



NUS
National University
of Singapore



Annual Report 2021



NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE



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

Images on cover page (Clockwise from top):

- **Top:**
□ Peranakan-inspired colourful BIPV modules developed by PV Modules for Urban Solar Cluster at SERIS
- **Right:**
□ Singapore's Tengeh reservoir, showing the new 60 MW_p solar farm by Sembcorp, next to the 1 MW_p SERIS testbed (in collaboration with PUB and EDB). SERIS' scientific evaluations from the testbed were vital for the large-scale adoption of Floating PV in Singapore. (Image credit: Sembcorp Industries)
- **Bottom:**
□ A 23% efficient wide-bandgap (1.62 eV) perovskite solar cell made by the Perovskite-based Multijunction Solar Cells Group at SERIS
- **Left:**
□ CAiA Lab tool for single-sided plasma deposition of doped Si layers and transparent metal oxides

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Feedback from Key Stakeholders

National University of Singapore (NUS)

"At NUS, we are dedicated to the development of sustainability technologies and urban solutions that meet the challenges posed by a changing climate. SERIS, as a leader in the development and deployment of solar energy solutions, plays a pivotal role in the University's pursuit for green energy technologies, and is integral in the nation's effort to meet the sustainability targets outlined in the Singapore Green Plan 2030."

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

National Research Foundation Singapore (NRF)

"SERIS has built up capabilities over the years to provide novel solar solutions unique to Singapore's urban environment such as their work on floating solar PV on our reservoirs and building-integrated PV (BIPV). SERIS' efforts will continue to support the nation's solar ambition and contribute to our net zero emissions future."

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

Energy Market Authority (EMA)

"SERIS' research in solar plays an important role in supporting Singapore's goal to maximise the use of clean energy and to reduce our carbon emissions. They have been pushing the boundaries of solar research to develop new and innovative solar applications, such as on water spaces and on building facades, which would increase the solar deployment opportunities in land-scarce Singapore."

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

Singapore Economic Development Board (EDB)

"SERIS plays an important role in Singapore's decarbonisation journey by driving innovations in high-efficiency solar cell technologies and novel deployment solutions. Its work has facilitated further investments from large solar manufacturers, and enabled solar deployments in locations with space constraints. SERIS is expanding its activities by providing techno-economic expertise to investors and financiers. This will support Singapore's ambitions to become a green financing hub in Asia."

Mr Damian CHAN, Executive Vice President of the Singapore Economic Development Board (EDB) and member of the SERIS Supervisory Board

CEO's Foreword

Global news in 2021 were dominated by two topics - the COVID-19 pandemic and climate change. While the pandemic will soon be overcome as a result of technological breakthroughs with vaccines and prescription drugs, COP-26 in Glasgow showed that the world is less united in the fight against global warming and rising sea levels, and that some countries remain reluctant to quickly phase out coal, the most polluting fossil fuel. However, COP-26 was a success by demonstrating that close to 200 nations are firmly committed to the transformation of their energy systems towards sustainability and a low-carbon future.

To avoid excessive warming and achieve the 1.5°C goal of the 2015 Paris Agreement (COP-21), as many countries as possible must stabilise their carbon emissions during this decade and achieve net-zero emissions by the middle of the century. Singapore is part of these global efforts. In February 2021, to accelerate the local energy transformation, the government launched the *Singapore Green Plan 2030* (or *SG Green Plan* for short), 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.

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.

Despite numerous challenges brought about by the COVID-19 pandemic, SERIS continued to operate smoothly in 2021 and there were no employee retrenchments. With the increasing importance of solar deployment in the city-state, on 1st April 2021 the Energy Market Authority (EMA) of Singapore became SERIS' new Implementing Agency (or main grantor), and SERIS has since been further enhancing its programmes in the "downstream" areas, i.e. solar PV system and deployment-related activities. SERIS is presently in the final months of Phase-3 funding, and is on track to achieving the Phase-3 KPIs (key performance indicators). NUS and the grantors remain highly supportive of SERIS, and it is expected that the institute will continue to receive government core funding in its next funding period (Phase 4, FY2022 - FY2026).

This report presents SERIS' major achievements in calendar year 2021 and the R&D plans for 2022. It also describes the institute's research departments ("clusters") and groups, as well as its facilities & laboratories, services, and outreach activities. In 2021, SERIS' R&D focus was on its three flagship projects (tandem solar cells, building-integrated PV modules & systems, floating solar systems), the further development of our proprietary monoPoly™ and biPoly™ passivated-contact silicon solar cell technologies, the invention of a solar testing dome for the accurate characterisation of novel PV modules with natural sunlight, the implementation of an operational solar forecasting system for Singapore, and on collaborative research projects with industry partners.

Notable SERIS achievements in 2021 include polysilicon-based tunnel junctions for perovskite/silicon tandem solar cells, the development of a 23.3% efficient wide-bandgap perovskite solar cell, a 23.6% perovskite/organic tandem solar cell and a 26.1% perovskite/silicon tandem cell (small-area cells), the demonstration of 24% efficiency for large-area monoPoly™ silicon cells, the invention & development of a unique PV module technology coined the "Peranakan" BIPV module, the development of a novel measurement technology for the characterisation of the incident angle modifier of large-area commercial modules, the completion of three comprehensive PV module reliability analyses for "old" (up to 10 years) PV systems in Singapore, a comprehensive analysis of near- and off-shore Floating Solar technologies (36 floats, 29 PV modules, 73 potential risk factors identified), a global assessment of water bodies suitable for floating solar (TW-scale opportunities), and the launch of the International Floating Solar Society (IFS²). SERIS also contributed to the national standards for Renewable Energy Certificates (RECs) and for Floating Solar systems.



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 (EMA), the Singapore Economic Development Board (EDB), our Supervisory Board, our International Advisory Panel, and other collaborators in the public and private sectors.

Singapore is small and its fight against global warming might appear less significant compared to other countries. However, since half of the world's population already lives in urban areas, and with projections that this share will increase to more than 75% by the end of the century, Singapore's efforts towards becoming a Global City of Sustainability could serve as a role model for many other large cities in Asia-Pacific and beyond. Given solar energy's huge potential for rural and urban areas, 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
17 December 2021

Highlights 2021



Dec: A record efficiency of 23.3% for “p-i-n” structured perovskite single-junction solar cells was achieved by Assistant Prof Hou’s group at SERIS. The “p-i-n” structured perovskite solar cell device was fully prepared at SERIS and certified by NREL.



Nov: SERIS secures the extension of SERIS' scope of ISO/IEC 17025 accreditation to solar simulator classification (IEC 60904-9). This will allow SERIS to provide a fundamental support to the local and regional industry in their highest quality standards for module manufacturing.

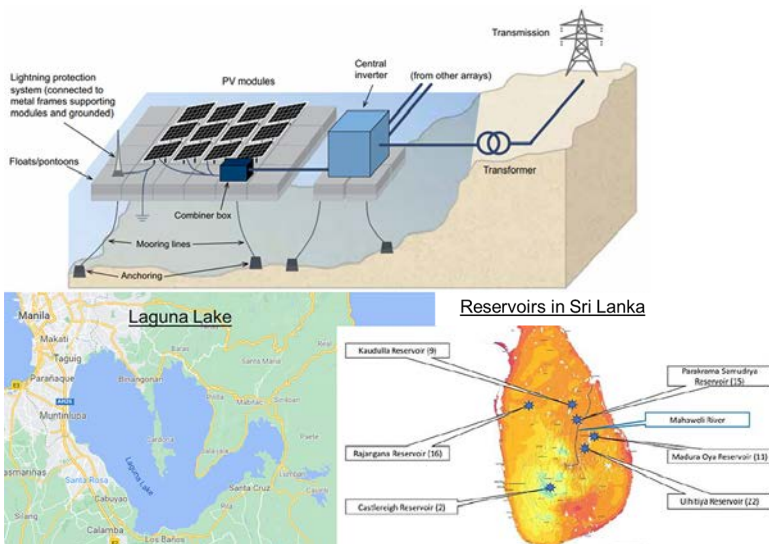


Inspired by the Peranakan culture, these innovative PV modules developed by SERIS are well suited for integration into the facades of buildings, both old and new.

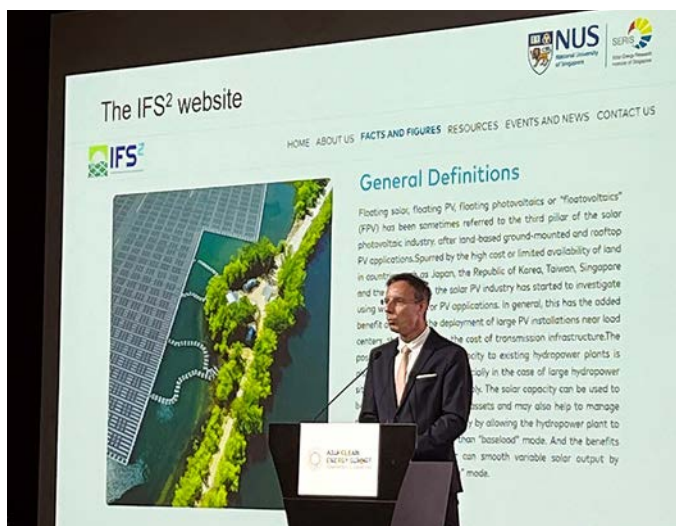
Nov: SERIS invents a PV module inspired by Singapore and Malaysia’s “Peranakan” culture

With appropriate selection of colour and pattern, all solar cells in Peranakan modules are designed to have uniform optical transmittance, so there is no current mismatch between the individual cells and thus also no “hot spots”. These colourful PV modules are well suited for integration into the facades (building-integrated PV, BIPV) of modern as well as heritage buildings, by enhancing their aesthetic appeal and at the same time linking the Peranakan tradition with the generation of clean and sustainable energy.

This innovative PV module technology developed by SERIS has been filed with the Registry of Patents, Singapore.



Nov: SERIS’ expertise in Floating Solar is well sought after by regional governments and multi-national lenders such as the World Bank Group (World Bank, IFC) and the Asian Development Bank (ADB) for countrywide assessment of reservoirs and guidance in adoption of Floating PV in their national solar deployment strategies. After successful projects in Myanmar and Vietnam, SERIS is working now with its long-term partner, Suntrace GmbH (Germany) in Sri Lanka and the Philippines where the scope also includes Laguna Lake (near Manila) which has a size of 900 km² and a shoreline of 220 km in length.

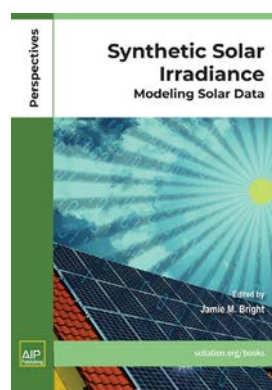


Oct: Launch of the International Floating Solar Society (IFS²) at Asia Clean Energy Summit Conference & Exhibition 2021

Singapore continues its leading role in the area of "Floating Solar". After having started the first conference series dedicated to Floating PV (FPV), the International Floating Solar Symposium (IFSS), as early as 2017, the Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore (NUS) now launches the International Floating Solar Society (IFS²). IFS² is a web-based community that aims to further evolve and nurture the exchange of experiences, information, and data across the sector and to provide a one-stop shop for people interested in Floating Solar, be it from academia, industry, public sector, investors, developers, or financing.



Jul: Stanford University (USA), together with the publishing company Elsevier (Netherlands) and SciTech Strategies (USA), has created a list of 2% of the best scientists in the world based on their career performance. The list includes three members of NUS-SERIS, all ranked in the top 0.4%: Prof Armin ABERLE (left), Prof Seeram RAMAKRISHNA (middle) and Prof Dipti SRINIVASAN (right). The database of top scientists provides standardised information on the total number of citations in Scopus (Elsevier's abstract & citation database), h-index, the Schreiber coauthorship-adjusted hm index, citations to papers in different authorship positions, and a resulting overall score ("composite indicator"). The database is publicly available at <https://dx.doi.org/10.17632/btchxktzyw>



Apr: A book entitled "Synthetic Solar Irradiance: Modeling Solar Data", edited by SERIS Senior Research Fellow Dr Jamie BRIGHT was published by AIP Publishing LLC.



(Image: Reproduced from Synthetic Solar Irradiance: Modeling Solar Data, edited by Jamie M. Bright [AIP Publishing (online), Melville, New York, 2021], available at: <https://doi.org/10.1063/9780735421820>, with the permission of AIP Publishing. © 2021 AIP Publishing LLC)



May: An image showing photovoltaic panels integrated onto 4 prefabricated concrete units at the Prefabricated Prefurnished Volumetric Construction (PPVC) factory in Johor Bahru, Malaysia. This is a Building-integrated Photovoltaics (BIPV) innovative project developed by SERIS to explore various BIPV integration methods and interconnection technology.



Jan: SERIS installed and commissioned a Solar Artwork in CDL City Square Mall, outside the Singapore Sustainability Academy.



Institute In Brief



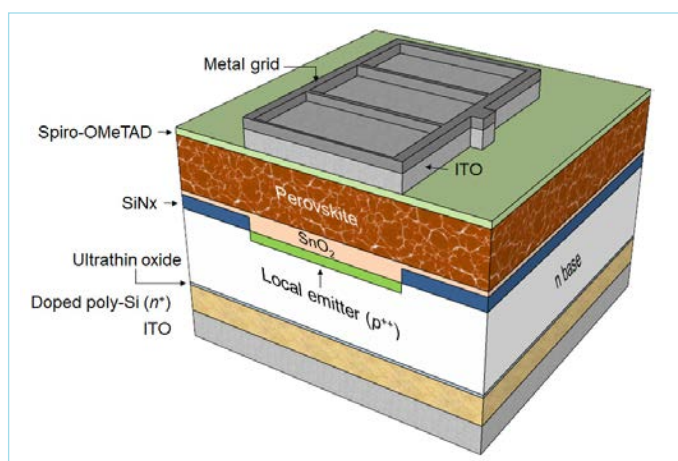
Introduction

The Solar Energy Research Institute of Singapore (SERIS) at the National University of Singapore is the city-state's national institute for applied solar energy research. SERIS is supported by the National University of Singapore (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 commenced operations in 2008 and has emerged as one of the leading solar laboratories in the world. SERIS conducts research, development, testing and consulting on solar energy technologies and their integration into 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 cells, modules and systems.

As the national solar energy research institute, SERIS is one of the pillars of Singapore's efforts towards reducing its greenhouse gas emissions and carbon intensity. Through its R&D and innovations on solar cells, modules and systems, training of local talents, and provision of technical expertise to government agencies and the solar industry, SERIS continues to play a critical role in building the local solar ecosystem and supporting the solarisation of Singapore.

