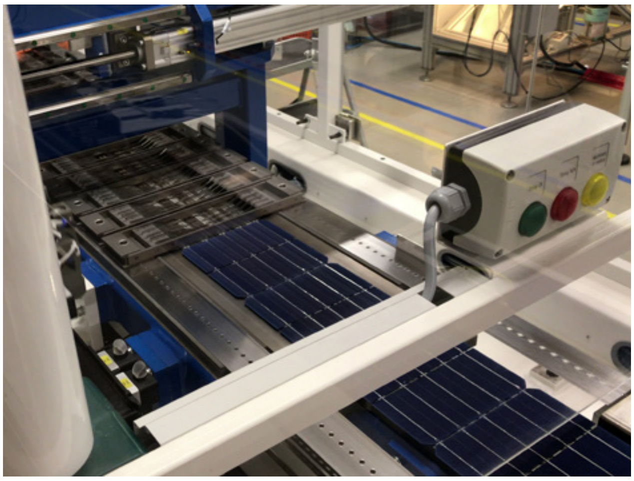
Metrology simulation
We have developed various programmes for reliable simulations of the PV device characterisation methods in use at SERIS. For example, we can simulate injection dependent carrier lifetime measurements, bias and injection dependent quantum efficiency (EQE/IQE) measurements, as well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

Web based simulation platform
A web based simulation platform (XSolarAI) has been developed which enables SERIS researchers to (1) upload/simulate/compare measurements, and (2) to apply machine learning models to the collected data. Our current focus is on the simulation and calibration of perovskite-silicon tandem solar cells, including contact passivated (biPoly) silicon bottom cells and various perovskite top cells.

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

PV MODULE DEVELOPMENT LABORATORY

Located at CleanTech Park, SERIS' 300-m^2 PV Module Development Laboratory houses a fully equipped PV module pilot line for industry-scale PV module R&D and related services.



(Left) - Automatic solar cell stringer and (right) TLS cell cutter at 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 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 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 cells strings or manual ribbon soldering.

PV module multi-level laminator (Bürkle, YPSATOR 1222-5 HKV)
This 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 house with an industry partner where it is used for collaborative PV module R&D as well as SERIS' internal module research.

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 180ºC.

Bürkle multi-level laminator

Contact person:
Dr LEOW Shin Woei (swleow@nus.edu.sg)

SERIS' ISO/IEC 17025 LABORATORY FOR 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 has expanded its accreditation to reliability and safety tests, with special focus to the degradation modes that occur in the hot and humid tropical climate of South-East Asia. In 2021 it has further expanded its scope to bifacial modules, potential induced degradation, and to 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 of 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.

Complimentary 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 lab on two of the best solar simulators in the market:

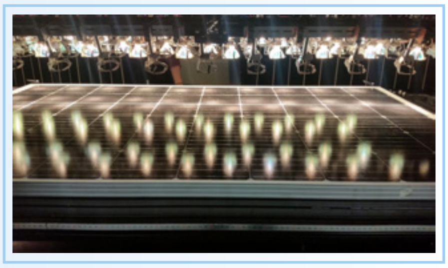
- the 10-ms pulse Pasan SunSim 3B by Meyer Burger;
- the 100-ms ModuleTest3 solar simulator by h.a.l.m. for slow-response high-capacity modules.

"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

PV module characterisation

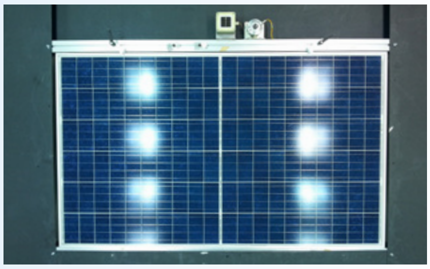
Incident Angle Modifier (IAM)
The level of irradiance that a PV module receives varies with sun elevation throughout the day and over the seasons. It is therefore important to determine the impact of the angle of incidence on the output of PV modules and evaluate a correction, commonly referred to as 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.

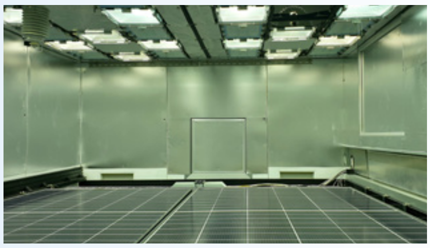
The same simulator allows to determine the maximum reference temperatures of the various components and materials used in the PV module, in order to verify their safety according to the IEC 61730 standard.



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).



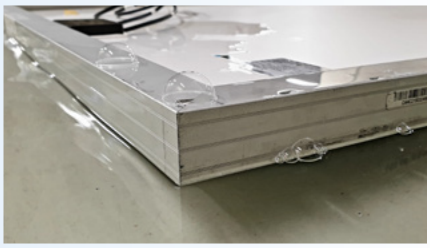
UV exposure test

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.



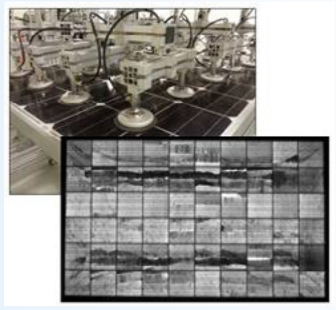
Wet leakage test

PV module reliability and durability testing

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

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.

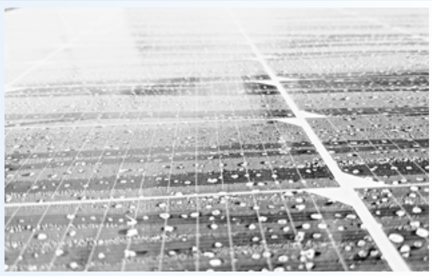
Given the PV industry trend to larger modules, the laboratory's climate chambers were upgraded in 2022 to larger volumes, now capable of testing modules up to 3 m long and 2 m wide.

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
- Six different salt mist corrosion tests
- Hot-spot identification due to soiling
- Acid rain impact to the modules
- Assessing degradation of the encapsulants
- Testing of BOS components for floating PV systems
- Customised mechanical load testing for modules in floating PV applications



Salt mist test

Contact person:
Dr Mauro PRAVETTONI (mauro.pravettoni@nus.edu.sg)

OUTDOOR PV MODULE AND SYSTEM TESTING FACILITIES IN DIFFERENT CLIMATES

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

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

The various PV module and system data (available in intervals as short as 10 seconds) include:

- Module temperature
- DC characteristics: V_{oc}, V_{mpp}, I_{sc}, I_{mpp}, P_{mpp}, IV 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)

Contact person:
Dr Carlos RODRÍGUEZ (carlos.rodriguez@nus.edu.sg)

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)

PV SYSTEM MONITORING LABORATORY

The PV System Monitoring Laboratory at SERIS conducts real-time analytical monitoring 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 EMA PSO data requirements 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), live sky images, 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. the Energy Market Authority of Singapore (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
- 1-minute sky images from different locations in Singapore, also available on the NSR website
- 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 (top) and a motion monitoring sensor for floating PV systems (bottom).

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

ELECTRONICS LABORATORY

SERIS' Electronics Laboratory is a general purpose workshop and laboratory space that enables research and development in areas including meteorological observations, PV system monitoring, power electronics, battery testing, 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 batteries and other electronic components.

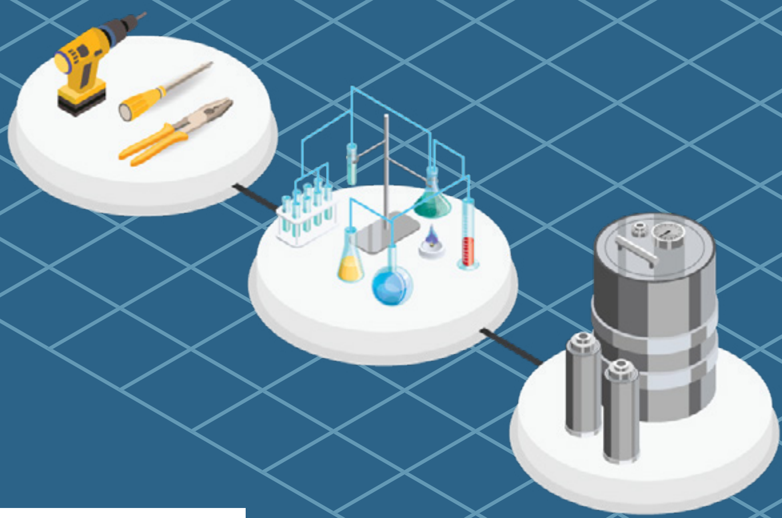
Lead-free solder stations for SMD (Surface Mounted Device) soldering (Weller), equipment for testing and wiring
All types of surface mounted device components can be soldered with high-precision solder stations, and electrical circuits can be tested and verified after soldering. Large-scale monitoring 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.

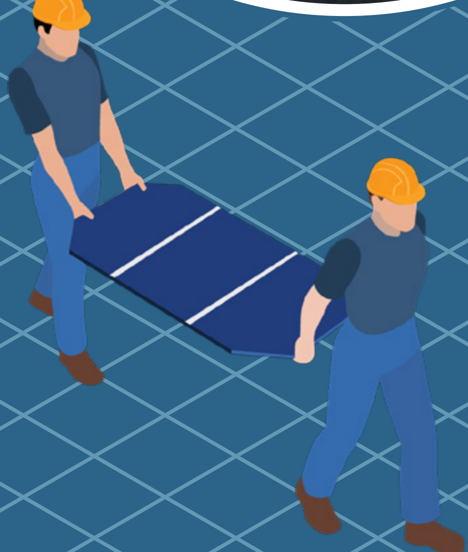
3D printer

Multiple Lab equipment for electrical works

Contact person:
Dr Carlos RODRÍGUEZ (carlos.rodriguez@nus.edu.sg)



SERIS SERVICES



PROCESSING SERVICES FOR SILICON SOLAR CELLS

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

Processing of large-area silicon solar wafers and cells:

- M2 and M4 wafer size (up to 161.7 mm x 161.7 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 A_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
- Single- or double-sided inline plating of metals (Ni, Sn, Cu, Ag)
- Inline plating resist stripping and seed layer etch-back for selective emitters or patterned junctions

SERIS' Silicon solar cell laboratory: (Top, left) PECVD tool for deposition of polysilicon and dielectric layers for application in passivated contact solar cells in zone 1B; (top, right) Inline single-side wet-chemical processing tool in zone 1A; (bottom, left) PECVD tool for deposition of intrinsic and doped amorphous silicon layers for applications in heterojunction solar cells in zone 1B; (bottom, right) Versatile inkjet printer for depositing masking layers for patterning and coating applications in zone 2A.

Contact person:
Dr Pradeep PADHAMNATH (pradeep_p@nus.edu.sg)

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 400ºC. This allows to deposit thin layers of metals, TCOs and dielectrics onto various substrates. It is also possible to deposit graded layers, or multi-layer stacks of up to six different materials, without breaking the vacuum conditions. As the platform is comparable with large-scale production machines, the processes developed on this machine can easily be scaled up to industrial production lines. At SERIS we use this tool for depositing metal layers, TCOs and multi-layers for Si and thin-film solar cells, as well as 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 400ºC
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

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

CHARACTERISATION AND TESTING OF PV MATERIALS AND SOLAR CELLS

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

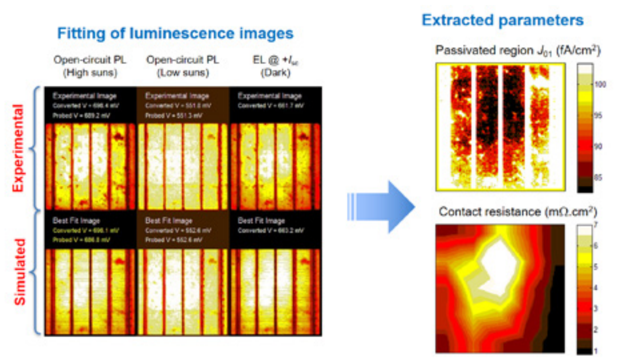
- Solar Cell Doctor: Detailed health check for solar cells
- High-precision steady-state light I-V and full-area spectral response measurements
- High-precision active-area spectral response and diffusion length mapping
- Photoluminescence and electroluminescence imaging
- Absolute luminescence quantum yield measurement of thin-film stacks and devices
- Mapping of impurity zones and defects in silicon wafers
- Angle-resolved hemispherical and diffused spectral transmission and reflection measurements
- Determination of optical and dielectric properties of thin films by spectroscopic ellipsometry
- Scanning electron microscopy, including cross-sectional elemental analysis by energy dispersive X-ray (EDX), p-n junction location by electron beam induced current (EBIC), and determination of crystalline grain orientation by electron back scatter diffraction (EBSD)
- Line scans and 3D surface profiles
- Carrier concentration and carrier mobility determination of transparent conductive oxides, conductive films and semiconductor layers by the Hall effect
- Steady-state and transient carrier lifetime characterisation by photoconductance and photoluminescence based measurements
- Dopant profile determination by electrochemical capacitance-voltage (ECV) measurements

PV product validation and improvement

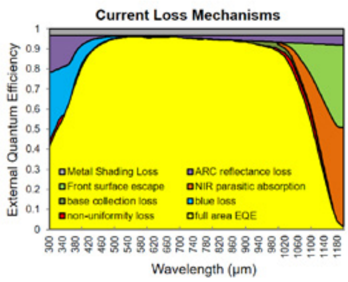
- Technical consultancy for industrial silicon solar cell development, process optimisation, metal grid design, production yield improvement
- Analysis and simulation of advanced silicon solar cell concepts such as the heterojunction architecture, passivated contacts, local back-surface-field (PERC/PERL), 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 can be identified. Design and process changes can also be evaluated in terms of their influence on cell efficiency.