SERIS collaborates closely with universities, research organisations, government agencies and industry, both locally and globally. The collaborations with companies from the global solar sector span from small start-ups to industry leading heavyweights. SERIS is globally active but focuses on technologies and services for tropical regions, in particular for Singapore and South-East Asia.



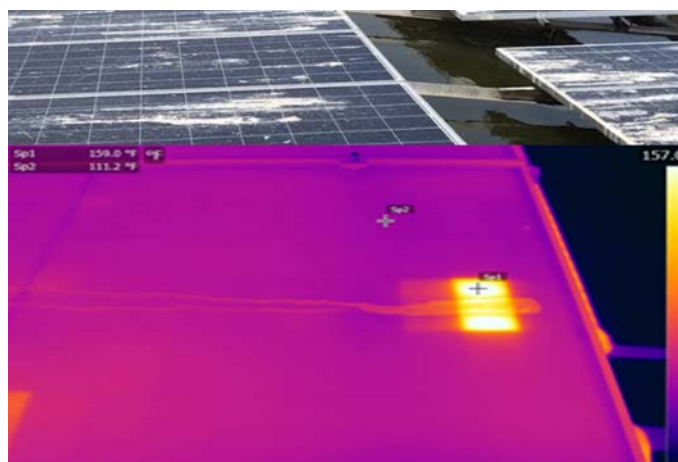
 Schematic structure of a perovskite/Si 2-terminal tandem solar cell made in SERIS, which includes a customised monoPoly™ silicon bottom cell and a spin-coated perovskite top cell



 Inline wet-chemistry tool for single-side processing of silicon wafers in the SERIS cleanroom laboratory



 A "modular pod" developed by SERIS, currently installed at Central Mall, containing prefabricated BIPV elements that would allow architects and developers to easily adopt BIPV into buildings



 Infrared (IR) assessment of a "hot spot" from soiling (here: from bird droppings) on a Floating Solar module at the 1 MW_p FPV testbed at Tengeh reservoir

Business Areas

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

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

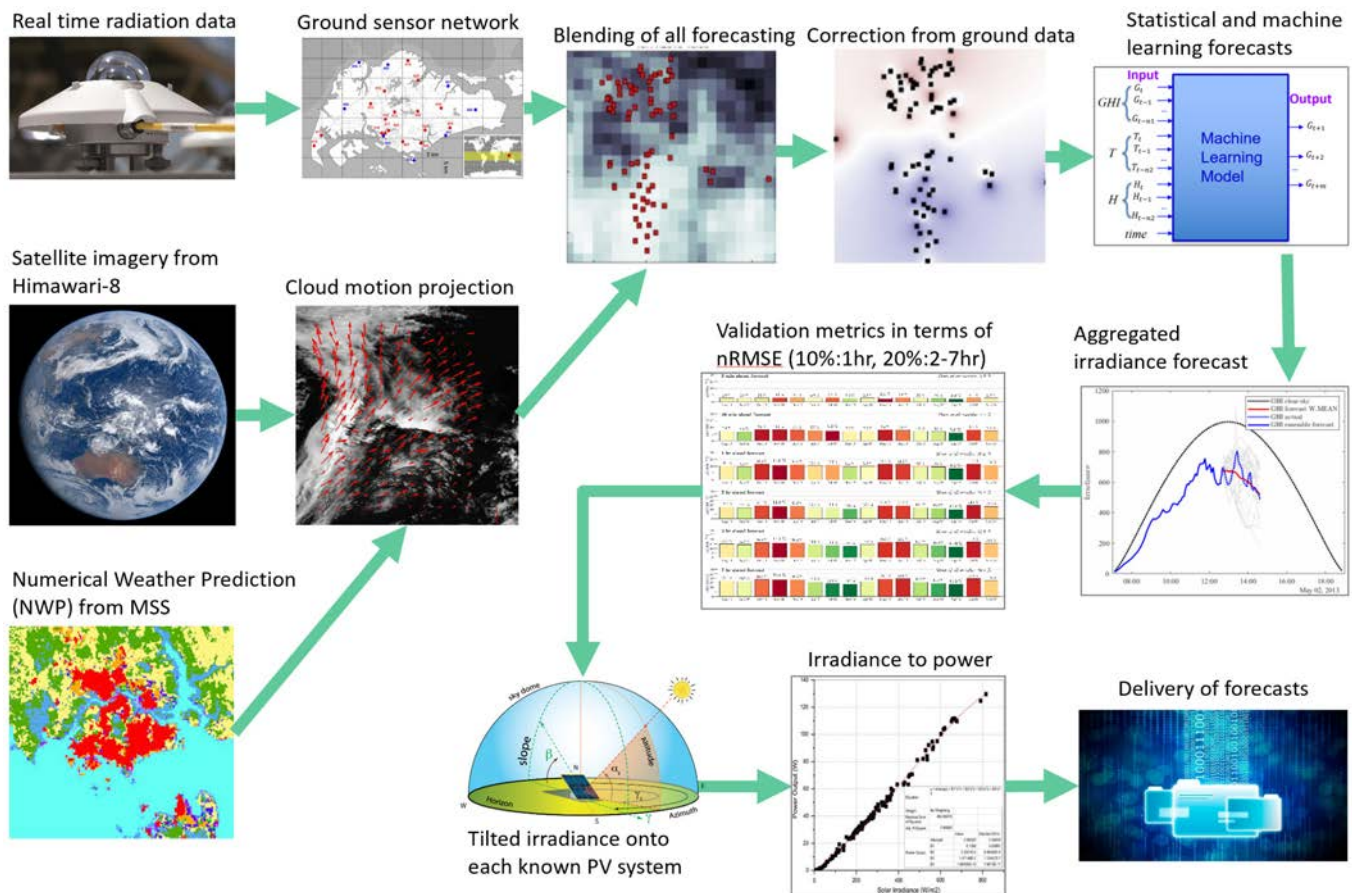
Collectively, these 4 research clusters operate and support SERIS' three main business areas:

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



A robust and fully operational solar power forecasting system designed and developed by SERIS. The system is being trialed, and subsequently deployed, at the Energy Market Authority's Power Systems Operation Division to forecast solar power generation over different time horizons from 5 minutes to 7 hours, and day-ahead.

Finances

For Financial Year (FY) 2021, core funding from the National Research Foundation Singapore (NRF) and the National University of Singapore (NUS) is anticipated at SGD 16.8 million. The core funding is complemented by grants from public competitive R&D programmes and funds from industry contracts of approximately SGD 10.4 million and SGD 2.0 million, respectively. These are projected amounts, as FY 2021 will end on 31 March 2022. The distribution of the projected SERIS funding of SGD 29.2 million for FY 2021 is displayed in Figure 1.

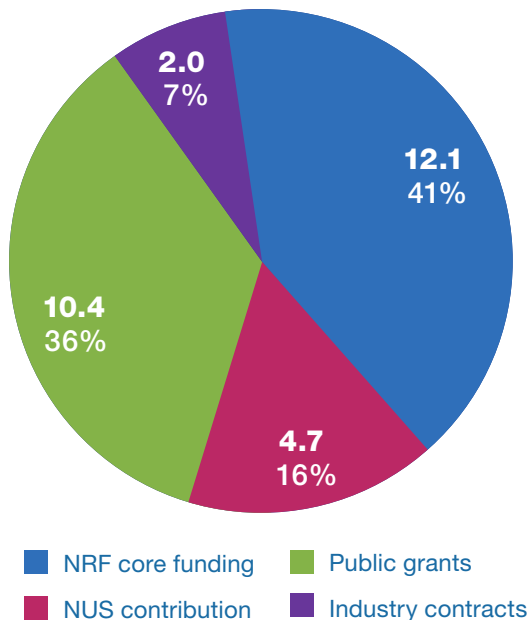


Figure 1: Projected SERIS funding for FY 2021 (1 Apr 2021 to 31 Mar 2022, in SGD million)

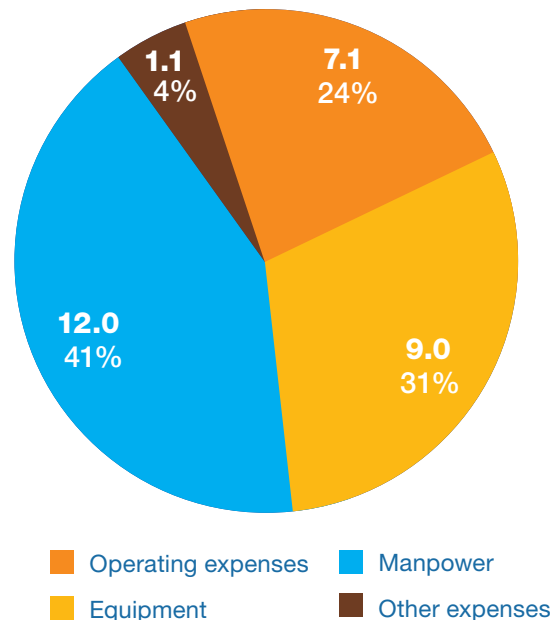


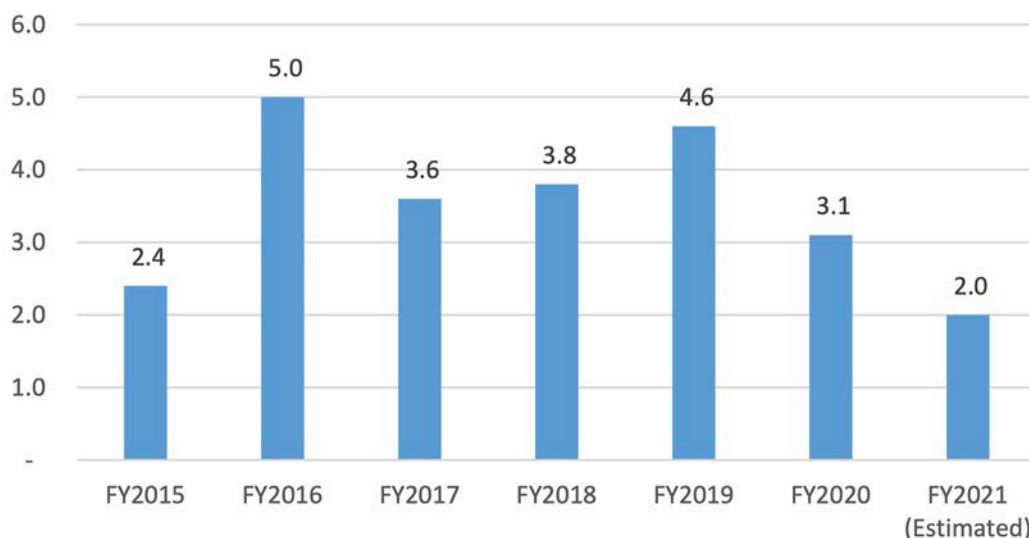
Figure 2: Projected expenses for FY 2021 (1 Apr 2021 to 31 Mar 2022, in SGD million)

In FY 2021, SERIS projects expenditures of SGD 12.0 million on manpower, SGD 9.0 million on equipment, and SGD 7.1 million on operating expenses (Figure 2). Other expenses of SGD 1.1 million include infrastructure, indirect research costs, and non-refundable GST (Goods and Services Tax).

Evolution of SERIS' industry income

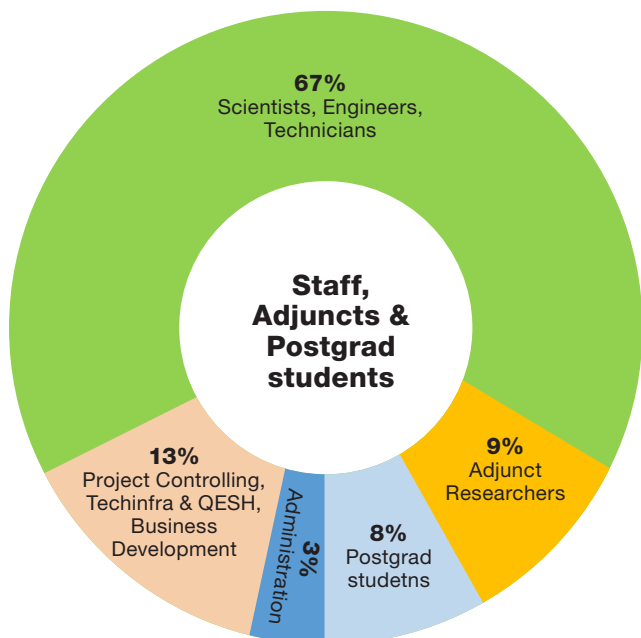
As shown in the graph below, SERIS' annual industry income in the last six years has been in the range of SGD 2.4 to 5.0 million, with an average of about SGD 3.8 million per year. The expected drop in FY 2021 to SGD 2.0 million is due to the continuing effect from the outbreak of the global coronavirus pandemic since early 2020, which is severely affecting SERIS' ability to secure new research projects with industry collaborators.

SERIS Industry Income (in SGD million)

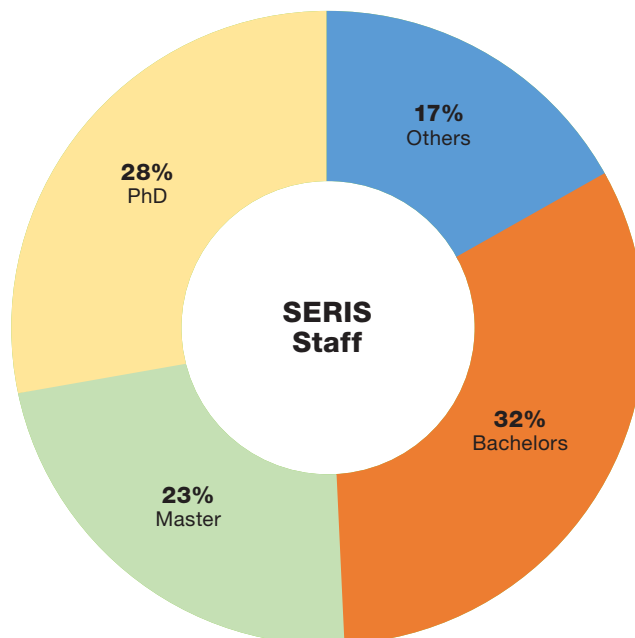


Headcount

At the end of calendar year 2021, the SERIS headcount was 138, including postgraduate students and adjunct researchers from NUS. The figure shows that research personnel - including scientists, engineers, technicians, postgraduate students and adjunct researchers – constitute 84% of the total SERIS headcount. Employees from Project Controlling, Technical Infrastructure & QESH and Business Development form 13% of the total headcount, while administrative staff represent 3% of the headcount.



Breakdown of SERIS headcount in November 2021



Educational qualification of SERIS staff

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 1,720 m² of laboratory and office space at its off-campus locations at CleanTech Park and JTC MedTech Hub (until Oct 2021), where the PV Module Development and Testing laboratories 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 Clean Tech Park



PV System Monitoring laboratory at SERIS, NUS

International Advisory Panel

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

Chairman of the SERIS IAP



Prof Andrew BLAKERS

Professor
School of Engineering,
Australian National University (ANU),
Australia

Members of the SERIS IAP



Dr Dan ARVIZU

Chancellor
New Mexico State University System
USA



Prof Sarah KURTZ

Professor
University of California Merced
USA



Mr Steve O'NEIL

REC Board of Directors
Singapore & Norway



Mr Frank PHUAN

CEO & Executive Director
Sunseap Group Pte Ltd
Singapore



Dr SHI Zhengrong

Chairman and Founder
Sunman Energy Co. Ltd.
PR China



Prof Eicke WEBER

Professor Emeritus,
Department of Materials Science
University of California, Berkeley,
USA

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.

Chairman of the SERIS Supervisory Board



Prof LIU Bin

Vice President (Research & Technology)
Office of the Deputy President (Research & Technology),
NUS, Singapore

Members of the SERIS Supervisory Board



Mr ANG Kian Seng

Group Director
Environmental Sustainability Group
Building and Construction Authority (BCA)
(since Sep 2021)



Mr Damian CHAN

Executive Vice President
Economic Development Board of
Singapore (EDB)
(until Aug 2021)



Ms Irene CHEONG

Director, Technology Translation and
Venture Creation
NUS Industry Liaison Office
NUS, Singapore
(until Feb 2021)



Mr Ralph FOONG

Deputy Chief Executive
Energy Planning & Development Division
Energy Market Authority, Singapore
(since Apr 2021)



Mr HONG Howe Yong

Deputy Head, Group Centre
of Excellence
Sembcorp Industries Ltd.
(since Sep 2021)



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



Dr Richard KWOK Wai Onn

Assistant Chief Executive Officer,
Trains, and Chief, Joint Readiness
Inspection (READI)
SMRT Trains Ltd
(until Aug 2021)



Mr LIM Wey Len

Senior Vice President
Head, Energy & Resources, and
Environmental Sustainability,
Economic Development Board of
Singapore (EDB)
(since Sep 2021)



Mr Bernard NEE Seng Soon

Deputy Chief Executive
Energy Planning & Development Division
Energy Market Authority, Singapore
(until Feb 2021)



Mr NI De En

Director, Urban Solutions & Sustainability
National Research Foundation
Singapore (NRF)
(since Sep 2021)



Dr Shankar SRIDHARA

Chief Technology Officer
REC Solar Pte Ltd, Singapore



Dr Subramanian VENKATRAMAN

Executive Director, IPM and
Commercialisation
Industry Liaison Office
NUS, Singapore
(since Feb 2021)



Mr Kelvin WONG

Chief Executive Officer
Building and Construction Authority of
Singapore (BCA)
(until Aug 2021)



Prof YEOH Lean Weng

Senior Director, Urban Solutions
& Sustainability
National Research Foundation
Singapore (NRF)
(until Jul 2021)



Organisation Structure



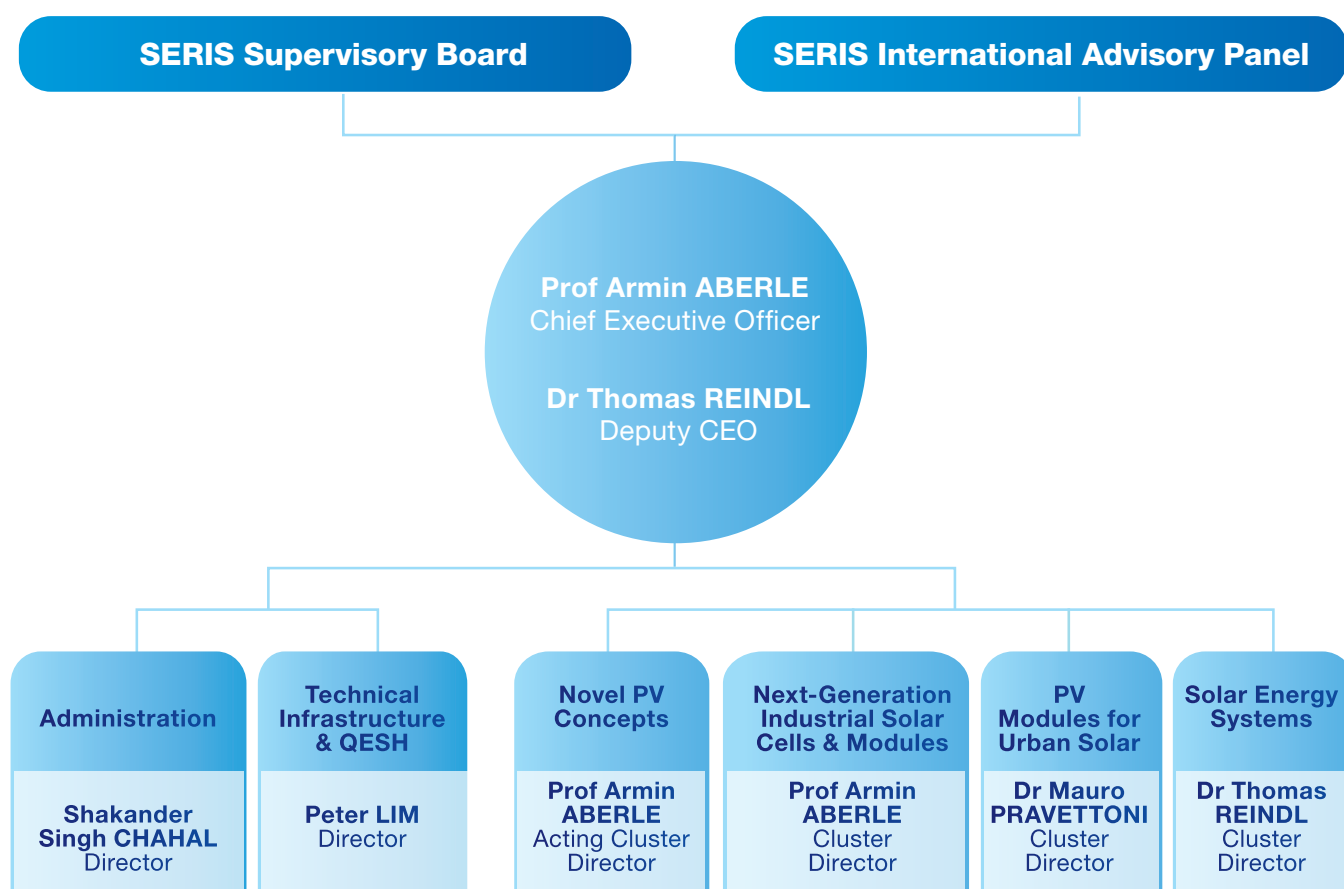
Organisational Chart

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

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

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

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



SERIS Senior Management

- CEO
- Deputy CEO

Research Clusters

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

Central Service Units

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

Management Team



 SERIS Management Team (left to right): Mr Shakander Singh CHAHAL, Dr Thomas REINDL, Prof Armin ABERLE, Dr Mauro PRAVETTONI, Mr Peter LIM
(The above management team photo is edited with photoshop from a previous photo taken before the COVID pandemic)

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

Management Team

Prof Armin ABERLE

CEO
 Cluster Director, Next-Generation Industrial Solar Cells and Modules
 Acting Cluster Director, Novel PV Concepts
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Dr Thomas REINDL

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 Cluster Director, Solar Energy Systems
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Dr WANG Yan

Cluster Director, PV Modules for Urban Solar (until Mar 2021)

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Mr Peter LIM

Director, Technical Infrastructure and QESH
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Secretary to CEO



Mythel Ann ROBERTS

Secretary to CEO and Next-Generation Industrial Solar Cells & Modules 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, 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.



Assoc Prof Karl Erik BIRGERSSON
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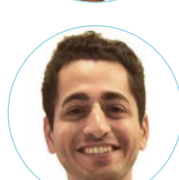
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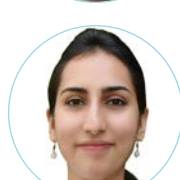
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(since Jun 2021)



Dr YAN Xia
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(until Sep 2021)



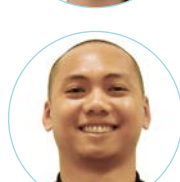
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(until Mar 2021)



Dr Naomi NANDAKUMAR
Team Leader, Solar Cell Innovations
Advanced Solar Cells Group
NISCM Cluster
naomi.nandakumar@nus.edu.sg



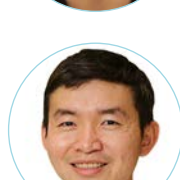
Dr Nitin NAMPALLI
Team Leader, Heterojunction Solar Cells
Advanced Solar Cells Group
NISCM Cluster
nitin.nampalli@nus.edu.sg



Dr John RODRIGUEZ
Team Leader, Passivated Contact Solar Cells
Advanced Solar Cells Group
NISCM Cluster
john.rodriguez@nus.edu.sg
(until Mar 2021)



Dr Prabir Kanti BASU
Team Leader, Front-End R&D Support
PV Production Technologies Group
NISCM Cluster
prabir.basu@nus.edu.sg
(until Mar 2021)



Dr KHOO Yong Sheng
Head, PV Module Development Group
PV Modules for Urban Solar Cluster
yongshengkho@nus.edu.sg
(until May 2021)

**Dr TAI Kong Fai**

Head, PV Module Development Group
PV Modules for Urban Solar Cluster
kongfai.tai@nus.edu.sg
(since Jun 2021)

**Dr Carlos RODRÍGUEZ**

Head, Solar System Technology Group
SES Cluster
carlos.rodriguez@nus.edu.sg
(since Jun 2021)

**Dr KAM Zhi Ming**

Head, PV Quality Assurance Group
SES Cluster
zhiming.kam@nus.edu.sg
(since Dec 2021)

**Dr Veronika SHABUNKO**

Head, Centre of Competence for
Building-integrated PV, SES Cluster
veronika.shabunko@nus.edu.sg

**TAN Congyi**

Head, Urban Solar Group, SES Cluster
Head, National Solarisation Centre
congyi.tan@nus.edu.sg
(until Jan 2021)

**HOO Shan Shan**

SERIS Business Partner Finance
NUS
shanshan@nus.edu.sg

**Dr LUO Wei**

Team Leader, PV Module Reliability
PV Modules for Urban Solar Cluster
luowei@nus.edu.sg
(until Aug 2021)

**Dr Abhishek KUMAR**

Head, Solar System Technology Group
SES Cluster
abhishek.kumar@nus.edu.sg
(until Apr 2021)

**Dr Darryl WANG**

Head, PV Quality Assurance Group
SES Cluster
darryl.wang@nus.edu.sg
(until Dec 2021)

**Eddy BLOKKEN**

Business Development
SES Cluster
eddy.blokken@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

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 2021, the following Adjunct researchers from NUS have been working with SERIS:

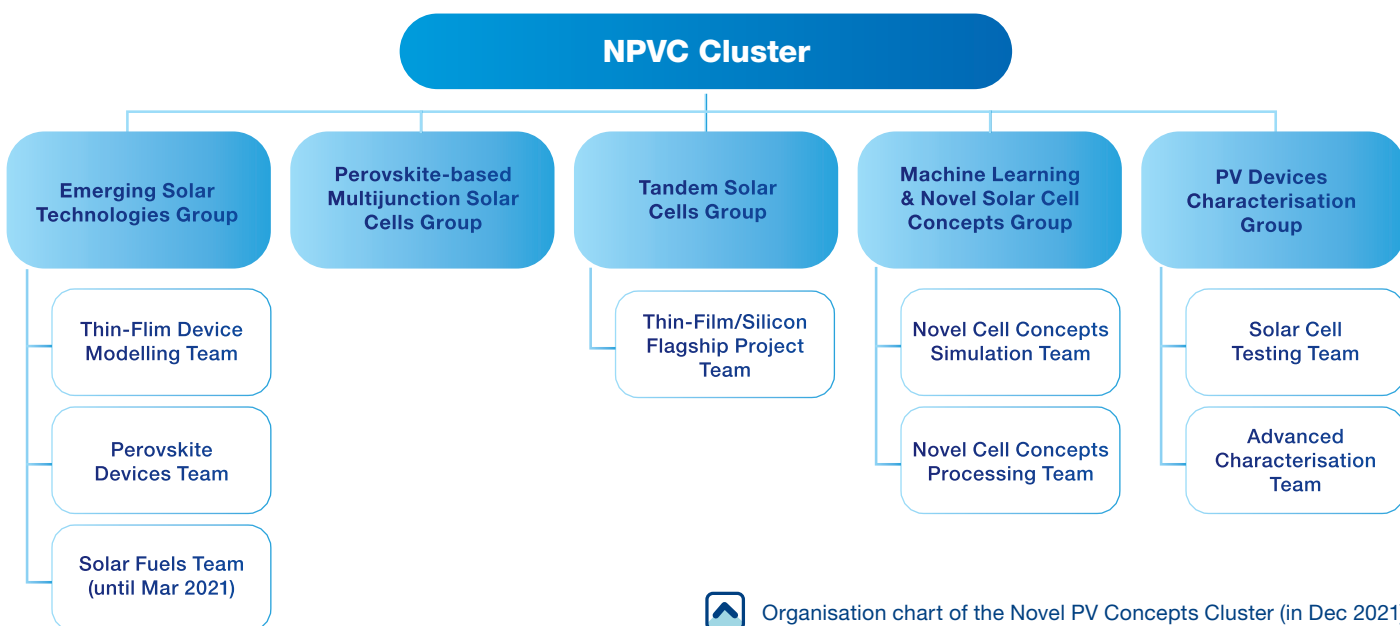
Name	NUS Department	Research area / role at SERIS
Prof Armin ABERLE	Electrical and Computer Engineering	Photovoltaic materials, devices and modules / CEO and Cluster Director
Assoc Prof Stefan ADAMS (until Mar 2021)	Materials Science and Engineering	Modelling of nano-structured solar cells
Assoc Prof Andrew BETTIOL (until Mar 2021)	Physics	Characterisation of photovoltaic materials and solar cells
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 Peter HO (until Mar 2021)	Physics	Organic photovoltaic materials, solar cells and solar modules
Prof HONG Minghui	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 Anjam KURSHEED (until Mar 2021)	Electrical and Computer Engineering	Developing novel SEM based solar cell characterisation tools
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
Prof LOH Kian Ping (until Mar 2021)	Chemistry	Organic photovoltaic materials, solar cells and solar modules
Assoc Prof Thomas OSIPOWICZ (until Mar 2021)	Physics	Analysis of ultra-thin films using high resolution (magnet spectrometer) RBS and ERD
Assoc Prof OUYANG Jianyong (until Mar 2021)	Materials Science and Engineering	Nano-structured solar cells
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
Assoc Prof Jason YEO Boon Siang (until Mar 2021)	Chemistry	Solar fuels



RESEARCH & DEVELOPMENT CLUSTERS & GROUPS

1. Novel PV Concepts Cluster

This Cluster researches novel and emerging solar materials, devices and applications that have the potential to gain market entry within the next 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 2021, the Cluster had 48 members (including 18 PhD students and 3 Masters students) spread over five R&D Groups.