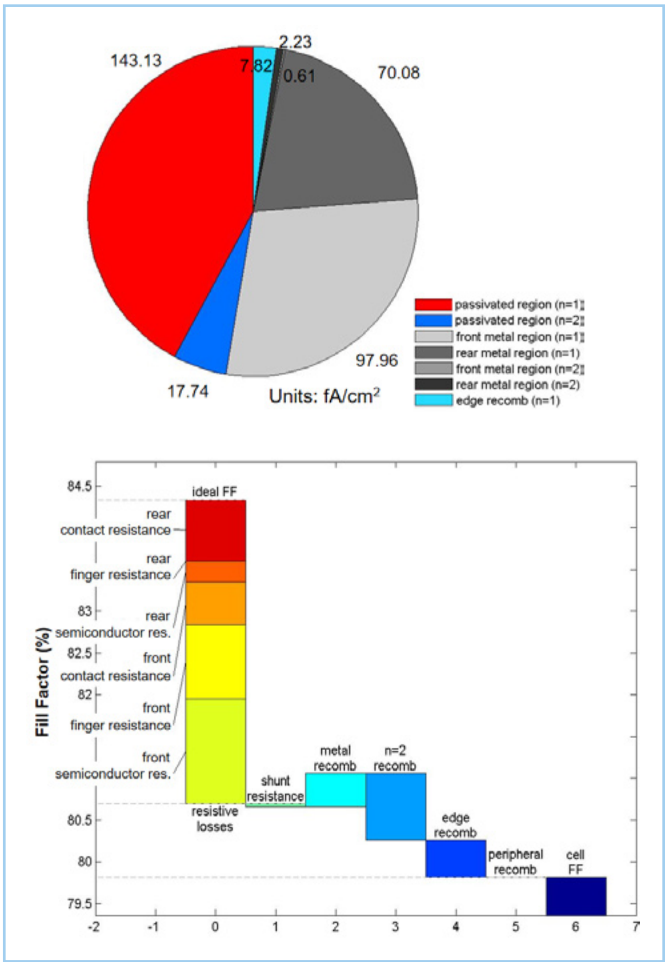


Fitting of Griddler simulated luminescence images to experimental data allows the extraction of device parameters in this p-type multicrystalline silicon solar cell. This includes the spatial distribution of the saturation current density J_{01} of the passivated region and the contact resistance.

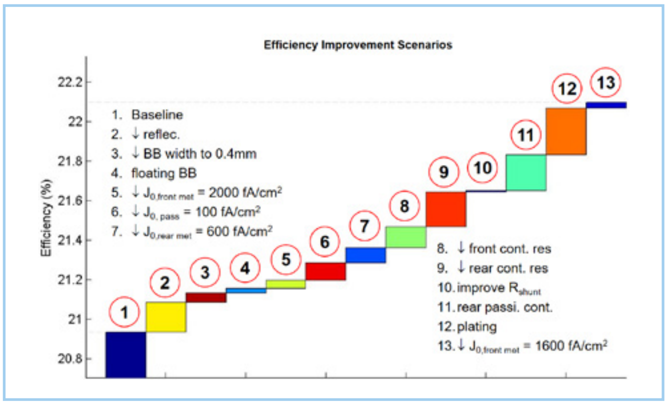


J_{sc} Breakdown (mA/cm²)	
Cell Current	40.062
Base collection loss	0.314
NIR parasitic absorb	1.550
Front surface escape	1.287
ARC reflectance	0.977
Blue loss	0.464
Metal shading	1.567
Non-uniformity loss	0.207
WAR (300-1000nm) %	1.762
Base eff. diffusion length (µm)	3478

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.



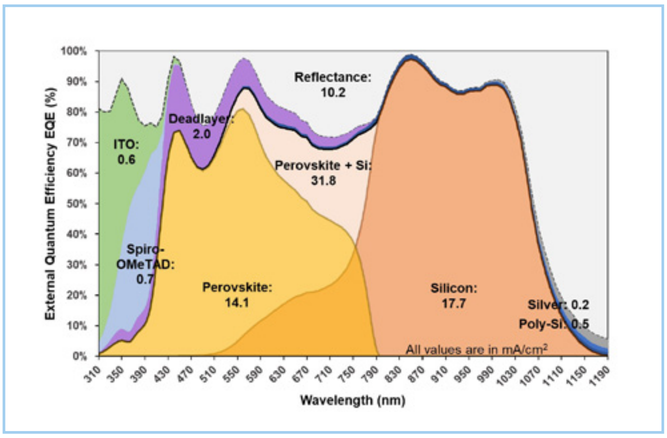
The accurate representation of a crystalline silicon solar cell allows the precise quantification of the various recombination currents at open circuit that affect its voltage, as well as the myriad of factors which influence its fill factor.



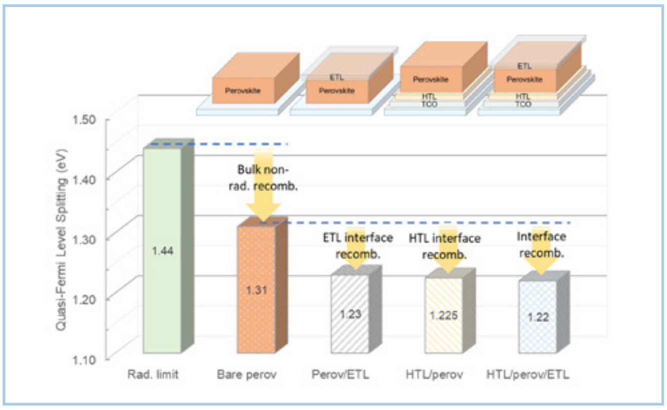
Griddler prediction of incremental silicon solar cell efficiency improvements due to specific process or cell design changes

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 films 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 various layers to the J_{sc} losses facilitates better solar cell design and optimisation.



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

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

DEVELOPMENT OF PV MODULES

SERIS operates a PV Module Development and Application Laboratory where PV modules ranging from small single-cell modules for testing purposes up to full-size 72-cell modules 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 Retrofit and BIPV Installation

- 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 Peranakan PV modules
- 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.

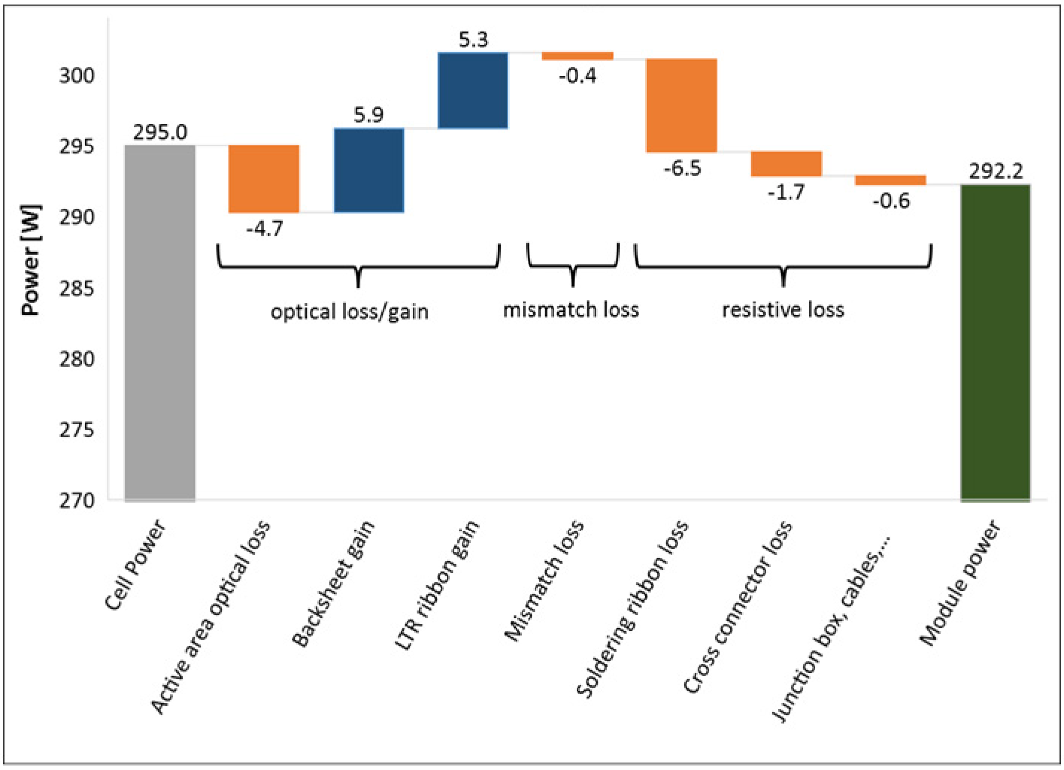
Selected elements of our PV module service:

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 difference in maximum power point currents (I_{mp}) of the individual series-connected solar cells.

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

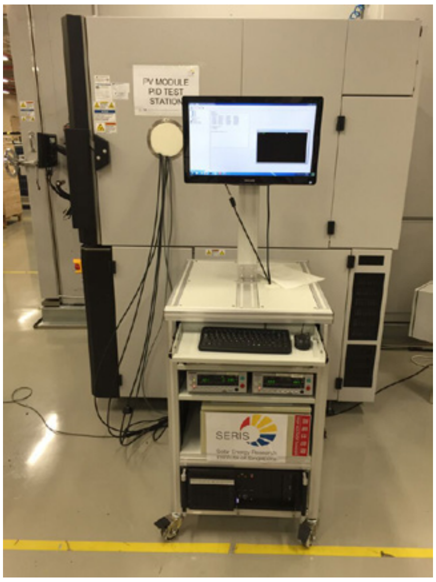


Cell-to-module (CTM) power loss analysis at SERIS

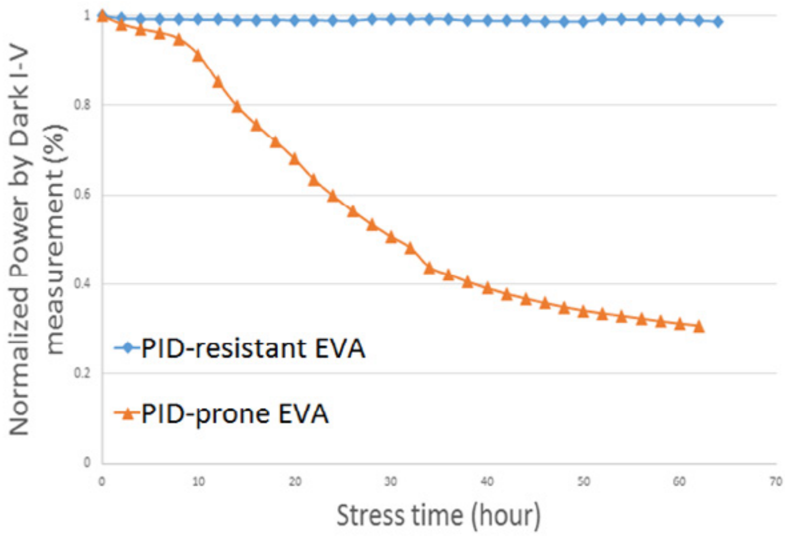
Contact person:
Dr LEOW Shin Woei (swleow@nus.edu.sg)

PID TESTING OF PV MODULES

Potential-Induced Degradation (PID) is one of the most damaging degradation processes of PV modules in field conditions. As a pioneer in PID studies, since 2010 SERIS has been devising various indoor test methods to detect PID. PID of PV modules can be continuously monitored in indoor and outdoor experiments.