Organisation chart of the Novel PV Concepts Cluster (in Dec 2021)

Cluster Director's Office

Prof Armin ABERLE, Acting Cluster Director
Mythel Ann ROBERTS, Cluster Secretary

Group Heads

Assoc Prof Karl Erik BIRGERSSON, Emerging Solar Technologies
Asst Prof HOU Yi, Perovskite-based Multijunction Solar Cells
Dr Serena LIN Fen, Tandem Solar Cells
Dr Rolf STANGL, Machine Learning & Novel Solar Cell Concepts
Dr HO Jian Wei, PV Devices Characterisation

Team Leaders

Dr CHOI Kwan Bum, Solar Cell Testing
Assoc Prof TAN Zhi Kuang, Perovskite Devices
Dr XUE Hansong, Thin-Film Device Modelling;
Novel Cell Concepts Simulation
Assoc Prof Jason YEO Boon Siang, Solar Fuels (until Mar 2021)

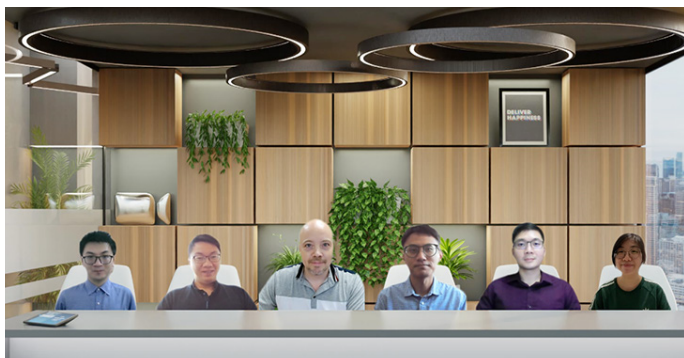
Laboratory Manager

Dr Firdaus Bin SUHAIMI (since Apr 2021)
Thomas GASCOU (until 31 Mar 2021)

Adjunct Researchers, NUS

Prof Armin ABERLE, Dept of Electrical and Computer Engineering (Photovoltaic materials, devices & modules)
Assoc Prof Stefan ADAMS, Dept of Materials Science & Engineering (Modelling of nanostructured solar cells) (until Mar 2021)
Assoc Prof Karl Erik BIRGERSSON, Dept of Mechanical Engineering (Modelling, optimisation and characterisation of solar cells; Modelling of PV modules)
Prof Peter HO, Dept of Physics (Photovoltaic materials, solar cells and solar modules) (until Mar 2021)
Asst Prof HOU Yi, Dept of Chemical and Biomolecular Engineering (Perovskite-based multijunction solar cells)
Prof LOH Kian Ping, Dept of Chemistry (Photovoltaics materials, solar cells and solar modules) (until Mar 2021)
Assoc Prof OUYANG Jianyong, Dept of Materials Science and Engineering (Nanostructured solar cells) (until Mar 2021)
Assoc Prof TAN Zhi Kuang, Dept of Chemistry (Perovskite devices)
Assoc Prof Jason YEO Boon Siang, Dept of Chemistry (Solar fuels) (until Mar 2021)

Emerging Solar Technologies Group



This group researches promising solar materials, devices and applications that have the potential to gain significant market share in the next 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 Jason YEO Boon Siang (Solar Fuels) (until Mar2021)
- Dr XUE Hansong (Thin-film Device Modelling)

PhD Students

- Cheryldine LIM Qiu Xuan
- LOW Qi Hang
- ONG Cheng Wai
- ONG Woan Yuann Evon
- TAN Hu Quee
- TAY Shao En
- Timothy TEH Wei Jie
- Louisa TING Rui Lin
- XIE Chenchao (until May 2021)
- 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 multi-junction solar cells. Our research directions consist of three main thrusts:

1. Materials innovation

The core of this thrust is materials innovation for enabling new functionalities in devices. We primarily 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 will develop 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 CHEN Wei
- Dr FENG Jiangang
- Dr Donny LAI Jiancheng (since Sep 2021)
- Dr LI Jia (since Jun 2021)
- Dr LIU Shunchang

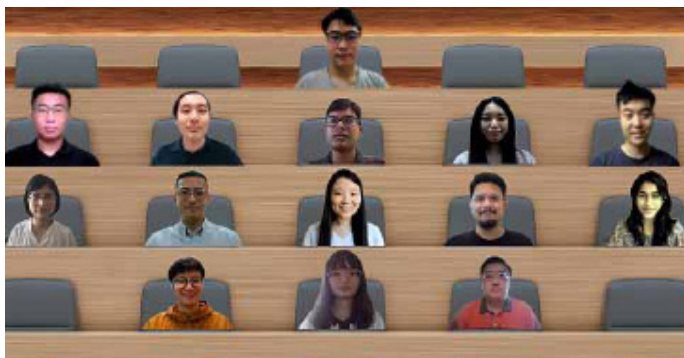
PhD Students

- Ezra ALVIANTO (since Aug 2021)
- CHEN Jinxi (since Aug 2021)
- GUO Xiao (since Aug 2021)
- LIANG Haoming
- LUO Ran (since Aug 2021)
- SHI Zhuojie
- WANG Xi (since Aug 2021)
- ZHANG Yan (since Aug 2021)

Masters Student

MA Hanxue (since Aug 2021)

Tandem Solar Cells Group



The group's major goal is to develop cost-effective small-area high-efficiency (> 30%) thin-film on silicon tandem solar cells and mini-modules that can potentially be upscaled to large-area devices with good long-term stability. The silicon bottom cells are specifically designed and optimised for tandem applications. As part of SERIS' tandem cell flagship project, the group is researching infrared-transparent perovskite solar cells for tandem applications. Perovskite/Si tandem solar cells and mini-modules with both 4-terminal and 2-terminal configurations are being developed using top and bottom cells fully made by the group.

Group Head

Dr Serena LIN Fen

Research Scientists

- Dr CHENG Yuanhang (until May 2021)
- Dr Cho Fai Jonathan LAU (since Nov 2021)
- Dr LI Xin (since Sep 2021)
- Dr Firdaus Bin SUHAIMI (since Apr 2021)
- Dr Maung THWAY (until Jan 2021)
- Dr WANG Puqun (50%, since Apr 2021)

Research Engineers / Associates

- LEE Ling Kai (since Jun 2021)
- Damien LIU Tianyuan
- YAP Qi Jia

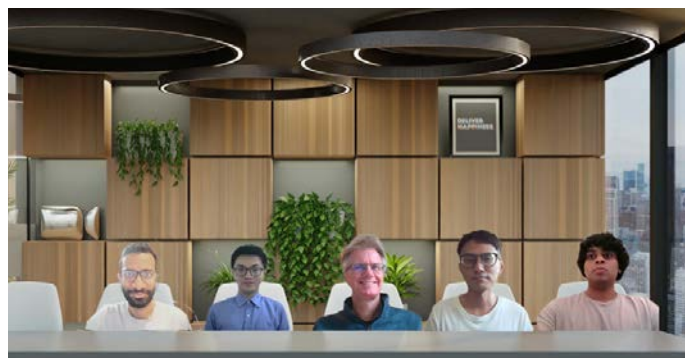
PhD Students

- LEE Ling Kai (until Jun 2021)
- Laxmi NAKKA
- Samuel NG Xin Ren
- Danny REN Zekun (until Jan 2021)
- Guibin SHEN (since Nov 2021)
- TIAN Siyu
- WEI Zhouyin (since Aug 2021)

Masters Student

- Nikhil PAPINENI (50%)

Machine Learning & Novel Solar Cell Concepts Group



The group researches novel concepts for solar cells, with a particular focus on perovskite/silicon tandem devices. The Simulation team develops a web-based PV simulation platform (XSolar-Hetero) to upload/simulate/compare measurements and to apply machine learning to the collected data, with a focus on the simulation of perovskite solar cells and perovskite/silicon tandems (in cooperation with the Emerging Solar Technologies Group). Novel structures investigated are local-area double-side contact passivated ("biPoly") silicon bottom cells and various tunnel junctions to couple the silicon and perovskite sub-cells. The machine learning activities aim at extracting various device parameters from PL images of silicon solar cell precursors. The Processing team (until Apr 2021) developed silicon solar cells for use as bottom cell in 2-terminal perovskite/silicon tandems, with a focus on biPoly cells and on abcPoly cells (which have both contacts at the rear).

Group Head

Dr Rolf STANGL

Team Leaders

- Dr Rolf STANGL (Novel Cell Concepts Processing Team)
- Dr XUE Hansong (Novel Cell Concepts Simulation Team)

Research Scientists / Engineers

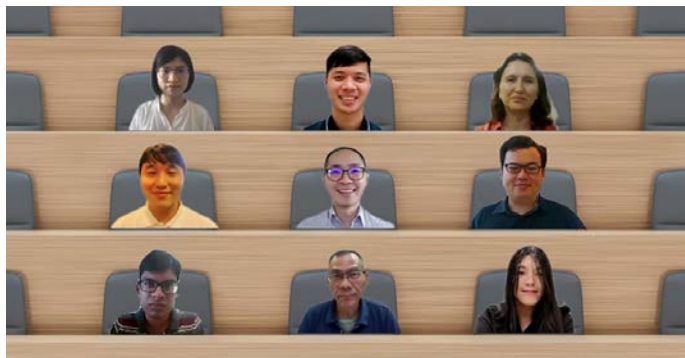
- Mehul GARG (external research cooperation)
- Rahul JAISWAL (external research cooperation)
- Sayyad Ali KHAN (until May 2021)
- Aniruddhan MURALI (external research cooperation)
- Ranjani SRIDHARAN (until Mar 2021)
- Dr WANG Puqun (50%, until Apr 2021)

PhD Student

ZHAO Xinhai (50%)

PV Devices

Characterisation Group



The PV Devices Characterisation Group focuses on the research & development of innovative characterisation & analysis solutions for solar materials and solar cell devices. The Group's activities involve disciplines of science and engineering, with applications covering the entire photovoltaic value chain. It is equipped with a raft of measurement, diagnostics and analysis tools. Selected R&D activities in 2021 have been:

- (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 material and device properties.
- (iii) Analysis into 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 HO Jian Wei

Team Leaders

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

Project Manager

Dr CHAN Keng Siew

Research Scientists / Engineers

- CHUAH Tuang Heok
- HENG Ming Xuan Clarence
- Elisaveta UNGUR
- Dr WANG Puqun (50%)
- YE Jiayi

PhD Students

- Sagnik CHAKRABORTY
- Sai Prasanth JOYSULA (since Nov 2021)
- LAN Yuchi (since Oct 2021)

Masters Students

- Ziqiong HUANG (since Nov 2021)
- Nikhil PAPINENI (50%)

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 enable the transformation of the global energy systems towards sustainability, continuous improvements of the manufacturability, manufacturing cost, long-term stability and, most importantly, the 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) on upscaling of perovskite/silicon tandem solar cells (SERIS flagship project). In December 2021, the Cluster had 31 members spread over three R&D Groups.



Cluster Director's Office

Prof Armin ABERLE, Cluster Director
Mythel Ann ROBERTS, Cluster Secretary

Deputy Cluster Director

Dr Shubham DUTTAGUPTA

Group Heads

Dr Shubham DUTTAGUPTA, Advanced Solar Cells
Dr Ankit KHANNA, Emerging Silicon Solar Cells (until Mar 2021)
Dr Pradeep PADHAMNATH, Solar Cell Metallisation (since Jun 2021)
Dr YAN Xia, PV Production Technologies (until Sep 2021)

Team Leaders

Dr Prabir Kanti BASU, Front-End R&D Support (until Mar 2021)
Dr Nitin NAMPALLI, Heterojunction Solar Cells
Dr Naomi NANDAKUMAR, Solar Cell Innovations
Dr John RODRIGUEZ, Passivated Contact Solar Cells (until Mar 2021)

Adjunct Researchers, NUS

Prof Armin ABERLE, Dept of Electrical and Computer Engineering (PV materials, devices and modules)
Assoc Prof Andrew BETTIOL, Dept of Physics (Characterisation of photovoltaic materials and solar cells) (until Mar 2021)
Assoc Prof Aaron DANNER, Dept of Electrical and Computer Engineering (Ultra-thin films for high-efficiency silicon solar cells)
Prof HONG Minghui, Dept of Electrical and Computer Engineering (Fabrication and characterisation of solar cells)
Assoc Prof Anjam KURSHEED, Dept of Electrical and Computer Engineering (Novel SEM based solar cell characterisation) (until Mar 2021)
Assoc Prof Thomas OSIPOWICZ, Dept of Physics (Analysis of ultra-thin films using high-resolution RBS and ERD) (until Mar 2021)

Advanced Solar Cells Group



The Advanced Solar Cells Group focuses on the development and commercialisation of high-efficiency solar cells. The group has two scientific-technical aims: (a) to develop technologies that approach the limit of silicon-based single-junction cell efficiency while maintaining low manufacturing costs (\$/W_p) and (b) to upscale process technologies for large-area (> 250 cm²) thin-film on silicon tandem cells. The group collaborates with several solar cell, equipment, automation, and materials companies to jointly develop technologies. The group has access to SERIS' industrial solar cell pilot lines, enabling silicon and tandem cell R&D on n and p-type industrial Cz silicon substrates. Both rigid (180 µm thick) and flexible (< 100 µm) wafers are used. Selected research topics of the group include development of passivated contacts, upscaling of next-generation thin-film semiconductors (e.g., perovskites) & related equipment R&D, novel nanoscale charge carrier transport layers, transparent metal oxides (conducting, passivating, or insulating), and advanced metallisation schemes.

Group Head

Dr Shubham DUTTAGUPTA

Team Leaders

- Dr Nitin NAMPALLI (Heterojunction Solar Cells)
- Dr Naomi NANDAKUMAR (Solar Cell Innovations) (until Nov 2021)
- Dr John RODRIGUEZ (Passivated Contact Solar Cells) (until Mar 2021)

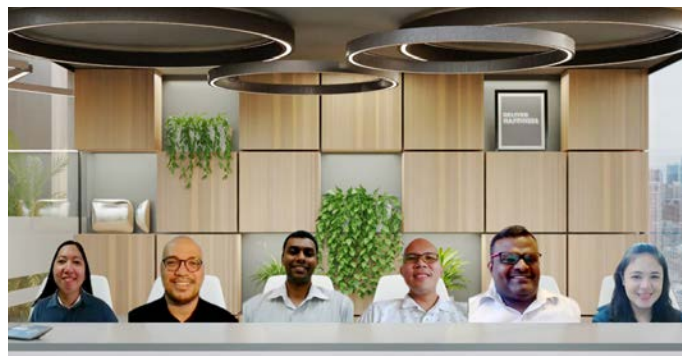
Research Scientists / Engineers

- ANG Pun Chong
- John Derek ARCEBAL
- Jamaal Kitz BUATIS
- Teena Percis CHRISTOPHER SUBHODAYAM (until Oct 2021)
- Gabby Alonzo DE LUNA (since Apr 2021)
- Jennifer Jordan EPISTOLA
- Michelle Liwanag ESBER (until May 2021)
- Thomas GASCOU (until Mar 2021)
- Jeffrey ISON
- Maria Luz MANALO
- Mohd Asri Bin MOHD HAMDAN
- Balaji NAGARAJAN (until Sep 2021)
- Marvic John Santos NAVAL
- Dr Pradeep PADHAMNATH (until Jun 2021)
- Delio Justiniani PEREZ
- Dr Amit Singh RAJPUT (until Mar 2021)
- Kaylynn SEW
- Ranjani SRIDHARAN (since Apr 2021)
- TAN Chuan Seng
- Bobby Salinas UNGOS
- Dr Selvaraj VENKATARAJ
- Jack Garcia VILLANUEVA
- Dr Jeremie WERNER

Technician

CHOY Woon Loong (until Jul 2021)

Solar Cell Metallisation Group



The Solar Cell Metallisation Group develops next-generation 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' monoPoly™ and biPoly™ technology platforms. The group also works closely with other research groups in SERIS to develop next-generation metallisation solutions for heterojunction silicon solar cells and perovskite-on-silicon tandem cells. Furthermore, the group collaborates with several solar cell companies and metal paste manufacturers.

Group Head

Dr Pradeep PADHAMNATH

Research Scientists / Engineers

- Edwin Decena CARMONA
- Michelle Liwanag ESBER
- Rosalie GUERRA
- Balaji NAGARAJAN
- Rowel Vigare TABAJONDA

PV Production Technologies Group



The PV Production Technologies Group investigates advanced materials and processes which have the potential to be integrated in the mass production of industrial solar cells. The group conducts joint research collaborations with companies as well as lab-to-fab technology transfers, and provides technical consultation and process services.

Group Head

Dr YAN Xia (until Sep 2021)

Team Leader

Dr Prabir Kanti BASU (Front-End R&D Support)
(until Mar 2021)

Research Scientists / Engineers

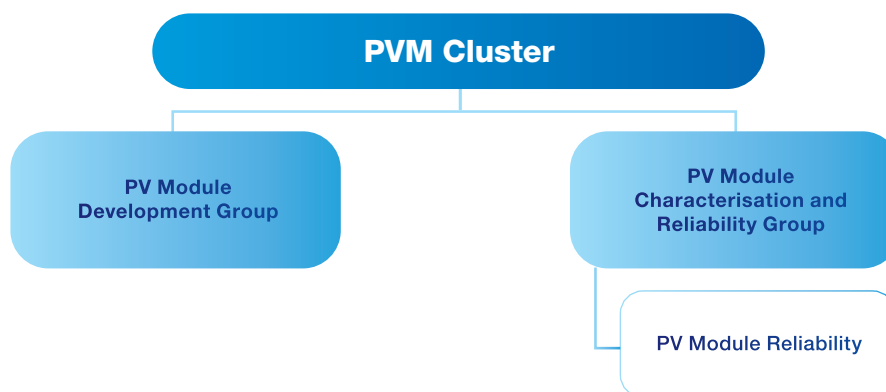
- Edwin Decena CARMONA (until Jun 2021)
- Rosalie GUERRA (until Sep 2021)
- Dr Donny LAI Jiancheng (until Sep 2021)
- Rainer LEE Cheow Siong (until Jun 2021)
- Dr LONG Jidong (until Mar 2021)
- Balaji NAGARAJAN (until Sep 2021)
- Dr Firdaus Bin SUHAIMI (until Mar 2021)

PhD Student

LAN Yuchi (until Sep 2021)

3. PV Modules for Urban Solar Cluster (PVM)

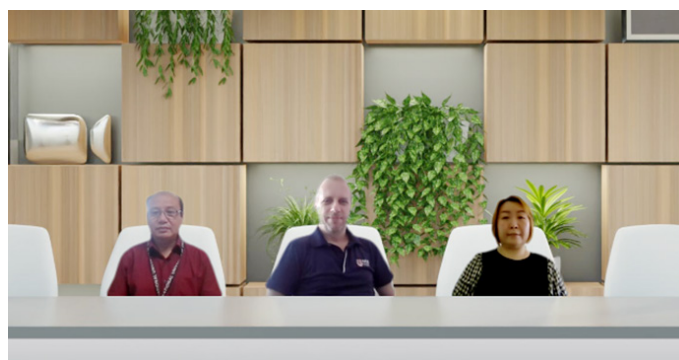
The Cluster develops and characterises novel and advanced PV module technologies suited for urban and tropical applications. It consists of two research groups - the PV Module Characterisation and Reliability (PVMC&R) Group and the PV Module Development (PVMD) Group. The Cluster operates laboratories at two off-campus locations - at CleanTech Park (the ISO/IEC 17025 accredited laboratory for PV module testing and the PV module technology R&D laboratory) and at JTC MedTech Hub (PV module development laboratory). The Cluster's main R&D activities are: Development of building-integrated PV technologies (for SERIS' BIPV flagship project) and of 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 2021)

Cluster Director's Office

Dr Mauro PRAVETTONI, Cluster Director (since Apr 2021)
Dr WANG Yan, Cluster Director (until Mar 2021)
Mabel LEOW Siew Hwa, Cluster Secretary
Dr LONG Jidong (Lab Manager, since Apr 2021)



Group Heads

Dr TAI Kong Fai, PV Module Development (since Jun 2021)
Dr KHOO Yong Sheng, PV Module Development (until May 2021)
Dr Mauro PRAVETTONI, PV Module Characterisation and Reliability

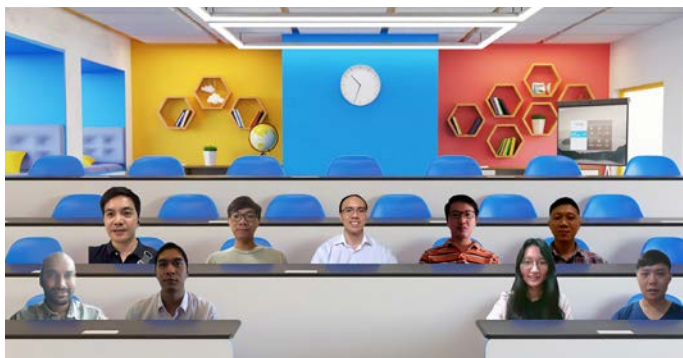
Team Leader

Dr LUO Wei, PV Module Reliability (until Aug 2021)

Adjunct Researchers, NUS

Prof Seeram RAMAKRISHNA, Department of Mechanical Engineering (PV modules)
Assoc Prof Karl Erik BIRGERSSON, Department of Mechanical Engineering (Modelling of PV modules)

PV Module Development Group



The PV Module Development (PVMD) group's research focus is on the development of (i) innovative PV technologies for urban solar applications such as building-integrated PV (BIPV), PV noise-barriers (PVNB) and PV for IoT, (ii) innovative PV modules or integrated PV solutions for tropical & hot climates, and (iii) advanced PV module recycling processes.

Group Head

Dr TAI Kong Fai (since Jun 2021)

Dr KHOO Yong Sheng (until May 2021)

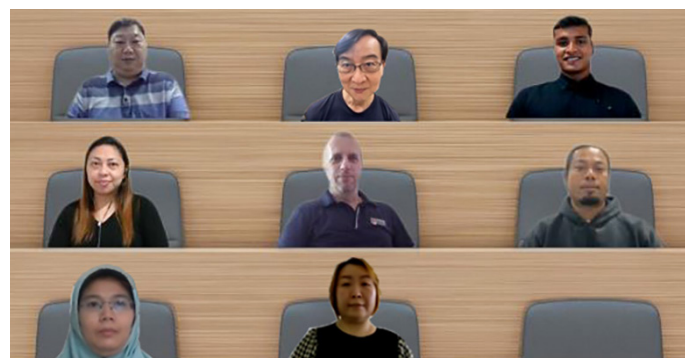
Research Scientists / Engineers

- Ryan ALINSOD
- ANG Kim Wee (since Sep 2021)
- Dr Karl Georg BEDRICH (until Mar 2021)
- CAI Yutian (until May 2021)
- Dr LEOW Shin Woei (since Oct 2021)
- Srinath NALLURI
- Gavin Prasetyo RAHARJO (since Oct 2021)

PhD Students

- Carlos Enrico Cobar CLEMENT
- LIANG Tian Shen
- SAW Min Hsian

PV Module Characterisation & Reliability Group



The group researches new metrology methods for PV modules and 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 (for BIPV applications) 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). Pre-normative module metrology activities are routinely conducted in liaison with the International Electrotechnical Commission (IEC) and with research partners worldwide.

Group Head

Dr Mauro PRAVETTONI

Team Leader

Dr LUO Wei (PV Module Reliability)
(until Aug 2021)

Research Scientists / Engineers

- Maryknol Estrada DELOS SANTOS (since Apr 2021)
- Henry LIM Kian Meng
- Daren POH (until Jan 2021)
- Dr Amit Singh RAJPUT (since Apr 2021)

R&D Project Executives

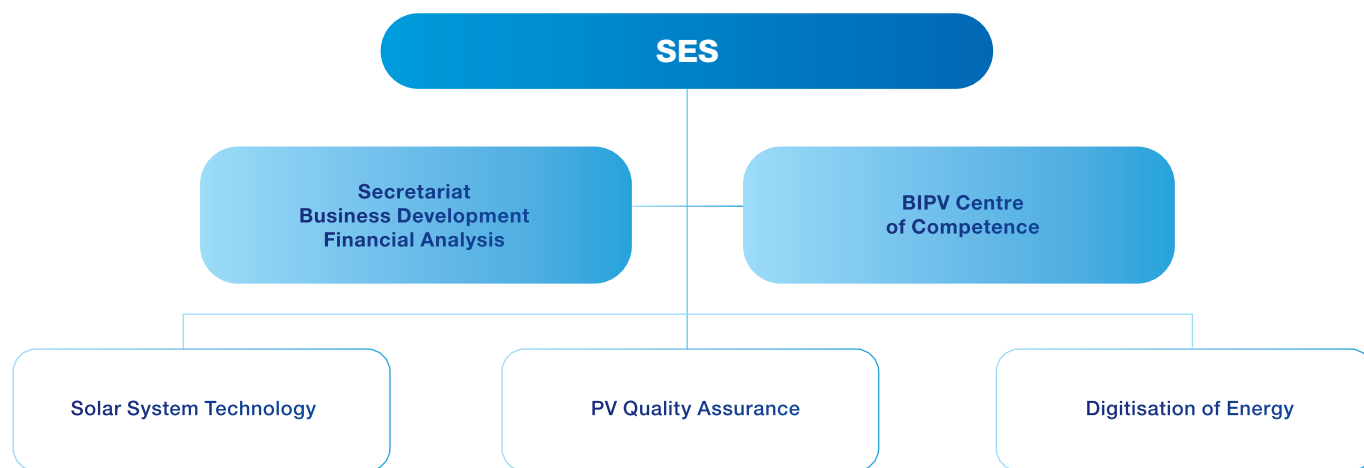
- Zuraidah BINTE JA'AFAR
- Mabel LEOW Siew Hwa

Technicians

- 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 involved in two SERIS flagship projects (BIPV, Floating Solar) and drives 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 2021)

Cluster Director's Office

- Dr Thomas REINDL, Cluster Director
- Dr Ramprakash KATIRESAN, Product Manager (until Apr 2021)
- Eddy BLOKKEN, Business Development Manager
- Celine PATON, Senior Financial Analyst (until Jun 2021)
- Marinel DUNGCA, Cluster Secretary



Group Heads

- Dr Thomas REINDL, Digitisation of Energy (acting)
- Dr Carlos RODRÍGUEZ, Solar System Technology (since Jun 2021)
- Dr Abhishek KUMAR, Solar System Technology (until Apr 2021)
- Dr KAM Zhi Ming, PV Quality Assurance (since Dec 2021)
- Dr Darryl WANG Kee Soon, PV Quality Assurance (until Dec 2021)
- TAN Congyi, Urban Solar (until Jan 2021)

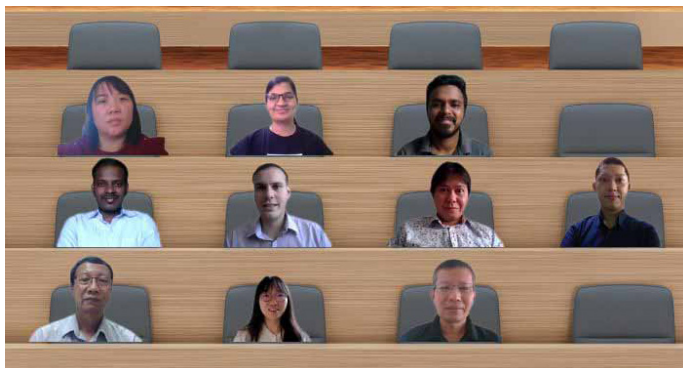
Centre Head

Dr Veronika SHABUNKO, Centre of Competence for Building-integrated PV (BIPV)

Adjunct Researchers, NUS

- Assoc Prof Ashwin KHAMBADKONE, Department of Electrical and Computer Engineering (Analysis and solutions for PV grid integration through energy system modelling and advanced power electronics & control for smart grids)
- Assoc Prof Sanjib Kumar PANDA, Department of Electrical and Computer Engineering (High-performance control of power electronic converters)
- Prof Dipti SRINAVASAN, Department 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. The PV system studies include traditional monofacial modules with fixed-tilt orientation as well as bifacial modules and tracking solutions. 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 replacement or multi-purpose use of existing infrastructure with PV, for example PV noise barriers or over-arching of car parks, roads and flood canals.