SERIS in-situ PID test station



Continuous power monitoring of two different modules subjected to PID testing

In Singapore, PV module temperature can exceed 60°C during daytime, whereby the annually averaged relative humidity is 81%. The conventional PID testing as per IEC 61215 does not seem to be sufficient in tropical climates such as Singapore. SERIS has therefore set up an Outdoor Module PID Test Facility in Singapore to monitor PV modules for PID. It is very likely that PV modules that are free from PID in Singapore will suffer minimal PID effects in other climates. 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.

PID is also an important topic for the emerging deployment of offshore floating PV systems in salty water. The presence of salt mist is known to augment the risk of PID, and our laboratory can perform combined PID + salt mist tests to investigate this specific reliability challenge of PV modules.

SERIS' Outdoor Module PID Test Facility

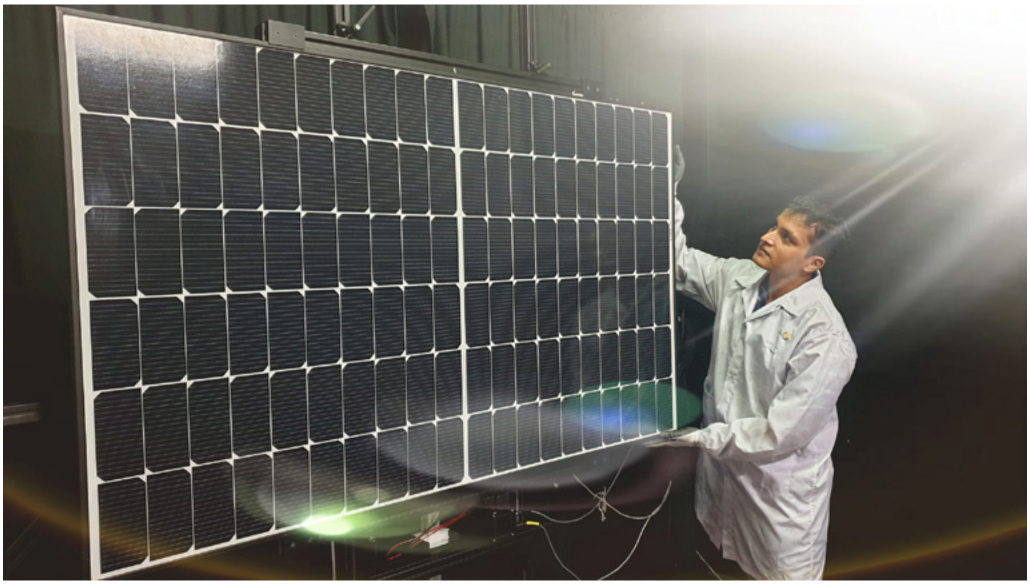
Contact person:
Dr Mauro PRAVETTONI (mauro.pravettoni@nus.edu.sg)

CHARACTERISATION AND RELIABILITY OF PV MODULES

SERIS' ISO/IEC 17025 accredited PV Module Laboratory started its testing operations in 2010. Located in CleanTech Park, it has regularly embarked on equipment upgrades and system updates to remain relevant to the changing needs of research centres and the solar industry. In addition to 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

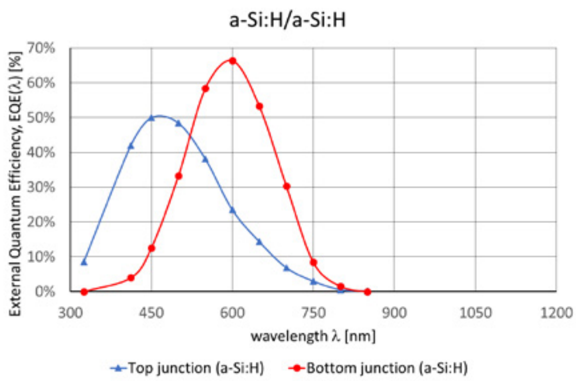
Equipped with two Class A+ large-area pulsed solar simulators (a 10-ms Pasan SunSim 3B and a 100-ms halm solar simulator), the Laboratory can characterise all types of commercially available PV modules at Standard Test Conditions (STC), including bifacial and heterojunction modules. This is particularly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

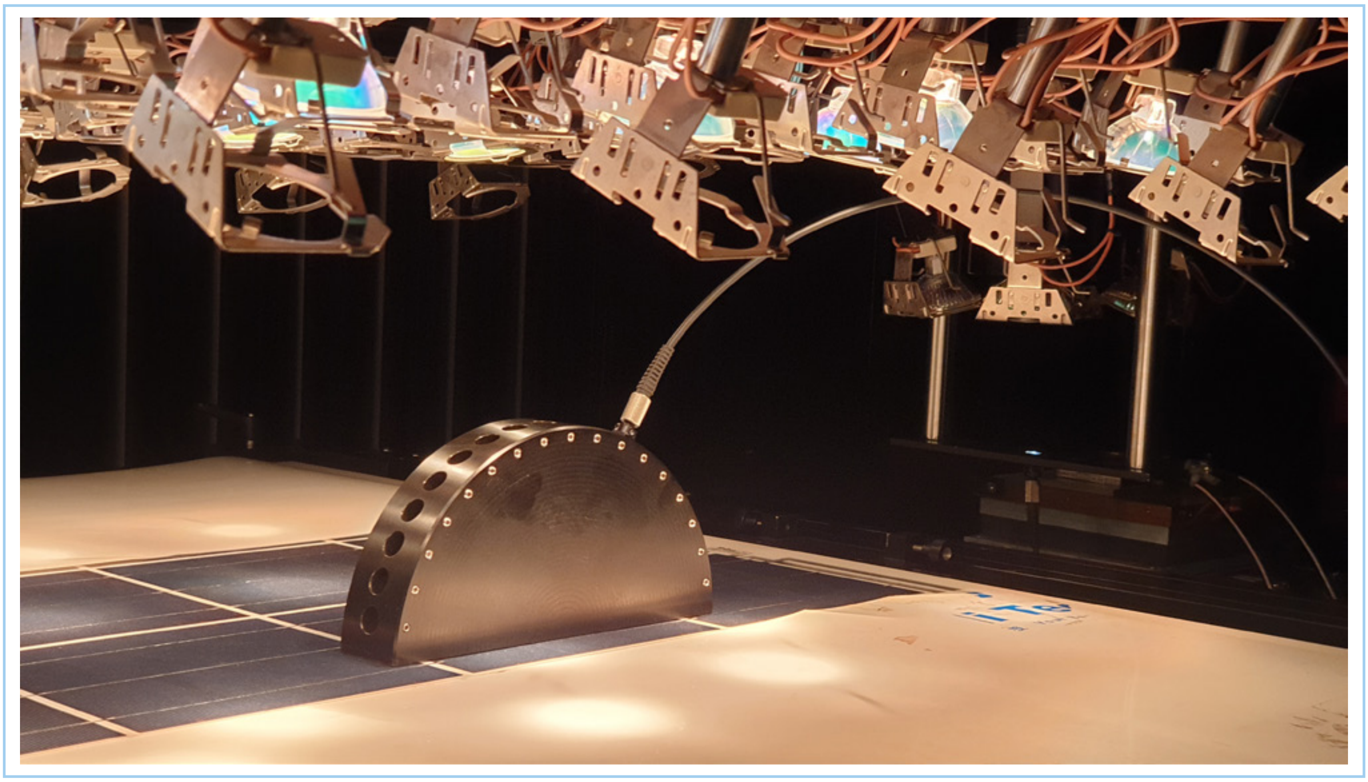
In view of the possible future revival of multi-junction terrestrial PV modules, and aligned with the new frontiers of research on perovskite-on-silicon tandem solar cells, SERIS' Laboratory is now equipped with an External Quantum Efficiency (EQE) measurement system for multi-junction modules, with 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.

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.



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

Contact person:
Dr Mauro PRAVETTONI (mauro.pravettoni@nus.edu.sg)

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}, IV 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 assist project owners and developers in the design of their PV systems for performance optimisation and to meet the highest quality standards, in particular for installations in the tropics. For example, SERIS has designed and commissioned a PV system that, since 2011, has been operating in Singapore with an exceptionally high performance ratio (PR) of almost 90%. SERIS' project services start with initial energy yield estimations and cover the entire project period until the PV systems are fully operational and perform as originally planned.

Typical PV system services offered by SERIS are tabled below.

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 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 benchmarks
Third-party verfication	**Project due diligence**	**Full project partnership**
All "Optimised system design for high performance" services, plus: • Suitability of the key plant components • Detailed review of system design (mechanical, electrical up to medium voltage) and cross-check against current best industry practices Optional: • Review against given guidelines (statement of compliance)	All "third-party verification" services, plus detailed review of: • Track record of suppliers and turnkey providers • Project structure and obligations of project parties • Technical warranties • Project management • Operations and maintenance concept • Project risks and mitigations • Financial modelling • Factory inspections	All "Project due diligence" services, plus: • Site visit prior to project closure • Construction monitoring • Testing & Commissioning (T&C) • Final acceptance • Operations and maintenance reviews • Analytical on-site monitoring with calibrated equipment Optional: • Sample testing of PV modules

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

(Left): SERIS engineer performing on-site measurements during testing & commissioning; (Right): Rooftop PV installation on a residential block in Singapore, for which SERIS has acted as Owner's Engineer under the SolarNova programme

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

PV SYSTEM PERFORMANCE MONITORING

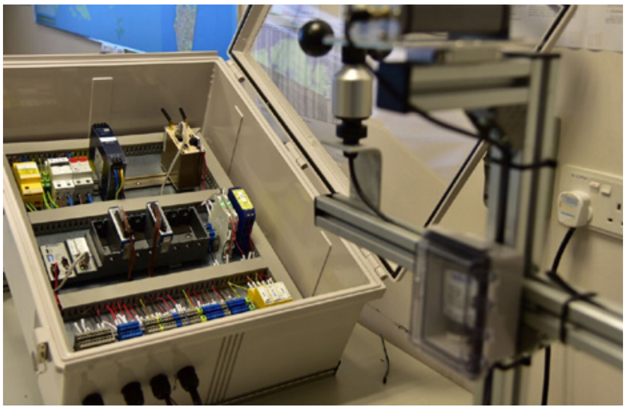
We offer a cloud-based real-time Analytical Monitoring of PV installations - from small rooftop systems, large ground-based PV power plants to floating PV systems in the multi-MW range. SERIS has developed a highly reliable and scalable monitoring platform to accommodate multiple deployments in different 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, Malaysia, Vietnam and Philippines.