Group Head

Dr Carlos RODRÍGUEZ (since Jun 2021)
Dr Abhishek KUMAR (until Apr 2021)

Research Scientists / Engineers

- Myint Khaing AUNG
- Naga Sravani ISUKAPALLI
- Rachel TAN Yek Wha (since Sep 2021)
- TING Shi An
- Lokesh VINAYAGAM
- Dr Muhammad Arifeen WAHED (until Jun 2021)
- Dr Jaffar Moideen YACOB ALI
- ZHAO Shengnan

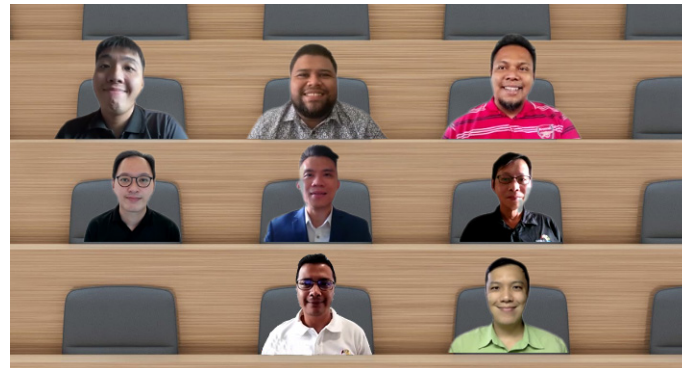
Technicians

- David KHUP
- Jamil Bin ZAINAL

PhD Student

Christoph LUERSSSEN (until Apr 2021)

PV Quality Assurance Group



The perceived quality of a PV system includes a wide range of aspects, from components, 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 via energy yield assessments of PV systems to feasibility studies and full due diligence evaluations. The group also carries out comparative research on PV module and system performance across different climate zones (within the "TruePower™" project). 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

- Dr KAM Zhi Ming (since Dec 2021)
- Dr Darryl WANG Kee Soon (until Dec 2021)

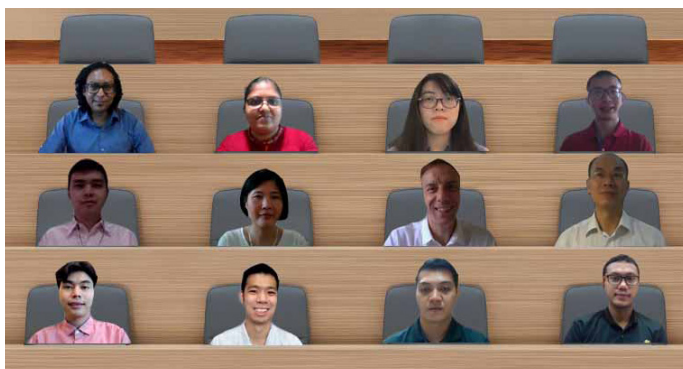
Research Scientists / Engineers

- Stanley PHUA Chee Siang
- Dr Carlos RODRÍGUEZ (until May 2021)

Technicians

- Norhisham Bin HABDIN
- Muhammad Fahmie Bin IDRUS
- KOH Jun Yong
- Kendrick LOH Chun Ming (since Mar 2021)
- Muhamad Firdaus Bin YUSOF (since Apr 2021)

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 is being 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)

Research Scientists / Engineers

- Dr James Matthew BRIGHT (until Sep 2021)
- Dr Oktoviano GANDHI
- GENG Hui (until Mar 2021)
- Sasi Kala GNANAMUTHU
- Dr HE Yaohua
- Dr Anupam KUMAR (until Nov 2021)
- Julia KHIN Thu Zar Zaw (since Nov 2021)
- KYAW Zin Win
- David LEE Soon Kiat
- David LIM Han Yang (until Mar 2021)
- Ivan POON Kin Ho
- Sholihin Bin SANI
- SOE Pyae
- Dr SUN Huixuan
- Dr Gokhan Mert YAGLI (since Dec 2021)
- Dr ZHAN Yanqin
- Dr ZHANG Ji (until Jun 2021)

PhD student

SUN Xixi

Centre of Competence for **Building Integrated Photovoltaics (BIPV)**



The Centre was established in 2017 to develop innovations in the field of BIPV for Singapore and the region and remove industrially relevant barriers towards the accelerated adoption of BIPV, while providing a collaborative platform with relevant stakeholders from the private and public sectors.

A key element of sustainable buildings is the passive design of their envelope, especially the facades. In hot climates such as the tropics, the thermal properties of the facades determine the solar heat gain, and thus the energy consumption, of the entire building. The possibility of integrating PV into facades offers great opportunities for increasing the share of renewables and improving the energy balance of buildings in the tropics.

SERIS has broad expertise in the areas of BIPV system design & evaluation, energy yield projections, technical verification, project risk assessment, real-time analytical monitoring of PV/ BIPV installations, project management, owner’s engineer, and quality assurance.

Centre Head

Dr Veronika SHABUNKO

Research Scientists / Engineers

- Samyuktha BADRINARAYANAN (until Aug 2021)
- Dr Dhanup SOMASEKHARAN PILLAI

PhD Student

Jovan TAN



Administration



SERIS' Administration Unit works closely with NUS' centralised administration team 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 (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

- Manimaran S/O ASHUKUMAR (until Jul 2021)
- CHUA Ai Leng (since Nov 2021)
- Fion KONG Pui Fong (until Jan 2021)
- June KWAN (since Nov 2021)
- Sherlyn LOW Si Ning (since Sep 2021)
- Noor A'ishah Bte MOHAMAD
- Mitchell SENG Honghui
- Eric YANG Yiwen (until Aug 2021)



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. 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

- LEE Buan Heng (Silicon Solar Cell Lab, until May 2021)
- Peter LIM Young Leng (QESH)
- LOI Teck Shiun (Technical Infrastructure)

Staff, Technical Infrastructure Team

- Anja Marion ABERLE
- CHEANG Kong Heng
- CHEW Siow Choen
- Kenneth GOH (until Mar 2021)
- 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

"Our aim is to develop novel solar cells that have 1-Sun efficiencies of well above 30% and good potential for long-term stability and low fabrication costs."

Research Focus / R&D portfolio of NPVC Cluster

In 2021, the Cluster's research focused 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 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 2021

Emerging Solar Technologies Group

The group focuses on the development of the science and technology of emerging solar technologies. In 2021, the group's main activities were:

- Development of morphological, optical and device modelling capabilities for perovskite-based tandem solar cells to predict and optimise power losses and PV efficiency.
- Design of multifunctional organic molecules for perovskite composites.

Major achievements in 2021:

- Established multiscale optoelectronic models to optimise the PV efficiency of 2- and 4-terminal (2T, 4T) perovskite/perovskite tandem solar cells.
- Demonstrated stand-alone, easy-to-use apps based on physics-based machine learning for performance predictions of all-perovskite tandem devices.
- Developed a mathematical model for tunnelling/ recombination junctions for 2T perovskite-based tandem solar cells that captures features such as S-shaped current-voltage characteristics.

Selected publications:

- H.Q. Tan *et al.*; Optoelectronic modelling and sensitivity analysis of a four-terminal all-perovskite tandem solar cell - Identifying pathways to improve efficiency; *Solar Energy* 216, p 589 (2021)
- T. Wang *et al.*; The role of subsurface valence band localisation in the passivation of perovskite nanocrystals; *Advanced Optical Materials* (in press).

Perovskite-based Multijunction Solar Cells Group

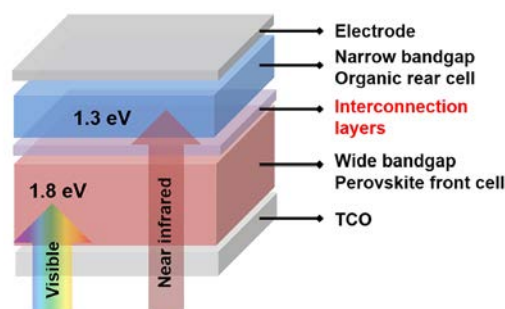
The group's research efforts bridge broad chemistry, physics and engineering disciplines, and are primarily focused on materials, assembling, and device innovation for perovskite multi-junction solar cells. In 2021, the group's main activities involved:

- Developing new wide-bandgap perovskite absorbers, interface passivation materials, and metal oxide charge transporting layers.

- Exploring new schemes of processing and assembling perovskites to create improved light management in perovskite solar cells.
- Developing different device architectures and new recombination junctions for two- and three-junction tandem solar cells.

Major achievements in 2021

- 23.3% efficient wide-bandgap perovskite solar cell
- 23.6% efficient perovskite/organic tandem solar cell
- 26.1% efficient perovskite/silicon tandem solar cell (Si cell from industry partner)



Schematic of the tandem architecture

Selected publication:

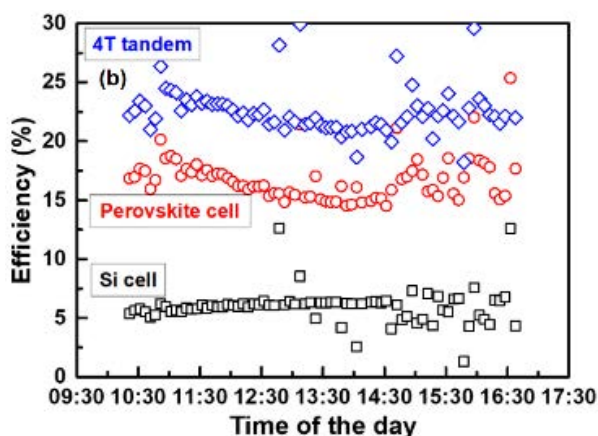
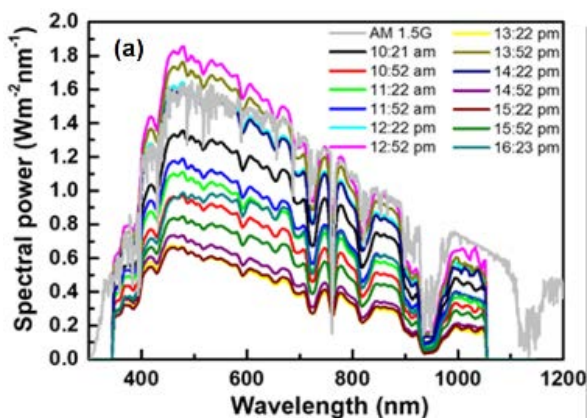
- F. Fu *et al.*; Monolithic perovskite-silicon tandem solar cells: from the lab to fab?; *Advanced Materials* (under review).

Tandem Solar Cells Group

The group focuses on the research and development of cost-effective small-area high-efficiency (> 30%) thin-film on silicon tandem solar cells and mini-modules that can potentially be upscaled to large-area devices with good long-term stability. The key research includes the development of infrared-transparent perovskite solar cells and specially designed & optimised silicon bottom cells for tandem applications. Perovskite/Si tandem solar cells and mini-modules with both 4T and 2T configurations are being developed using top and bottom cells fully made by the group.

Major achievements in 2021:

- 22.0% efficient perovskite/silicon 2T tandem solar cell (0.5 cm²) with biPoly™ Si bottom cell.
- Customised small-area biPoly™ Si bottom cells with implied Voc of ~710 mV. The cells feature a planar front surface and a textured rear surface.
- Development of polysilicon-based tunnel junctions for 2T perovskite/silicon tandem solar cells.
- Outdoor performance test of perovskite/Si 4T tandems.



(a) Solar irradiance spectra during the outdoor performance test of perovskite/Si 4T tandem solar cells. (b) Measured outdoor efficiencies of the perovskite top cell, Si bottom cell and the 4T tandem cell.

Selected publications:

- X.R. Ng *et al.*; Thermally stable poly-Si tunnel junctions enabling next-generation high-efficiency Si solar cells. *Progress in Photovoltaics* 2021, 10.1002/pip.3462.
- X. Li *et al.*; High-efficiency and durable inverted perovskite solar cells with thermally-induced phase-change electron extraction layer. *Advanced Energy Materials* 2021, 10.1002/aenm.202102844
- Y. Cheng *et al.*; Amorphous CdO-In₂O₃ electrode for perovskite-based bifacial and tandem photovoltaic technologies with high energy production; *Solar RRL*, (10.1002/solr.202100809)
- Y. Cheng and F. Lin; Semitransparent perovskites for solar cells and smart windows; Invited book chapter in "Perovskite Materials and Devices", Wiley (in press).

Machine Learning & Novel Solar Cell Concepts Group

The group researches novel solar cell concepts, materials and processes. It also develops XSolar-Hetero, a web-based PV simulation platform for uploading, simulating & comparing measurements, and for applying machine learning concepts to the collected data.

Major achievements in 2021:

- Development of poly-silicon tunnel junctions (together with the Tandem Solar Cells Group), and their integration into biPoly and abcPoly silicon bottom cells.
- Development of laser processes for the defect-free formation of local contact openings of (i) all-back-contact silicon cells and (ii) small-area silicon bottom cells for tandem integration.
- Creation of a perovskite research environment within the web-based simulation platform XSolar-Hetero, and a first machine learning deployment.

Prediction of metal recombination

Using simulated PL, training an ANN (Tensorflow).
PL imaging: → get metal j_0 fast and non-destructive!

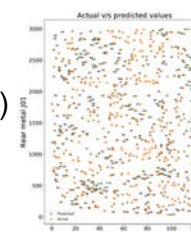


Input:

- PL image (1 sun)
- PL image (0.1 sun)

Output:

- j_{01} -MetalRear
- j_{02} -MetalRear



Accuracy:

for sim. PL
> 96%

But:

ANN to be re-trained with measurements

First machine learning deployment (serving a trained artificial neural network, ANN, using Tensorflow serving) within XSolar-Hetero: Prediction of metal recombination (j_0) from photoluminescence (PL) images.

Selected publication:

- P. Wang *et al.*; Development of TOPCon tunnel-IBC solar cells with screen-printed fire-through contacts by laser patterning; *SOLMAT* 220, p 110834 (2021).