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

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

ON-SITE PV SYSTEM ASSESSMENTS

On-Site PV System Performance Testing and Commissioning

SERIS offers on-site PV system performance testing and commissioning services accredited by SAC-SINGLAS. This provides key stakeholders an independent verification of the actual system installation against original design drawings and good practices, and its performance level against expected values. Calibrated measurement equipment is used to conduct ISO/IEC 17025 compliant testing of important PV system parameters. These measurements can be corrected for prevailing environmental conditions, such as module temperature and irradiance. The inspection and test results are also referenced against local and/or IEC standards. Our services include:

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

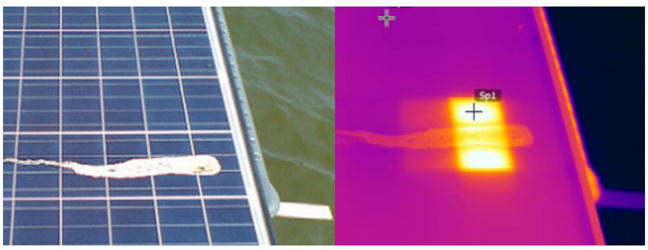
On-site measurement of PV system performance

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

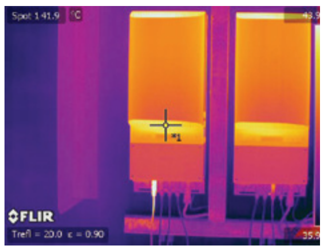
Thermographic Analysis of PV Systems

SERIS offers thermographic analysis of PV installations, both at system and component level. This enables the detection of various forms of thermal stresses within a PV system. Thermal stresses can be symptomatic of an underlying issue with the PV system that may affect system performance or result in safety hazards. We typically focus on:

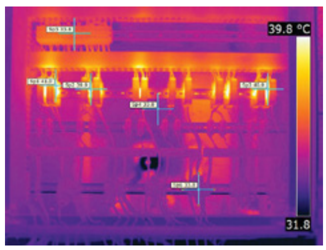
- PV string and module temperature measurements: This helps to determine whether there are faulty solar modules in a DC string, or faulty/overheated solar cells within a PV module (left image). Unusual thermal behaviour of module junction boxes can also be detected.
- DC and AC cable operating temperature measurements: Hotspots do not only occur in system parts that are exposed to sunlight, but may also be found within the wiring setup. Loose connectors and undersized cables can result in overheated parts (middle image). This lowers the PV system's power output.
- Component temperature measurements: Component failures do not only cause PV system downtime, but can also be a potential fire hazard. Proper fuse ratings and component selection targeted for hot climate conditions are crucial but often neglected. Thermographic analysis enables an in-depth analysis of component operating temperatures in DC field junction boxes all the way to AC distribution boards (right image).



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



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



Thermographic image of overheated components in a DC distribution box.

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

SPECIALISED SERVICES

Real-Time Monitoring System of Meteorological Parameters

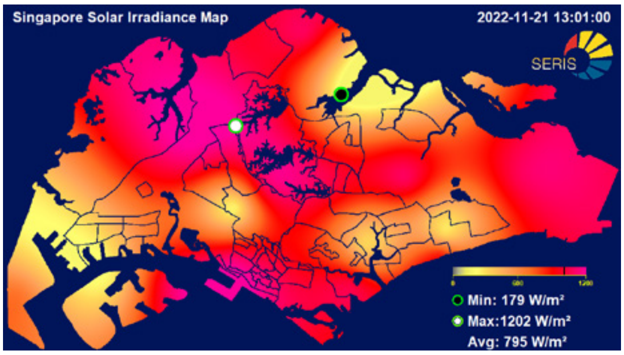
SERIS operates a network of 25 irradiance stations in Singapore measuring global horizontal irradiance (GHI) across the city-state on a ~5 km x 5 km grid, enabling a live (i.e., real time) solar irradiance map for Singapore based on irradiance measurements. The live irradiance map developed by SERIS 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 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).

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



Snapshot of a typical irradiance distribution in Singapore

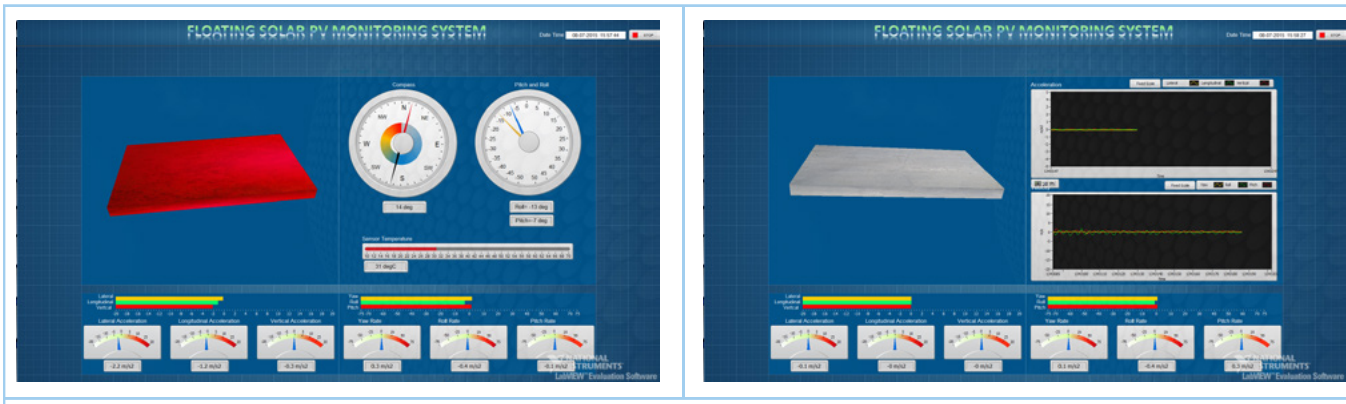
Six-Degree Freedom Motion Monitoring for Floating PV System Applications

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)

Glare Analysis of PV Installations

With increasing PV systems deployment, potential glare from the glass surface 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.

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 Figure 1.

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 – 73 locations
   ii. Malaysia – 15 locations
   iii. Cambodia – 1 location

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.*

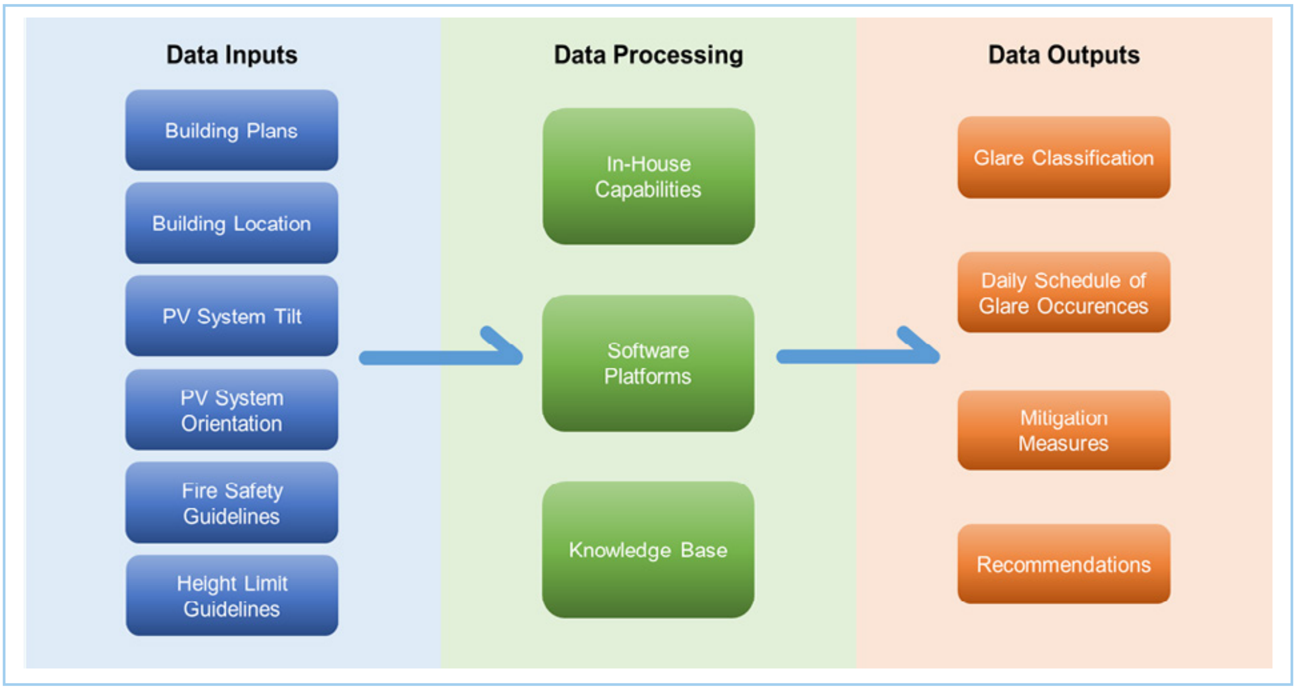


Figure 1. Glare analysis framework at SERIS. Customised solutions can be designed to suit the needs of individual clients

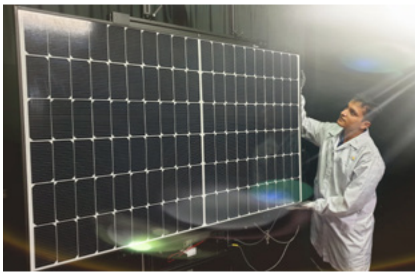
Contact person:
David LEE (david.lee@nus.edu.sg)

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.

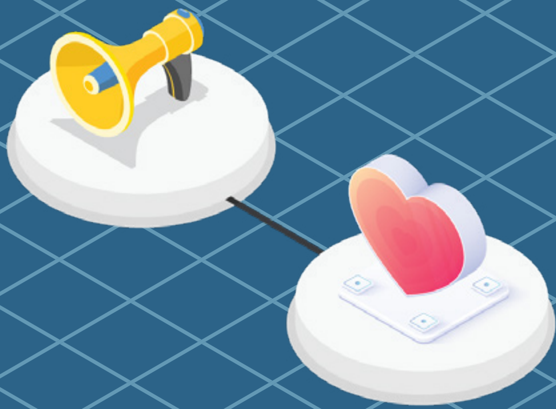
Selected topics for technical consulting include:

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





Top row: (left) SERIS' Perovskite Solar Cell Lab; (centre) "Golden module" characterisation at SERIS' off-campus PV Module Lab at CleanTech Park; (right) PV system installed on the roof of a HDB residentiial block in Singapore where SERIS performed various PV system quality assurance services.
Middle row: (left) SERIS' innovative Peranakan-themed building integrated photovoltaics (BIPV) modules; (right) "Solar Artwork" balustrade installed and commissioned by SERIS at CDL City Square Mall
Bottom row: (left) SERIS' agrivoltaics testbed (i.e., agriculture combined with a solar PV system) at the Singapore Discovery Centre; (image credit:Singapore Discovery Centre) (right) Floating Solar PV testbed at Tengeh reservoir, Singapore



OUTREACH ACTIVITIES

Conferences, Workshop and Webinars Co-organised By SERIS

1st International Integrated-PV Workshop (Online), 07-08 Apr 2022

The inaugural workshop was jointly organised by Forschungszentrum Jülich, Germany, Solar Energy Research Institute of Singapore (SERIS, NUS), Southwest Petroleum University (SWPU), China, and Sun Yat-sen University (SYSU), China, supported by media partners by SOLARBE, and Taiyang News. It brought together, for the first time, experts in the areas of Building integrated PV (BIPV), Floating PV, Agro-PV, Vehicle-integrated PV (VIPV) and others to discuss the way forward and generate synergies between the various disciplines. It provided an exchange between academia and industry about latest technology options and also addressed concerns and provided solutions for governments and planners.

Dr Thomas REINDL (Deputy CEO of SERIS) delivering his welcome message and opening talk on "100% Renewable Energy scenario with IPV" at the 1st IPV workshop.

Dr Carlos RODRÍGUEZ, Head of SERIS' Solar System Technology Group, shared key learnings from the floating PV testbed in Singapore.

PV Market Insights 2022, KIER-SERIS Urban Solar/BIPV Session at the International Green Energy Conference 2022, South Korea, 13-15 Apr 2022

SERIS collaborated with the Korea Institute of Energy Research (KIER) to co-organise a BIPV session as part of the International Green Energy Conference and PV Market Insights 2022 on 13-15 Apr 2022 in South Korea. This BIPV session proceeded in a hybrid mode (both physical and online) and included insightful discussions on:

(i) Policy and Market Trends of Urban Solar / BIPV;
(ii) Future Technologies for Urban Solar / BIPV and BIPV industry talks;
(iii) Solar Architecture and Regulatory Aspects. International experts, distinguished speakers, developers and BIPV/PV manufacturers exchanged information about the latest innovative solar technologies, trends in the clean energy industry, and pathways for decarbonisation in South-East Asia and beyond.

Dr Veronika SHABUNKO giving a talk on "Global Market Trends of Urban Solar" at the BIPV session of the International Green Energy Conference 2022.

Solar Industry Workshop, Singapore, 21 Nov 2022

As part of Singapore's commitment to global climate action, solar energy deployment has been identified as one of the key strategies under the "Energy Reset" pillar of the Singapore Green Plan 2030. Singapore is expecting a massive push towards solar photovoltaic (PV) adoption due to the soaring costs of conventional electricity and the increasing awareness about sustainability. Many building owners would therefore like to install solar panels on their rooftops and other facilities but are uncertain as to what would be the process and what are the long-term commitments.

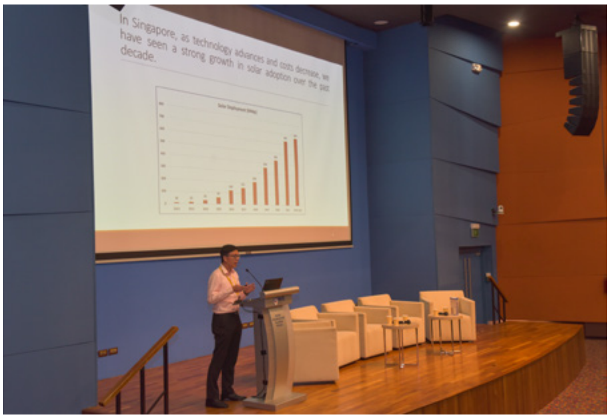
Co-organised by the Energy Market Authority of Singapore (EMA), Building and Construction Authority of Singapore (BCA) and the Solar Energy Research Institute of Singapore (SERIS), this half-day workshop aimed to provide such information to building owners in the private sectors on the various solar solutions & financing options available to help them kick-start their solar deployment journey.

In the first session of the workshop, invited speakers who are PV developers and solar system integrators shared with the audience the typical project process - covering project planning, financing, licensing, implementation, as well as O&M. In the second session, invited speakers who are building owners (self-owned and lessees of real estate) shared their motivation and experiences in 'going solar', the main drivers for them, and the final outcome versus their expectations for the project.

The workshop attracted more than 130 attendees. Participants had the opportunity to gain a better understanding on solar deployment projects during the Q&A sessions with the speakers, and also network with workshop attendees who have a common interest in exploring solar deployment projects.

SERIS Deputy CEO Dr Thomas REINDL welcoming participants to the Solar Industry Workshop held at NUS

Dr Thomas REINDL (left) with invited speakers of the Solar Industry Workshop



Mr TOH Wee Khiang, Director, National Energy Transformation Office, EMA, gave an overview of solar deployment in Singapore.

Mr ANG Kian Seng, Group Director, Environmental Sustainability, BCA, presenting his remarks before the 2nd session of the workshop

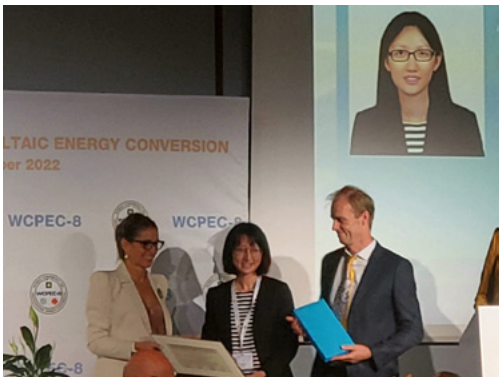
Panel discussions and Q&A sessions with the participants. Both sessions were moderated by Dr Thomas REINDL, SERIS.

SERIS Booths at International Conferences & Exhibitions

8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Milan, Italy, 26-30 Sep 2022

WCPEC-8 in Milan, Italy was a joint in-person meeting of the three largest and most prestigious international PV conferences: the European Photovoltaic Solar Energy Conference (39th EU PVSEC), the IEEE Photovoltaic Specialists Conference (IEEE PVSC-49) and the International PV Science and Engineering Conference (PVSEC-32). SERIS was one of the supporting organisations of WCPEC-8. The conference offered an extensive technical programme with more than 1100 presentations and a large industry exhibition. The conference was attended by more than 1500 paying delegates from all over the world.

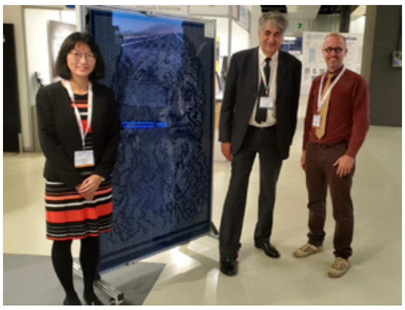
Dr Thomas REINDL, Deputy CEO of SERIS, giving a plenary talk on "100% Renewable Energy Scenario – What are the options to deploy all the solar panels?"



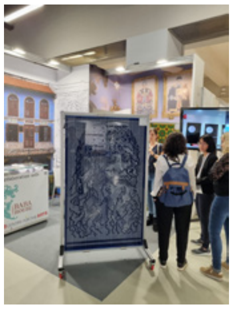
SERIS PhD student SAW Min Hsian winning a WCPEC-8 Student Award, in the theme area of PV Systems Engineering, Integrated/Applied PV ("PV and Buildings")

At the WCPEC-8 exhibition, SERIS showcased an innovative PV module that is well suited for integration into facades (with particular attention to heritage buildings). Inspired by Singapore and Malaysia's Peranakan culture, thus coined as the "Peranakan modules", these colourful PV modules enhance the aesthetic appeal of building facades and at the same time link the Peranakan tradition with the generation of clean and sustainable energy. This SERIS invention attracted many visitors, including well-known PV experts from both academia and the solar industry.

SERIS' booth at the WCPEC-8 exhibition



The SERIS team with Dr Heinz OSSENBRINK (middle), Chair of the International Advisory Committee to the WCPEC



SAW Min Hsian (right) introducing the novel SERIS PV modules to booth visitors.

Prof Marko TOPIČ (left) from the University of Ljubljana and the recipient of the Becquerel Prize 2022, with Dr Mauro PRAVETTONI of SERIS

Dr Mauro PRAVETTONI presenting samples of SERIS' innovative modules to (left) Dr Robert KENNY, Technical Programme Chair of EU PVSEC and (right) Dr Tony SAMPLE, Convenor of IEC TC82 WG2.

Asia Clean Energy Summit (ACES) Conference & Exhibition, Singapore, 26-27 Oct 2022

SERIS set up a 9-m^2 “Peranakan-theme” booth to showcase its innovative coloured PV modules at the two-day ACES 2022 exhibition. Visitors also had the opportunity to view a series of 5 different “Peranakan-patterned” PV modules (produced by SERIS) at the ACES meeting area located next to the SERIS booth.

SERIS booth at ACES 2022, showcasing the innovative “Peranakan module” invented by SERIS

Dr Mauro PRAVETTONI, Director of SERIS’ PV Modules for Urban Solar Cluster, giving a talk on “The Making of Peranakan Modules” at the Technical Session of the ACES 2022 Exhibition.

The meeting area at the ACES Exhibition Hall, located next to the SERIS booth, was also decorated with the “Peranakan” theme - a series of 5 different “Peranakan-patterned” PV modules produced by SERIS were on display

Visitors at the SERIS booth learning more about SERIS’ innovative PV module technologies.

SERIS researcher Dr LEOW Shin Woei (left) describing to a visitor some of the challenges of putting graphics into solar modules for building integration.

Outreach Activities to Non-Scientific Communities

SERIS regularly engages in outreach activities targeting non-scientific communities and schools to increase the public awareness of solar energy research and deployment 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 and deployment in Singapore. Below is a collection of photos from selected outreach activities organised by SERIS in 2022. A full list of our outreach activities can be found in the Facts and Figures chapter of this Annual Report.

Physical Outreach Activities

With the further easing of pandemic-related social distancing measures and travel restrictions in 2022, SERIS was able to host physical visits again for both local and overseas students.

Visit by Methodist Girls School (Secondary) Singapore, 20 May 2022

This visit included a talk by Mr Eddy BLOKKEN (SERIS Business Development Manager) on "The challenges & opportunities of the solar industry & Singapore" and a dialogue session with SERIS Adjunct researcher Dr Stephen TAY and SERIS PhD student LEE Ling Kai about the qualifications and attitudes one needs to join the solar PV sector.

Visit by students from the University of Texas-Austin, USA, 30 May 2022

SERIS Deputy CEO, Dr Thomas REINDL, delivering a lecture on "Sustainable energy and land use in Singapore". The visit also included a guided tour of SERIS' facilities and laboratories at the NUS campus.

Visit by students from the King Fahd University of Petroleum and Minerals (KFUPM), Saudi Arabia, 01 Jun 2022

Mr Eddy BLOKKEN (SERIS Business Development Manager) gave a talk on solar energy to these undergraduate visitors, followed a tour of SERIS' PV System Monitoring Laboratory

Visit by students from the University of Twente, the Netherlands, 01 Aug 2022

This student delegation from the University of Twente, The Netherlands visited the SERIS PV System Monitoring Laboratory to learn about the solar energy forecasting system developed by SERIS

SERIS' participation at Emerson Singapore's in-house event "We Love STEM Day 2022", 09 Sep 2022

Dr Donny LAI, SERIS Senior Research Fellow, giving an engaging talk on "Solar and climate change - its impact to future generations" to 65 primary school students.

Dr Donny LAI engaging the young minds in an experimental demonstration of how solar energy is converted into electrical energy using solar cells.

Visit by students from the Singapore Institute of Technology, 14 Nov 2022

SERIS' Lab Manager Dr Firdaus Bin SUHAIMI explaining the solar cell fabrication steps to the students during a guided tour of SERIS' cleanroom laboratory

Visit by teachers from the Westwood Secondary School, 25 Nov 2022

Mr Eddy BLOKKEN (SERIS Business Development Manager) sharing details about solar panels and their applications, which the teachers can disseminate to their students via the school's "Climate Change Awareness Program"

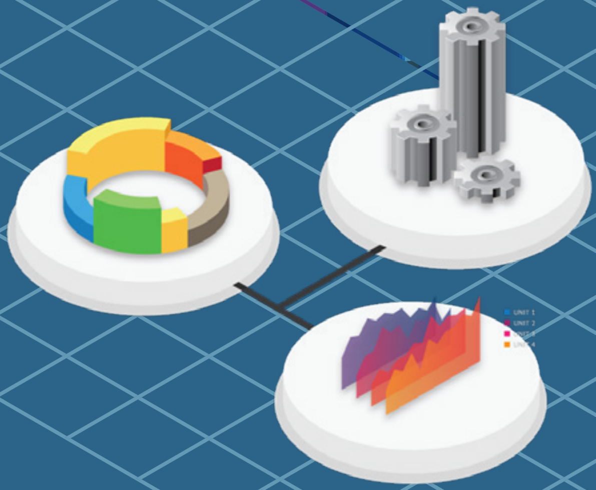
Virtual Outreach Activities

Virtual outreach via the Zoom platform was utilised for outreach to bigger groups of students to raise the awareness of solar energy and its applications.

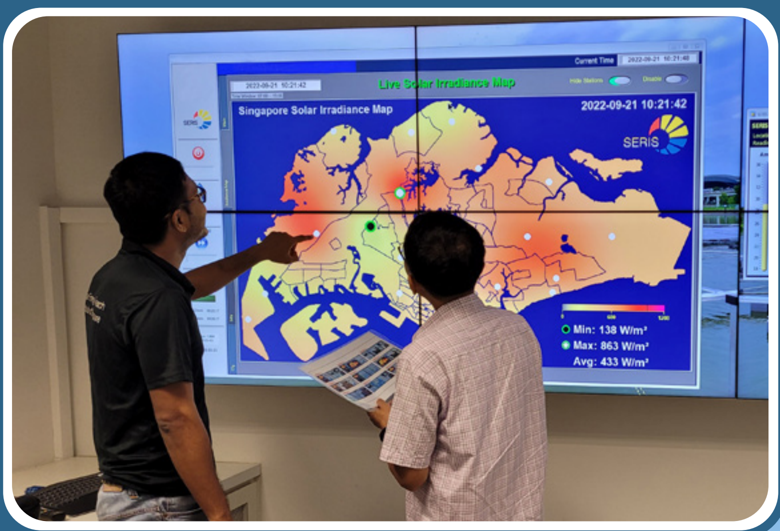
NUS-BES Environmental Conference 2022 - Panel Discussion: Climate Change in an Island State Context, 22 Jan 2022
Opened to all NUS students, this panel discussion aimed to explore how the various mitigation measures in addressing climate change have been adapted to match the specific needs of and threats to Singapore as an island state. Prof Armin ABERLE, CEO of SERIS, together with Prof HENG Chye Kiang - a Provost's Professor at the NUS School of Design and Environment (SDE) and Director of the Centre for Sustainable Asian Cities, and Prof Weina ZHANG - Deputy Director of the NUS Sustainable and Green Finance Institute (SGFIN) each gave a 10-minute presentation followed by an insightful 30-minute discussion session with the NUS students who participated at the event.