PV Devices Characterisation Group

The group focuses on the research & development of innovative characterisation & analysis solutions for solar cell materials and devices. In 2021, the group's main activities involved:

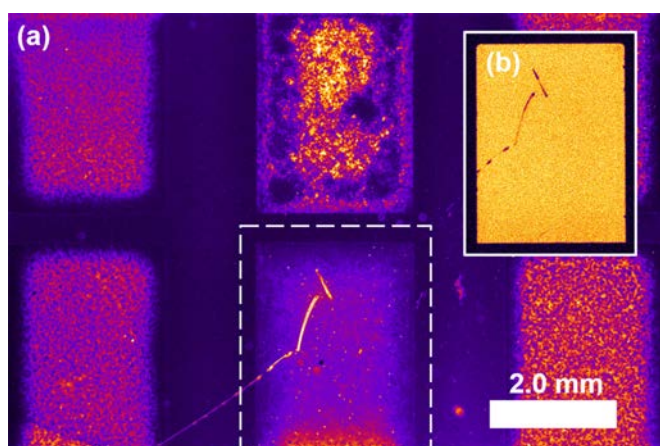
- Advanced characterisation and analysis of next-generation high-efficiency solar cells, for example perovskites and perovskite/silicon tandems.
- Future-ready solar cell manufacturing, as part of a public grant project (Solar CRP), exploring (i) Accelerated inspection, characterisation & analysis by artificial intelligence (AI) techniques, and (ii) Contactless high-throughput metrology.
- Accurate performance measurement of solar cells.
- Advanced solar cell power loss analysis, and identifying potential paths for efficiency improvements.

Major achievements in 2021:

- Establishing two industry research collaboration projects with a local industry partner (combined contributions ~S\$600k) on (i) the impact of high-performance modules on the LCOE of PV solar systems, and (ii) R&D of innovative PV modules.
- Renewing collaboration with a local start-up on in-depth characterisation and data analysis in solar cell manufacturing (combined contributions ~S\$350k).

Selected publications:

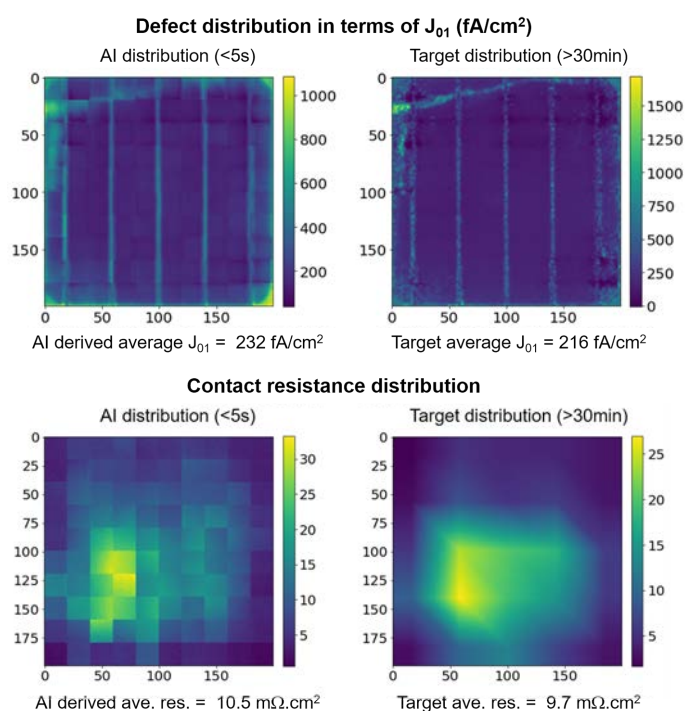
- J.W. Ho *et al.*; Metallisation and interconnection of crystalline Si solar cells; Book chapter, IET (under editorial processing).
- K.S. Chan *et al.*; Rapid non-contact quantum efficiency measurement for solar cell fabrication process insights; Solar Energy (under review).
- K.S. Chan *et al.*; Predicting 2D loss analysis from luminescence images in solar cells with convolutional neural networks (in preparation).



(a) Photoluminescence image of 6 perovskite solar cells showing the spatial variation in optoelectronic quality for process optimisation and materials analysis; (b) Electroluminescence image of the device boxed in the white dashed line.

2. Plans of NPVC Cluster for 2022

- Further enhance the fabrication and characterisation capabilities for small-area perovskite solar cells and mini-modules.
- Achieve > 29% efficiency for a perovskite/silicon tandem solar cell with active area of at least 1 cm².
- Achieve > 20% efficiency for a perovskite/silicon mini-module with active area of at least 10 cm².
- 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 next-generation high-efficiency solar cell devices, e.g. perovskites and perovskite/silicon tandems.
- Develop metrology techniques and high-granularity data analytics that are suitable for commercialisation.
- Further development of the PV simulation platform XSolar-Hetero via external research collaborations.
- Achieve ISO17025 accreditation of solar cell performance measurement.



Comparison of defect and contact resistance distribution of a solar cell computed by high-throughput artificial intelligence (AI) technique vs conventional more time-consuming fitting technique (target), showing the close similarities of the two.



NISCM Cluster Director's Foreword



Prof Armin ABERLE

Director, Next-Generation Industrial Solar Cells and Modules Cluster

"We are developing the next generation of industrial solar cells and modules that provide superior performance at lower cost than today's technologies."

Research Focus/R&D portfolio of NISCM Cluster

In 2021, the Cluster's research focus shifted to next-generation industrial solar cells and modules that provide superior performance at 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) on upscaling of perovskite/silicon tandem solar cells (SERIS flagship project). In response to the modified scope of its R&D activities, the Cluster has been re-named to "Next-Generation Industrial Solar Cells and Modules".

1. Major activities / achievements in 2021

Advanced Solar Cells Group

The group's major activities in 2021 were the further development of SERIS' n-type bifacial monoPoly™ passivated-contact silicon solar cell, the development of 'biPoly™' solar cells, implementing novel transparent metal oxides (TMOs) on silicon heterojunction cells, and setting up a lab & pilot-scale R&D infrastructure for the upscaling of perovskite-on-silicon tandem solar cells.

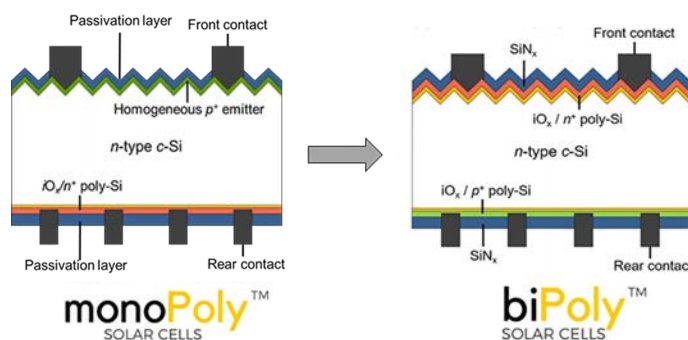
Major achievements in 2021

- Demonstration of ~24% efficiency for n-type monoPoly™ cells utilising SERIS' proprietary monoPoly™ passivated-contact technology platform, achieved in collaboration with our industry partners
- Integration of boron-doped monoPoly™ passivated-contact layers at the rear and front side of solar cells
- Development of a 'thin' monoPoly™ layer stack, enabling biPoly™ solar cell precursors with very high implied open-circuit voltage (~740 mV)
- Initiating next-generation equipment R&D for novel nanolayers and thin films (e.g. perovskites)

monoPoly™ technology platform:

SERIS is an international leader in R&D for industrial passivated-contact silicon solar cells with screen-printed contacts. In collaboration with strategic industry partners, we have developed the monoPoly™ technology platform to address the cost-effective passivation and metallisation needs of the PV industry. The efficiency of our monoPoly™ solar cells has improved rapidly in recent years, with a learning rate of about 1% absolute per year, and the technology is now being expanded to enable biPoly™ solar cells featuring passivated contacts on the front and rear of the cell. Continued development of the monoPoly™ technology platform (& related processes) is projected to lift

the silicon cell efficiencies at SERIS towards 25%. Preliminary results for unmetallised biPoly™ cell precursors with an ultra-thin (~25 nm) front n⁺ poly-Si layer are an implied V_{oc} of 740 mV and an implied cell efficiency of up to 24.8%.



Transition from (left) a bifacial monoPoly™ cell to (right) a bifacial biPoly™ cell with a semi-transparent electron-selective passivating contact stack on the front and a hole-selective passivating contact stack at the rear.

Selected publications:

- J.W. Rodriguez, N. Nandakumar, S. Duttagupta; 'SolarEYE' loss analysis of screen-printed n-type silicon solar cells with 'monoPoly' PECVD rear passivated contacts; Solar Energy Materials and Solar Cells 233, p. 110961 (2021)
- N. Nandakumar, N. Nampalli, P. Padhamnath, A.G. Aberle, S. Duttagupta; monoPoly™ silicon solar cells: Status, progress and outlook towards 25% efficiency; Progress in Photovoltaics (Special issue), in press

Solar Cell Metallisation Group

The group develops next-generation industrial metallisation solutions for both established and next-generation solar cell technologies. The group's major activities in 2021 were the development of industrial low-cost metallisation solutions for advanced silicon solar cells based on SERIS' monoPoly™ and biPoly™ technology platforms. The group also worked closely with other research groups in SERIS to develop next-generation metallisation solutions for heterojunction silicon solar cells and perovskite-on-silicon tandem cells. Furthermore, the group collaborated with several solar cell companies and metal paste manufacturers.

Major achievements in 2021:

- Development of an industrial etching process to pattern transparent conducting oxide (TCO) layers for integration into interdigitated back contact (IBC) silicon 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 an inline low-temperature (< 150°C) contact annealing process for integration of screen-printed metal contacts on perovskite/silicon tandem solar cells
- Analysis and development of advanced metallisation schemes for large-area monoPoly™ silicon solar cells achieving fill factors of > 82.5% and efficiencies exceeding 23%
- Development of next-generation low-temperature metal pastes compatible with industrial screen-printing technology for application on silicon heterojunction solar cells, jointly with our industry partners

Selected publications:

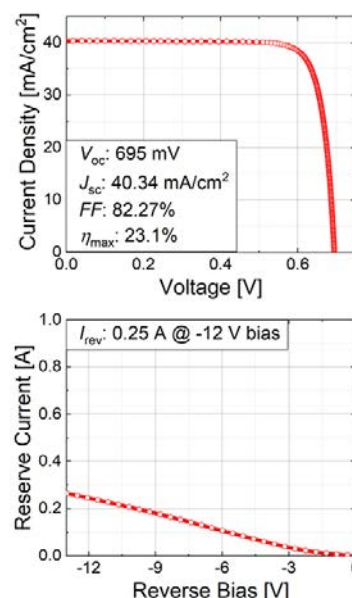
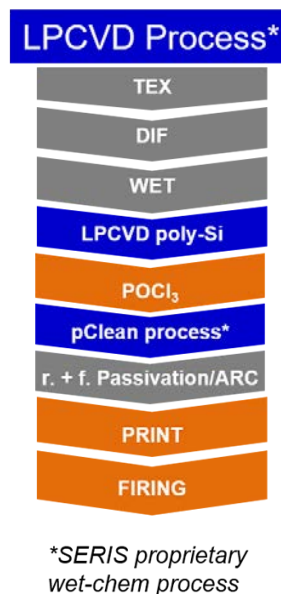
- P. Padhamnath, A. Khanna *et al.*; Impact of firing temperature on fire-through metal contacts to P-doped (n^+) and B-doped (p^+) poly-Si; Solar Energy Materials and Solar Cells 230, p. 111217 (2021)
- P. Padhamnath, Nitin Nampalli *et al.*; Progress with passivation and screen-printed metallisation of boron-doped monoPoly™ layers; Solar Energy, in press

PV Production Technologies Group

The group investigates advanced materials and processes that have the potential to be integrated in the mass production of industrial solar cells. The group conducts joint research collaborations with companies as well as lab-to-fab technology transfers, and provides technical consultation and process services.

Major achievements in 2021:

- Development of proprietary know-how for a mask-free fabrication process for monoPoly™ solar cells via low-cost LPCVD deposition of poly-Si layers, giving up to 23.1% efficiency with a low reverse current (I_{rev}) of < 0.3 A at -12 V reverse bias
- Process integration and demonstration of metallised biPoly™ solar cells with a high iV_{oc} of 725 mV, a proof-of-concept efficiency of nearly 20%, and a good firing stability. The developed rear-junction biPoly™ structure seems well suited as the bottom cell of perovskite/Si tandem solar cells
- Establishing an ex-situ doping process for ultra-thin poly-Si layers (~20 nm thick) on textured front surfaces
- Establishing screen-printed and high-temperature fire-through metallisation for monoPoly™ cells with thin (< 100 nm) doped poly-Si layers
- Analysis of nanosecond and femtosecond laser pulse ablation to achieve damage-free ablation of dielectrics for high-efficiency solar cells



(Left) SERIS' proprietary mask-free fabrication process for monoPoly™ solar cells via LPCVD. (Right) Light and dark I-V characteristics of a resulting monoPoly™ solar cell.

Selected publications:

- X. Yan, F. Suhaimi *et al.*; Process development and integration of double-side poly-Si passivated solar cells with printed contacts via LPCVD and ex-situ tube diffusion; Solar Energy Materials & Solar Cells 230, p. 111249 (2021)
- N. Balaji, D. Lai, V. Shanmugam *et al.*; Pathways for efficiency improvements of industrial PERC silicon solar cells; Solar Energy 214, pp 101-109 (2021)

2. Plans of NISCM Cluster for 2022

- Demonstration of 24.5% efficient solar cells made with a monoPoly™ layer (either at the front or rear, or both)
- Demonstration of alternative heterojunction contacts for advanced solar cells and modules
- Metallisation schemes for advanced solar cells
- Further improve the device architecture and efficiency of n-mono solar cells suitable for tandem application
- Successfully complete technology transfer to industry customers for the cluster's current projects
- Continue the work on low-temperature metallisation processes for tandem solar cell structures, using polymer Ag pastes and electrically conductive adhesives (ECA)
- Upscaling of tandem solar cells (jointly with industry partners):
 - Demonstration of a high- V_{oc} biPoly™ cell
 - Process development for wide-bandgap perovskite cells on large 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!"

Research Focus / R&D portfolio of PVM Cluster

In 2021, the Cluster's research focus shifted to the following three topics:

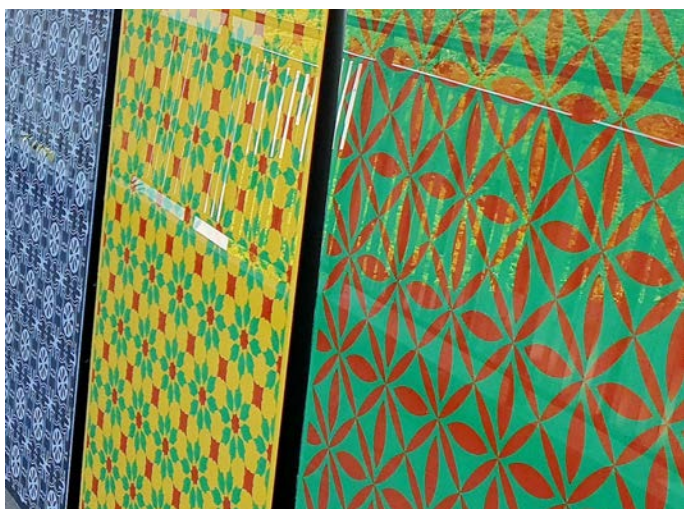
- i) Reliability of PV modules
- ii) Innovative PV modules for urban solutions
- iii) Building integrated photovoltaics (BIPV)

The first topic is handled by the PV Module Characterisation & Reliability Group, which also runs SERIS' ISO/IEC 17025 accredited laboratory for PV testing, while the other two topics are researched by the PV Module Development (PVMD) Group.