Kuo Chuan Presbyterian Primary School, Singapore, 04 Mar 2022
As part of the school's annual environmental camp programme, Dr Stephen TAY, SERIS Adjunct Researcher and Senior Lecturer from the Department of Building, College of Design and Engineering, NUS reached out virtually to P6 pupils on solar energy as a renewable source of energy for Singapore. The students were very enthusiastic and participated actively in the questions & answers segment of the session. It was encouraging to see the youngsters' passion and eagerness to learn about solar energy.

Zhonghua Primary School, Singapore, 19 Apr 2022
Dr Stephen TAY, SERIS Adjunct Researcher and Senior Lecturer from the Department of Building, College of Design and Engineering, NUS reached out virtually to about 650 Primary 1 to 6 students and informed them on solar PV adoption in Singapore, using examples of solar installations on rooftops, water reservoirs and building facades. It was an engaging event with enthusiastic students who participated actively during the Q&A session.



FACTS AND FIGURES



AWARDS AND ACHIEVEMENTS

Feb 2022: NUS Team Adustio (comprising undergraduates Alyssa Cheok and Yuan Hai Shu) clinched the top prize of the Samsung Solve for Tomorrow competition, University category. Mentored by SERIS' Senior Research Fellow, Dr. Donny Lai, and advised by Asst. Prof Hou Yi, Team Adustio integrated an in-house prototype of the tandem solar panel and organic carrageenan battery, with a mobile app-assisted asset management system.

13 Apr 2022: The poster entitled "Improvement of LED-based modulated photoluminescence technique for solar cell characterisation" won a Merit Award for ECE FYP E-Poster Competition, organised by the Department of Electrical and Computer Engineering (ECE), NUS. The poster was co-authored by FYP students Wong Shu Qi, Teo Yong Kang, Malcolm Teo, Paul Ashley Nathan and Oh Geok Kuan supervised by Prof Armin Aberle, SERIS.

30 Sep 2022: SERIS CEO Prof Armin ABERLE wins a PVSEC Award (PVSEC-32) for "his outstanding contributions to the development of photovoltaic science and technology". Prof Aberle was selected by the International Advisory Committee of the International Photovoltaic Science and Engineering Conference (PVSEC) according to nominations. The 32nd PVSEC was part of the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8) held during 26-30 Sep 2022 in Milan, Italy

30 Sep 2022: SERIS PhD student Min Hsian SAW, wins the WCPEC-8 Student Award, in the theme area of PV Systems Engineering, Integrated / Applied PV ("PV and Buildings") at the 8th World Conference on Photovoltaic Energy Conversion and Exhibition (WCPEC-8), held at Milan, Italy on 26-30 Sep 2022. Her outstanding scientific research work on "Design of "Hot-spot" free BIPV Modules – Peranakan PV" was deemed to be an exemplary contribution to WCPEC-8 by the conference official jury.

MEDIA COVERAGE

Jan 2022: Quantifying the true power of solar energy, in Innovation in Water, Singapore vol. 12, published by PUB, Singapore's National Water Agency

5 Jan 2022: Novel design for shingled solar modules. PV Magazine

21 Jan 2022: NUS research team sets new efficiency record for solar cell technology. NUS news, Impact Research Sustainability Press Releases, https://news.nus.edu.sg/nus-research-team-sets-new-efficiency-record-for-solar-cell-technology/

27 Jan 2022: NUS researchers bring perovskite/organic tandem solar cell efficiency to record 23.6%. SOLARBE Technology news

12 Feb 2022: The long read: Is the coast clear for solar to head offshore? PV Magazine

2 Mar 2022: Video episode on Solutions for Sustainable Tourism: Energy Management in Hospitality. This video is part of a series on sustainability for the German government aimed at the Tourism and Hospitality Industry. atingi eAcademy for Tourism and Hospitality. An eLearning project by Germany's Ministry of Development and Economic Cooperation (BMZ) implemented by Germany's development agency Gesellschaft für Internationale Zusammenarbeit (GIZ). Open Badges as stackable competency-based micro-certifications.

22 Mar 2022: Singapore's power sector can be net zero by 2050, says expert study which lays out various strategies. CNA Video

30 Mar 2022: PVEL and QE-Labs to offer exclusive drone EL inspection services to U.S. solar market. PR Newswire

30 Mar 2022: PVEL teams up with drone inspection specialist to provide aerial inspection as a service. PV magazine USA

2 Apr 2022: Ukraine war a perfect storm to spark global energy reset. Straits Times

19 Apr 2022: The WeatherPod. An audio production for broadcast at the Asia Climate Forum conference 2022.

June 2022: Why we should be putting solar panels on our fields and lakes? Video production, Planet A by Deutsche Welle

22 Aug 2022: Grappling with the end-of-life of renewable energy. The Business Times

11 Sep 2022: Increase in solar panel fittings in Singapore. Channel 5 and CNA news

11 Sep 2022: Increase in solar panel fittings in Singapore. Channel 8 news

12 Sep 2022: 组屋屋顶铺太阳能板有讲究 斜设计引雨自洁追太阳寸土必争. Zaobao news

14 Sep 2022: Aesthetically pleasing solar panels in the spotlight as demand for solar fittings rise. CNA news

20 Sep 2022: A Dutch-Norwegian startup wants to open 'a whole new frontier' of renewable energy with solar farms that float on the ocean's surface. Fortune.com

Oct 2022: Floating offshore solar: a global solution in the race to net zero. A 3 mins video by EDP and produced in partnership with the Financial Times Commercial department.

7 Oct 2022: SERIS Perovskite Lab featured in episode 2 of the CNA 3-part documentary on Food, Energy, Water.

12 Oct 2022: INDEOTEC SA delivers an Octopus-II PECVD after comprehensive FAT to the Solar Energy Research Institute of Singapore (SERIS). INDEOTEC press release

27 Oct 2022: Singapore exploring hybrid energy generation system that taps wind, solar and tidal energy. Straits Times

3 Nov 2022: Singapore Today on CNA938 – live talk interview with Dr Thomas Reindl about the solar forecasting model

5 Nov 2022: S'pore power market to use model that can predict solar output in advance by 2023. Straits Times

7 Nov 2022: Singapore to adopt solar forecasting model. PV Magazine

7 Nov 2022: Prefabricated BIPV wall for multi-floor buildings. PV Magazine

10 Nov 2022: Solar forecasting model by SERIS will boost reliability and resilience of Singapore's power grid. NUS news

13 Nov 2022: 太阳能产业拥抱可持续清洁能源. Zaobao news

18 Nov 2022: The floating solar panels that track the Sun. BBC Future

PRESS RELEASES/JOINT PRESS RELEASE

18 Jun 2022: Solar Energy Research Institute of Singapore (SERIS) Opts for SALD

3 Nov 2022: Enhancing Singapore's Solar Adoption and Grid Reliability with Solar Forecasting Tools

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)
- The Renewables Journal on Wind, Water and Solar, Springer, Germany (Dr Thomas REINDL, 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 2022)(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)
- Judging panel of the Singapore Energy Grand Challenge (SEGC) (Youth) 2022 organised by the Energy Market Authority of Singapore (EMA)(Prof Armin ABERLE, panel member)
- 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)
- Future Energy Asia (FEA) Exhibition and Summit 2022 (Dr Thomas REINDL, Executive Committee 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)
- WCPEC-8 Scientific Committee, Topic 4, PV Systems Engineering, Integrated/Applied PV (Dr Thomas REINDL, Co-Chair)
- WCPEC-8 Scientific Committee, Topic 4.5, Infrastructure-integrated PV (I2PV) and nature-inclusive PV (eco-PV); vehicle integrated PV (VIPV) (Dr Thomas REINDL, Co-Chair)
- 2nd International Conference on Materials for Humanity (MH 22), Organised by the Materials Research Society of Singapore. Theme 1, Perovskite-based Tandem Solar Cells Symposium (Asst Prof HOU Yi, Chair)
- Member of the "External Advisory Panel for Environmental Sustainability" of the Singapore Ministry of Defence (Dr Thomas REINDL, 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, attendees)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 15 (Dr Veronika SHABUNKO, attendees + sub-task leader until Aug 2022; Dr LEOW Shin Woei since Sep 2022)
- International Electrotechnical Commission (IEC) Technical Committee (TC) 82 ("Solar Photovoltaic Energy Systems"), (Dr Thomas REINDL and Dr Mauro PRAVETTONI, Singapore representatives; Dr Veronika SHABUNKO and Dr HO Jian Wei, as observers)
- National IEC Mirror Committee TC 1 WG10 ("Solar PV Product & Accessories"), Enterprise Singapore Dr Mauro PRAVETTONI, co-convenor; Dr HO Jian Wei, member)
- 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)
- Evaluation Committee of the 2022 Initiation into Research FONDECYT project competition, FONDECYT (Fondo Nacional de Desarollo Científico y Tecnológico - the National Fund for Scientific and Technological Development of Chile)(Dr Mauro PRAVETTONI, evaluator)
- 2022 Silicon PV, in Konstanz, Germany, co-chairmanship of the BiFiPV Workshop (Dr Mauro PRAVETTONI)
- Clean Energy Committee of the Sustainable Energy Association of Singapore (Mr Eddy BLOKKEN, Dr Veronika SHABUNKO, members)
- Energy Efficiency and Finance Committee of the Sustainable Energy Association of Singapore (Dr Veronika SHABUNKO, member)
- "BAPV Review" working group organised by SCDF, Singapore (Dr Thomas REINDL, Dr Veronika SHABUNKO, members)
- Institution of Engineers of Singapore (IES) (Dr Veronika SHABUNKO, member)
- European Metrology Programme, EURAMET2022, Integrated European Metrology (IEM) Review Conference, 10-11 Nov 2022 (Dr Mauro PRAVETTONI, invited referee)
- APEC Engineer and the International Professional Engineer and Institution of Engineer, Malaysia (IEM)(Rachel TAN, member)
- International Professional Engineer (IntPE) (Rachel TAN, Chartered Engineers (CEng) since Dec 2022)
- Asia-Pacific Economic Cooperation (APEC) Engineer (Rachel TAN, Registered since Dec 2022)
- ASEAN Chartered Professional Engineer (Rachel TAN, Chartered PE)
- Registered Foreign Professional Engineer (RFPE) of Professional Engineers Board (PEB), Singapore (Rachel TAN, Registered)
- Registered Professional Engineer of Board of Engineers Malaysia (BEM) (Rachel TAN, Registered)
- Institution of Engineer, Malaysia (IEM)(Rachel TAN, member)
- Technical Resource Group, Solar Decathlon India 2022, Dr Pradeep PADHAMNATH (member)

SERIS MEMBERSHIPS/PARTNERSHIPS

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

VISITORS

18 Feb 2022	Prof. Richard Parker (Chairman, Singapore Aerospace Programme, AStar)
22 Mar 2022	Ms Paula Conboy, Senior Counsel, Sussex Strategy Group and Board Member of PJM Interconnection (Board member of EMA)
20 May 2022	Methodist Girls School (Secondary) students and teachers
30 May 2022	Students from University of Texas-Austin
1 Jun 2022	Students from KFUPM, Saudi Arabia

15 Jun 2022	Delegation of the European Union to Singapore, led by Ms Signe Ratso, Deputy Director-General of Research and Innovation, European Commission
1 Aug 2022	Student delegation from University of Twente, the Netherlands
15 Aug 2022	Prof Harry ATWATER, Otis Booth Leadership Chair, Division of Engineering and Applied Science, Howard Hughes Professor of Applied Physics and Materials Science, and Director, Liquid Sunlight Alliance at the California Institute of Technology
14 Nov 2022	Student delegation from the Singapore Institute of Technology (SIT)
25 Nov 2022	Teachers from Westwood Secondary School
1 Dec 2022	Delegation from the Industrial Technology Research Institute (ITRI), Taiwan.

OUTREACH ACTIVITIES

7 Jan 2022	Eddy BLOKKEN provided e-consultation to student from Hwa Chong International for his project work (via Zoom)
22 Jan 2022	Prof Armin ABERLE reaching out to NUS undergraduates via the NUS-BES Environmental Conference (via Zoom)
4 Mar 2022	Dr Stephen TAY gave a talk to students from Kuo Chuan Primary School (via Zoom)
8 Apr 2022	Dr Amit Singh RAJPUT provided ideas to Hwa Chong JC1 students for their project work (via Zoom)
19 Apr 2022	Dr Stephen TAY gave a talk on Solar Energy Technology Development and Innovation in Singapore to students of Zhonghua Primary School (via Zoom)
23 May 2022	Eddy BLOKKEN provided e-consultation to student from UWCSEA for his project work (by Zoom)
1 Aug 2022	Eddy BLOKKEN gave a talk to students delegation from University of Twente, The Netherlands
19 Aug 2022	Dr Mauro PRAVETTONI providing technical advice to a group of students from Jurong Pioneer Junior College for their "A" Level Project Work (PW) Report on Ocean Acidification
9 Sep 2022	Outreach to kids at Emerson's event (Dr Donny LAI)
5 Oct 2022	Outreach to NTU Undergraduate and Postgraduate students - School of Materials Science and Engineering. Industry Coffee Chat on Environment and Sustainability at NTU (Dr Donny LAI)

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

7-8 Apr 2022	IPV Workshop, China (online)
14 Apr 2022	International Green Energy Conference 2022, PV Market Insights 2022, KIER-SERIS Urban Solar/ BIPV Session, South Korea
26-28 Oct 2022	Asia Clean Energy Summit Conference & Exhibition (ACES 2022), Singapore
21 Nov 2022	Solar Industry Workshop, co-organised by EMA, BCA and SERIS

TEACHING/LECTURES AT UNIVERSITIES

Prof Armin ABERLE, for NUS Graduate School for Integrative Sciences and Engineering (NGS) Module GS6883A Interface Sciences and Engineering (Renewable energy part), AY21/22, Semester 2, National University of Singapore (NUS)

Prof Armin ABERLE, for Electrical and Computer Engineering Module EE4438 Solar Cells and Modules, AY21/22 Semester 2, National University of Singapore (NUS)

Prof Armin ABERLE, for NUS Graduate School for Integrative Sciences and Engineering (NGS) Module GS6883A Interface Sciences and Engineering (Renewable energy part), AY22/23, Semester 1, National University of Singapore (NUS)

Dr Thomas REINDL. Guest lecture on 'Global Sustainability and Renewable Resources', invitation by Global Academic Ventures (GAV), May 2022

Dr Veronika SHABUNKO. Guest lecture PF 3301: Maintainability of Facilities, Department of the Built Environment, College of Design & Engineering, module PF3301 "Maintainability of Facilities", invited by Prof Chew Yit Lin, Michael (1 Mar 2022)

Dr Veronika SHABUNKO. Guest lecture for Department of Architecture, College of Design & Engineering, module AR2723 "Strategies of Sustainable Architecture", invited by A/Prof Yuan CHAO (31 Mar 2022)

Dr Serena LIN Fen. Guest lecture: Solar Cell Basics, Electronics and Data Engineering Programme, Singapore Institute of Technology (SIT), Module EDE3103 "Semiconductor Devices", invited by Prof Xiang Ning (7 Nov 2022)

PATENT APPLICATIONS IN 2022

Nitin Nampalli, Shubham Duttagupta. Multi-layer contact stack, photovoltaic cells made thereof and methods to form them. SG patent number 10202202509U, filing date 11 Mar 2022

Naomi Nandakumar, Shubham Duttagupta. Pradeep Padhamnath. High-efficiency solar cells and the fabrication methodology. SG patent application number 10202202513Q, filing date 11 Mar 2022

Pradeep Padhamnath, Shubham Duttagupta. Surface treatment method for forming a passivated contact of a solar cell, International Patent PCT/SG222/050169, filing date 28 Mar 2022, Publication date 6 Oct 2022

Mauro Pravettoni. Solar testing dome for electrical characterisation of solar photovoltaic modules (2021-059), SG patent number 10202203188V, filing date 29 Mar 2022

Nitin Nampalli, Jeremie Werner, Shubham Duttagupta. Electrodes for halide perovskite devices, SG non-provisional application number 10202250301J, filing date 27 Jun 2022

Ho Jian Wei, Chan Keng Siew, Heng Min Xuan Clarence, Xin Zheng. Machine learning accelerated extraction of diffusion and surface passivation parameters from finished solar cells. SG non provisional application number 10202250474W, filing date 15 July 2022

Khoo Yong Sheng, Wang Yan, Saw Min Hsian, Tai Kong Fai, Leow Shin Woei. An improved photovoltaic device. SG patent number 11202251769V, filing date 2 Aug 2022

Khoo Yong Sheng, Wang Yan, Saw Min Hsian, Tai Kong Fai, Leow Shin Woei. An improved photovoltaic device. PCT/SG2021/050073, filing date 11 Aug 2022

Jeremie Werner, Nitin Nampalli, Shubham Duttagupta. Semiconductor devices and methods of batch manufacturing thereof. PCT application number PCT/SG2022/050595, filing date 19 Aug 2022

Jeremie Werner, Nitin Nampalli, Shubham Duttagupta. Method of In-Line Manufacturing semiconductor devices and semiconductor devices thereof. PCT application number PCT/SG2022/050596, filing date 19 Aug 2022

Wang Puqun, Ho Jian Wei, Choi Kwan Bum. Method for luminescence characterisation of optoelectronic materials and devices based on modulated optical excitation. SG patent application No. 10202251380W, filing date 14 Oct 2022

Saw Min Hsian, Srinath Nalluri, Mauro Pravettoni, Gavin Prasetyo Raharjo, Leow Shin Woei, Tai Kong Fai, Khoo Yong Sheng. A cover member for a photovoltaic device. PCT application number PCT/SG2022/050737, filing date 14 Oct 2022

Muhammad Arifeen Wahed, Thomas Reindl. A floating apparatus, and a method of operating the floating apparatus. SG patent application number 11202260078S, filing date 9 Nov 2022

PUBLICATIONS

Book Chapter

Y. Cheng and F. Lin; Semitransparent perovskites for solar cells and smart windows; Invited book chapter in “Perovskite Materials and Devices”, Wiley (in press)

Ho, J.W., Dullweber, T., Fischer, M., Herritsch, S., Trube, J. Chapter 2: Main Requirements for Solar Cells” for a book “Silicon Solar Cell Metallization and Module Technology”, publisher IET, ISBN-139781839531552, ISBN-10183953155X, 10 Jan 2022

Padhamnath P., Khanna A., Aberle A.G., Duttagupta S., “Metallisation of poly-Si passivated contact cells”, book chapter, Silicon solar cell metallisation and module technology, publisher IET, ISBN-139781839531552, ISBN-10183953155X, 10 Jan 2022

Journal Papers

Ren, Z., Tian, S.I.P., Noh, J. et al. An invertible crystallographic representation for general inverse design of inorganic crystals with targeted properties. Matter Vol. 5, Issue 1, 314-335 (2022)

Pillai, D.S., Shabunko, V., Krishna, A. A comprehensive review on building integrated photovoltaic systems: Emphasis to technological advancements, outdoor testing, and predictive maintenance. Renewable and Sustainable Energy Reviews Vol. 156, 111946 (2022)

Tan, H.Q., Zhao, X., Jiao, A., Birgersson, E., Xue, H. Optimizing bifacial all-perovskite tandem solar cell: How to balance light absorption and recombination. Solar Energy Vol. 231, 1092-1106 (2022)

Gandhi, O., Kumar, D.S., Rodríguez-Gallegos, C.D., Zhang, W., Reindl, T., Srinivasan, D. Effects of ‘invisible’ energy storage on power system operations. Vol. 45, 103626 (2022)

Chen, W., Zhu, Y., Xiu, J. et al. Monolithic perovskite/organic tandem solar cells with 23.6% efficiency enabled by reduced voltage losses and optimised interconnecting layer. Nat Energy 7, 229–237 (2022)

Chan, K.S., Heng, M.X., Ananthanarayanan, D., Choi, K.B., Ho, J.W. Application of non-contact quantum efficiency measurement for solar cell fabrication process insights. Solar Energy 233, 494-503 (2022)

Nandakumar, N., Rodriguez,J.W., Padhamnath, P., Nampalli, N., Aberle, A.G., Duttagupta, S. Large-area monoPoly solar cells on 110 µm thin c–Si wafers with a rear n^+poly-Si/SiO_x stack deposited by inline plasma-enhanced chemical vapour deposition. Prog Photovolt Res Appl., 1–9 (2022)

Yeo, Z.Y., Ling, Z.P., Ho, J.W., et al. Status review and future perspectives on mitigating light-induced degradation on silicon-based solar cells. Renewable and Sustainable Energy Reviews 159, 112223 (2022)

Fu, F., Li, J., Yang, T. C.J. et al. Monolithic perovskite-silicon tandem solar cells: from the lab to fab? Adv. Mater., 2106540 (2022)

Nakka, L., Cheng, Y., Aberle, A.G., Lin, F. Analytical review of Spiro-OMeTAD hole transport materials: paths toward stable and efficient perovskite solar cells. Adv. Energy Sustainability Res., 2200045 (2022)

Li, J., Alvianto, E., Hou, Y. Developing the next generation perovskite/Si tandems: towards efficient, stable, and commercially viable photovoltaics. ACS Appl. Mater. Interfaces 14, 30, 34262–34268 (2022)

Xiao, K., Lin, Y.H., Zhang, M. Scalable processing for realizing 21.7%-efficient all-perovskite tandem solar modules. Science 376, 762–767 (2022)

Chen, T., Sun, H., Tai, K.F., Heng, C.K. Analysis of the barriers to implementing building integrated photovoltaics in Singapore using an interpretive structural modelling approach. Journal of Cleaner Production 365, 132652 (2022)

Sun, X., Yang, D., Gueymard, C.A., Bright, J.M., Wang, P. Effects of spatial scale of atmospheric reanalysis data on clear-sky surface radiation modeling in tropical climates: A case study for Singapore. Solar Energy 241, 525–537 (2022)

S. Kinsey, G.S., Riedel-Lyngskær, N.S., Miguel, A. et al. Impact of measured spectrum variation on solar photovoltaic efficiencies worldwide. Renewable Energy 196, 995-1016 (2022)

Ling, Z.P., Lim, Q.X., Lim, K.N., Ho, J.W., Wang, S. An industrial scale solution to achieving light-induced degradation (LID) free silicon solar systems: > 5% performance gain at system level with advanced hydrogenation technology. Solar Energy Materials and Solar Cells 246, 111888 (2022)

Ram, J.P., Pillai, D.S., Jayan, V. et al. A new minimal relocation framework for shade mitigation in photovoltaic installations using flower pollination algorithm. IEEE Journal of Photovoltaics, vol.12, no. 3 (2022)

Xu, L., Liu, J., Luo, W. et al. Potential-induced degradation in perovskite/silicon tandem photovoltaic modules. Cell Reports Physical Science 3, 101026 (2022)

Zhao, X., Tan, H.Q., Birgersson, E., Chen, W., Hou, Y., Xue, H. Modeling and sensitivity analysis of a two-terminal perovskite on organic tandem solar cell. Cell Reports Physical Science 3, 101038 (2022)

Gandhi, O., Rodríguez-Gallegos, C.D., Zhang, W., Reindl, T., Srinivasan, D. Levelised cost of PV integration for distribution networks. Renewable and Sustainable Energy Reviews 169, 112922 (2022)

Zhang, H., Cheng, Y., Lek, D.G. et al. Membrane-free redox flow cell based on thermally regenerative electrochemical cycle for concurrent electricity storage, cooling and waste heat harnessing of perovskite solar cells. Journal of Power Sources 548, 232081 (2022)

Chen, T., Tai, K.F., Raharjo, G.P., Heng, C.K., Leow, S.W. A novel design approach to prefabricated BIPV walls for multistorey buildings. Journal of Building Engineering 63, 105469 (2023)(published online 1 Nov 2022)

Saw, M.H., Pravettoni, M., Birgersson. E. STC short-circuit current prediction and I-V simulation of colored BIPV modules with machine learning and one-diode equivalent circuit models. IEEE Journal of Photovoltaics, vol. 12, no. 6, 1533-1542, (2022), doi: 10.1109/JPHOTOV.2022.3195693.

Dasgupta, S., Ok, Y.W., Upadhyaya, V.D., Choi, W.J., Huang, Y.Y., Duttagupta, S., Rohatgi, A. Novel process for screen-printed selective area front polysilicon contacts for TOPCon cells using laser oxidation. IEEE Journal of Photovoltaics, vol. 12, no. 6, 1282-1288 (2022), doi: 10.1109/JPHOTOV.2022.3196822

Karas, J., Repins, I., Berger, K.A., Jiang, F., et al. Results from an international interlaboratory study on light- and elevated temperature-induced degradation in solar modules. Prog Photovolt Res Appl. 30(11), 1255 - 1269 (2022), doi:10.1002/pip.3573

Li, X., Shen, G., Ng, X.R., Liu, Z., Meng, Y., Zhang, Y.-W., Mu, C., Yu, Z.G., Lin, F. (2022). Thermally evaporated ZnSe for efficient and stable regular/inverted perovskite solar cells by enhanced electron extraction. Energy Environ. Mater. Accepted Author Manuscript e12439. https://doi.org/10.1002/eem2.12439

Shen, G., Li, X., Zou, Y., Dong, H., Zhu, D., Jiang, Y., Ng, X.R., Lin, F., Müller-Buschbaum, P. and Mu, C. (2022), High-performance and large-area inverted perovskite solar cells based on NiO_x films enabled with a novel microstructure-control technology. Energy Environ. Mater. Accepted Author Manuscript e12504. https://doi.org/10.1002/eem2.12504

Conference papers/proceedings

Padhamnath, P., Nampalli, N., Werner, J., Aberle, A., Duttagupta, S. Modeling of contact resistivity of fire-through ag-al contacts to boron doped LPCVD polysilicon layers. Conference Proceedings of the MIW 2021, Belgium, published in Feb-Mar 2022

Li, W., Rajput, A.S., Pravettoni, M. analysis of soiling of a 10-year installation in the urban environment and tropical climate. Conference Proceedings of the 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 29 Mar 2022

Pravettoni, M., Chew, W.J., Saw, M.H., Tay, S. Designing the SERIS testing dome for the accurate measurement of large-area photovoltaic modules. Conference Proceedings of the 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 29 Mar 2022

Saw, M.H., Birgersson, E., Pravettoni, M. Spectral mismatch correction for multi-coloured BIPV modules with spot-area spectral responsivity measurements. Proceedings of the 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 29 Mar 2022

Saw, M.H., Nalluri, S., Pravettoni, M. Design of “hotspot-free” BIPV modules – Peranakan PV. Proceedings of the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022

Pravettoni, M., Sundar Das, M.M., Rajput, A.S., Li, W., Valliappan, S. A study of module degradation from a 10-year installation in the urban tropical environment. Proceedings of the 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022

Padhamnath, P., Nampalli, N., Werner, J., Aberle, A.G., Duttagupta, S. Modeling of contact resistivity of fire-through Ag-Al contacts to boron doped LPCVD polysilicon layers. AIP Conference Proceedings 2709, 020010 (2022); https://doi.org/10.1063/5.0126042 (published online 15 Nov 2022)

TALKS AT CONFERENCES, WORKSHOPS AND SEMINARS

(Speaker’s name underlined)

Hou, Y. Emerging perovskites-based tandem solar cells. SolarBE Webinar – Solar Cell PV Technology Series: Progress and New Heights on Perovskite, 11 Jan 2022 (invited speaker and panellist)

Li, J. Towards efficient, scalable and stable perovskite/silicon tandem solar cells. 6th Heterojunction Forum, China, 12-13 Jan 2022

Aberle, A. Implementation & growth of renewable energies in Singapore. NUS-BES Environmental Conference, Singapore, 22 Jan 2022 (invited)(virtual)

Hou, Y. Emerging Perovskites-based Tandem Solar Cells. REC Solar Pte Ltd., Singapore, 10 Mar 2022 (invited)

Pravettoni, M. Analysis of Soiling from a 10-year installation in the urban environment and tropical climate. 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 28-30 Mar 2022

Li, W., Rajput, A.S., Pravettoni, M. Analysis of Soiling of a 10-year installation in the urban environment and tropical climate. 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 29 Mar 2022

Lin, F. Perovskite/Si Tandem: Pathway towards >30% power conversion efficiency. SRM Institute of Science and Technology Symposium, India, 29 Mar 2022 (invited, virtual)

Reindl, T. 100% Renewable Energy scenario with Integrated PV (IPV). 1st International Integrated-PV Workshop, 7-8 Apr 2022 (invited, virtual)

Rodríguez, C. Key learnings from 6 years R&D on the MW-scale FPV testbed in Singapore. 1st International Integrated-PV Workshop, 7-8 Apr 2022 (invited, virtual)

Aberle, A. Solar Photovoltaics – latest trends and research at NUS. Asia-Pacific Carbon Neutrality Joint Symposium, 11-12 Apr 2022 (invited, virtual)

Shabunko, V. Global market trends of urban solar. International Green Energy Conference 2022, PV Market Insights 2022, KIER-SERIS Urban Solar/BIPV Session, South Korea, 14 Apr 2022 (invited, keynote)

Aberle, A. Implementation of growth of solar energy in Singapore. 5th CleanEnviro Summit Singapore (CESG) 2022, Clean Environment Convention (CEC), Sustainable Energy and Energy Efficiency Track, Singapore, 19 Apr 2022 (invited)

Reindl, T. Asia Climate Forum Conference, ACF Wrap-Up Panel Session. How extreme weather & climate change are impacting the routine applications of weather and related data, and how the public, private and academic sectors are responding to the challenges, Singapore, 20 Apr 2022 (invited, panellist)

Pravettoni, M., Rajput, A.S. Stability of silicon photovoltaic modules in intermediate precision conditions of measurement. 2022 MRS Spring Meeting, USA, 9-13 May 2022

Reindl, T. Challenges and outlook for floating solar. INTERSOLAR EUROPE 2022, Technical Conference, FSPV session, Germany, 10-11 May 2022 (invited)

Pravettoni, M. Enhanced stress tests for the reliability of integrated and floating PV. SOPHIA Reliability Workshop Neuchatel, Switzerland, 30 Jun – 1 Jul 2022 (invited)

Reindl, T. Hybrid use of hydropower and floating PV. APVIA Webinar on "Making Floating PV Solar Work in Asia", 1 Jul 2022 (invited)

Aberle, A. Implementation & growth of solar PV in Singapore. Global Photovoltaic Conference 2022 (GPVC), South Korea, 6-8 Jul 2022 (invited, virtual)

Reindl, T. Renewable Energy Panel – Theme: Renewable Energy: Here comes the Sun: Solar in Singapore. Westpac Scholars, Murdoch University & Common Purpose Disruptive Leaders Program, 14 Jul 2022 (invited panellist, virtual)

Wang, P., Lin, F. Detailed engineering of monolithic perovskite / Si tandem solar cells based on biPoly™ silicon solar cells. 2nd TOPCon international conference on Cell Technology and Equipment Innovation, 21-23 Sep 2022, China (virtual)

Aberle, A. PV research and deployment in Singapore. NextGen PV: International Outlook @ IPVF. France, 22-23 Sep 2022 (invited)

Reindl, T. 100% Renewable Energy Scenario – What are the options to deploy all the solar panels? 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022 (invited plenary talk)

Reindl, T. The status and outlook of Floating PV. 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022

Saw, M.H., Nalluri, S., Pravettoni, M. Design of "hotspot-free" BIPV modules – Peranakan PV. 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022

Pravettoni, M., Sundar Das, M.M., Rajput, A.S., Li, W., Valliappan, S. A study of module degradation from a 10-year installation in the urban tropical environment. 8th World Conference on Photovoltaic Energy Conversion (WCPEC-8), Italy, 26-30 Sep 2022

Reindl, T. The impact of resource forecasting on the integration of variable renewable energies into electric power grids. 2022 IEEE ISGT ASIA, 11th International Conference on Innovative Smart Grid Technologies (Asia), Singapore, 1-5 Nov 2022 (invited, keynote)

Liang, T.S., Tai, K.F., Leow, S. W. BIPV for high-rise residential building in Singapore: demonstration and lessons learned. 33rd International Photovoltaic Science and Engineering Conference (PVSEC-33), Japan, 13-17 Nov 2022

Reindl, T. Overview of latest developments in floating solar. Webinar organised by the Singapore Standards Council: TR 100:2022. Floating photovoltaic power plants - Design guidelines and recommendations. 17 Nov 2022 (invited panellist)

Aberle, A. Research, development and deployment of solar energy in Singapore. 3rd Asian Nations Joint Workshop on PV, satellite event of the 33rd International Photovoltaic Science and Engineering Conference (PVSEC-33), 18 Nov 2022 (invited)

Raharjo, G., Saw, M.H., Leow, S.W., Pravettoni, M. A novel pixelation approach to integrate photovoltaics for urban architecture conservation. 2022 Material Research Society (MRS) Fall Meeting & Exhibit, USA, 27 Nov - 2 Dec 2022

POSTERS AT CONFERENCES AND SEMINARS

(Presenter's name underlined)

Saw, M.H., Pravettoni, M. Evaluating spectral mismatch correction for multi-colored photovoltaics modules with spot-area spectral responsivity measurements. 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 28-30 Mar 2022

Pravettoni, M., Chew, W.J., Saw, M.H., Tay, S. Designing the SERIS testing dome for accurate measurement of large-area photovoltaic modules. 12th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2022), Germany, 28-30 Mar 2022

Nalluri, S., Leow, S.W. Electrohydraulic Fragmentation of PV Modules. Regional Industry Networking Conference 2022, Singapore, 1 Nov 2022

Liang, T.S., Leow, S. W., Pravettoni, M. Validation of bifacial PV's irradiance simulation software via En score to account for measurement and simulation uncertainties. 33rd International Photovoltaic Science and Engineering Conference (PVSEC-33), Japan, 13-17 Nov 2022

Padhamnath, P., Venkataraj, S., Nampalli, N., Aberle, A. Analysis of metal-TCO contacts for low-temperature screen-printed metallisation of silicon heterojunction and perovskite-based tandem solar cells. 33rd International Photovoltaic Science and Engineering Conference (PVSEC-33), Japan, 13-17 Nov 2022

Saw, M.H., Birgersson, E., Pravettoni, M. Spectrometric characterisation of polychromatic BIPV modules. 33rd International Photovoltaic Science and Engineering Conference (PVSEC-33), Japan, 13-17 Nov 2022

Yap, Q.J., Liu, T., Li, X., Wang, P., Lin, F. Effect of annealing on the electrical and optical properties of tin oxide electron transport layers for perovskite solar cells. Grand Renewable Energy 2022 International Conference (GRE2022), 13-20 Dec 2022 (online)

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EDITOR IN CHIEF
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Prof Armin ABERLE
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EDITORIAL ADDRESS
Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)
7 Engineering Drive 1
Block E3A, #06-01
Singapore 117574
SINGAPORE
Tel: +65 6516 4119
Fax: +65 6775 1943
seris-info@nus.edu.sg
www.seris.sg

SERIS at CleanTech Park (off-campus facilities)
Solar Energy Research Institute of Singapore (SERIS)
PV Modules for Urban Solar Cluster
1 CleanTech Loop
#06-01, CleanTech One
Singapore 637141
seris-info@info.edu.sg
(+65) 6567 8073
(+65) 6775 1943

SERIS at NUS (main facilities)
Solar Energy Research Institute of Singapore (SERIS)
National University of Singapore (NUS)
7 Engineering Drive 1
#06-01, Block E3A
Singapore 117574
seris-info@info.edu.sg
(+65) 6516 4119
(+65) 6775 1943

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