1. Major activities / achievements in 2021

Peranakan BIPV module

In line with the targets of SERIS' BIPV flagship project and highlighting the connection with the local environment and Singapore traditions, the PVMD group invented and developed a unique PV module technology coined the "Peranakan" BIPV module. This colourful and stylish PV technology - presented to the public for the first time via this Annual Report - is a unique solution that combines both tradition and innovation in a reliable and beautiful PV product.



 Photograph of several Peranakan BIPV modules (Singapore Patent Application 10202111422S, Oct 2021).

PV Module Characterisation & Reliability Group

Having successfully gained international recognition among other leading PV module testing laboratories in the last two years, in 2021 the group re-focused on the local market, assisting the two biggest module manufacturers in Singapore in their R&D activities to develop novel, > 20% efficient and reliable PV products. As an example, a collaborative project with REC led to a significant contribution to the systematisation of the I-V measurement challenges of highly capacitive PV modules using pulsed solar simulators. This project led to the publication in the *Journal of Physics D* of a review paper on the characterisation methods for highly-capacitive PV modules. The paper, which quickly reached thousands of downloads, includes a thorough investigation of the uncertainty components correlated to each of the module I-V testing methods available today, and allows to assess and solve the hysteresis effect observed in I-V measurements of certain types of PV modules.

Pre-normative activities on the electrical characterisation of curved (i.e., non-flat) PV modules are ongoing. The laboratory has participated in an International Round Robin exercise, in co-ordination with JET and JEMA (the Japanese standardisation authority). Furthermore, a novel approach for the measurement of the incident angle modifier (IAM) has been validated and presented in December 2021 at the PVSEC-31, Asia's leading scientific-technical PV conference. A testing procedure for the detection and recovery of light and elevated temperature induced degradation (LETID) has also been validated, through the participation in an international interlaboratory comparison led by NREL in the US.

Comprehensive PV module reliability analyses were conducted as part of three major case studies:

- i) A 10-year-old PV system decommissioned from the roof of Singapore's Khoo Teck Puat Hospital (KTPH), including degradation studies of both multicrystalline silicon and CIGS module technologies;
- ii) Another 10-year-old PV system decommissioned from the roof of the BCA Academy, with a focus on the effects of module soiling in Singapore;
- iii) A 4.5-year-old installation with organic PV (OPV) prototype modules, representing a rare opportunity for assessing the long-term reliability of this novel PV technology in a hot and humid climate. The results are planned to be published in a scientific journal.

Other selected activities in 2021:

- Development of a novel measurement technology for the characterisation of the incident angle modifier (IAM) of large-area commercial modules.

Selected publications:

- M. Pravettoni, D. Poh, J.P. Singh, J.W. Ho, K. Nakayashiki; The effect of capacitance on high- efficiency photovoltaic modules: a review of testing methods and related uncertainties; J. Phys. D: Appl. Phys. 54, p 193001 (2021) (20 pages).
- W. Luo, C.E. Clement, Y.S. Khoo, Y. Wang, A.M. Khaing, T. Reindl, A. Kumar, M. Pravettoni; Photovoltaic module failures after 10 years of operation in the tropics; Renewable Energy 177, pp 327-335 (2021).

PV Module Development Group

In 2021, the group shifted its focus to BIPV deployment, leveraging on the experiences from several public grant funded BIPV projects completed in the last 2 years. In addition, commercial entities are now showing a strong interest in adopting BIPV systems in their buildings, to align with the government's sustainability goals.

Leveraging on a significant portfolio of patents on BIPV modules and the existing PV module fabrication pilot line, the group can design and prototype BIPV modules that suit various building designs and requirements. The group has also enhanced its expertise in architecture and electrical engineering in building designs that harmonise with BIPV modules and BIPV system connection. In close collaboration with SERIS' Solar Energy Systems (SES) Cluster, the group can also provide BIPV design and consultancy services to asset managers or developers to deploy BIPV systems in their buildings, while conducting interesting research on BIPV for Singapore to achieve its sustainability goals.

Other than BIPV, the PVMD group is also working on PV module solutions for various urban applications, such as PV noise barriers and PV for urban farming ("Agri-voltaics"). In addition, the group is also involved in PV module life-cycle management, with a public grant awarded by NEA to demonstrate cost-effective PV recycling solutions. In this project, the group will explore an advanced physical separation process for recycling of PV modules, using an electrohydraulic fragmentation ("shockwave") process.

Other selected activities in 2021:

- Filed a PCT patent application for a superposition method to fabricate aesthetic BIPV modules with reduced power loss (PCT/SG2021/050073).
- Filed a Singapore patent application for design principles for multi-coloured and patterned photovoltaic modules (Singapore Non-Provisional Patent Application 10202111422S).
- Filed an Invention Disclosure with the NUS Industry Liaison Office (ILO) for a PV-integrated building element.
- Completed three BIPV projects: (1) *Solar Artwork* in the Singapore Sustainability Academy, City Square Mall; (2) BIPV integration onto concrete PPVC units; (3) BIPV integration into unitised curtain walls.

Selected publications:

- C.E. Clement, J.P. Singh, Y.S. Khoo, A. Halm, D. Tune, K.E. Birgersson; Design of shading- and hotspot-resistant shingled modules; Progress in Photovoltaics, <https://doi.org/10.1002/pp.3507>
- C.E. Clement, J. P. Singh, K.E. Birgersson, Y. Wang, Y.S. Khoo; Illumination dependence of reverse leakage current in silicon solar cells; IEEE J. Photovoltaics 11, pp 1285-1290 (2021).

2. R&D plans of PVM for 2022

- Conduct further pre-normative activities on: spectral and angular response of coloured BIPV modules; vehicle-integrated PV (VIPV); spectral transmittance and responsivity in the UV spectral range.
- Complete the reliability study for more than 70 PV modules taken from the roof of the BCA Academy (representing a 10% sample of the total original PV installation).
- Develop a prototype of a Testing Solar Dome for the outdoor characterisation of high-efficiency and/or slow-response PV modules (Singapore Patent Application 10202103889R).



 Artist's impression of the Testing Solar Dome for the electrical characterisation of high-efficiency and slow-response PV modules (Singapore Patent Application 10202103889R).

- Conduct R&D on advanced and novel BIPV modules and improve their performance.
- Offer research services in relation to BIPV design, prototyping, consultancy and project management, to help commercial entities deploy BIPV systems into their buildings.
- Develop PV modules suitable for urban applications, such as noise barriers and urban farming ("Agri-voltaics").
- Evaluate PV module recycling with the electro-hydraulic fragmentation ("shockwave") process.



Dr Thomas REINDL

Director, Solar Energy Systems Cluster (SES)

“It was heartening to see Prime Minister Lee inaugurating the 60-MW_p Floating Solar plant at Tengeh reservoir in June 2021. This not only shows the relevance of solar as the major source of renewable electricity generation in Singapore, but also pays tribute to the years of hard work and research excellence which SERIS has put into the MW-scale testbed at Tengeh, in close collaboration with PUB and EDB. The Solar Energy Systems Cluster will continue to support solar adoption in Singapore and the region with innovations, technical support and manpower training.”

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 2021

Solar System Technology Group

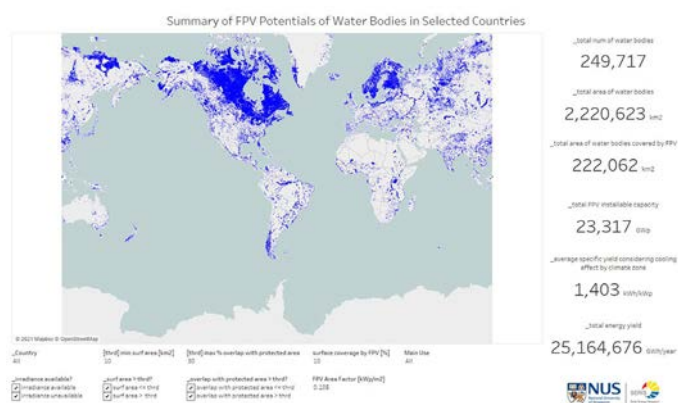
In 2021, the Solar System Technology and the Digitisation of Energy groups worked intensively on R&D activities in the area of floating PV (FPV). One of the key achievements was a global analysis of all in-land water reservoirs, using data from both the GRANd (Global Reservoir and Dam) and the GLWD (Global Lakes and Wetlands Database) databases. Overlaying the geo-referenced global water bodies with solar irradiance allows to estimate the potential of Floating Solar. The analysis showed that covering merely 10% of the surfaces of all in-land reservoirs with FPV would generate 25000 TWh per year – which was humanity's entire electricity consumption in 2021.

This work was carried out in collaboration with a major European investor in renewable energy assets. We also assessed the potential for combining floating solar with existing hydropower plants. For this purpose, the database was expanded by including technical details of each hydropower station in the 13 most promising countries around the world.

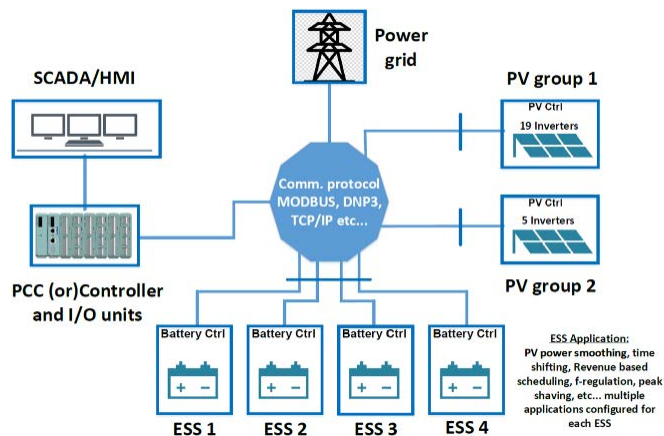
Our research work in the areas of near-shore and off-shore Floating Solar - jointly with industry partner Fred. Olsen Renewables (FOR) - led to a detailed assessment of existing float technologies and solar module types that are marketed specifically for Floating PV. A total of 36 floats and 29 PV modules were analysed and benchmarked across 10 different evaluation criteria. In addition, a detailed Failure Mode and Effects Analysis (FMEA) analysis was carried out, identifying 73 potential risk factors, out of which 4 are of high probability and thus need to be addressed with priority.

SERIS also launched the International Floating Solar Society (IFS²), which is a web-based community that aims to further evolve and nurture the exchange of experiences, information, and data across the sector and to provide a one-stop shop for people interested in Floating Solar, be it from academia, industry, public sector, investors, developers, or financing.

Beyond floating solar, the group also expanded its capabilities in the field of PV field testing and grid integration, by adding energy storage system (ESS) expertise. SERIS is currently working on an industry project to design, implement and operate a large (5 MW_p) test-bedding system in the region, which comprises several of the latest PV technologies (p-mono, n-type bifacial, HJT, single-axis tracking system), combined with testing different ESS systems (NMP, LFP, redox flow, fly wheel) as well as deploying multiple weather and electrical performance sensors. Starting from commissioning in early 2022, multiple data streams from this testbed will be collected to subsequently perform studies to analyse the characteristics as well as advantages and disadvantages of the employed technologies.



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



 Schematic of integrated large-scale (5 MW_p) PV and ESS testbed

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 ~1.5 GW_p in 6 countries. In 2021, the group was awarded and completed a Lender's Technical Advisory service for a consortium of Lenders covering the 70-MW_p SolarNova Phase 4 project. The group was also awarded a contract by HDB to act as the HDB representative overseeing the construction phase on HDB residential buildings in the SolarNova Phase 4 project. The group won another Owner's Engineering contract for a portfolio of PV systems on industrial buildings by an industrial REIT company.

TruePower™ Alliance

The PVQA 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. SERIS also became founding member of an international research alliance to align, compare and exchange data from outdoor test stations around the world (together with Sandia, Anhalt University of Applied Science, QEERI, KIER, Loughborough, and others), called PV CAMPER (Photovoltaic Collaborative to Advance Multi-climate Performance and Energy Research) [1]. SERIS contributed data from the TruePower™ project and is also co-author of several joint research papers.



 Upgrading works at the TruePower™ site at Marina Barrage, Singapore

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 2021 was to deploy a fully operational solar forecasting system at the Power System Operation Division (PSOD) of Singapore's grid operator EMA (Energy Market Authority). This is being trialled in a 24/7 mode with the research team supporting the operations at EMA. A graphic overview of the comprehensive solar forecasting system is shown on page 9 of this Annual Report on SERIS' [Business Areas](#). The developed system has achieved the target of 10% normalised root mean square error (nRMSE) for hour-ahead forecasts and 20% for 3-hour ahead forecasts – making it suitable for tropical climates.

The project team also carried out in-depth studies about the impacts of an increasing share of variable solar power in Singapore's electric power system. Several typical scenarios were assessed using the actual grid configurations and various levels of PV penetration. Numerous mitigations measures ranging from smart inverters to different storage options (e.g. central vs. sub-station level vs. decentralised) were evaluated.

The group also finalised the research and implementation work for moving its proprietary "live" PV monitoring system into the cloud. This was a major operation over several years and is key for making the operational system scalable for future expansion and commercialisation.

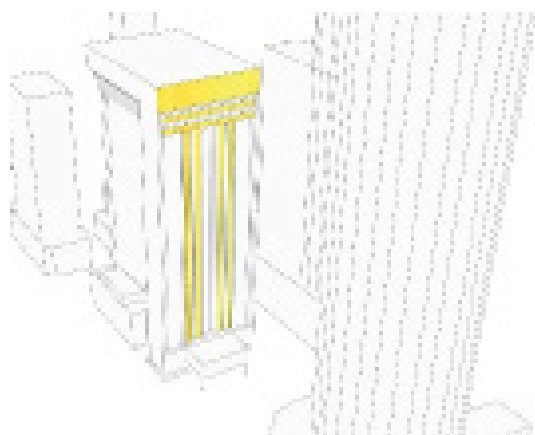
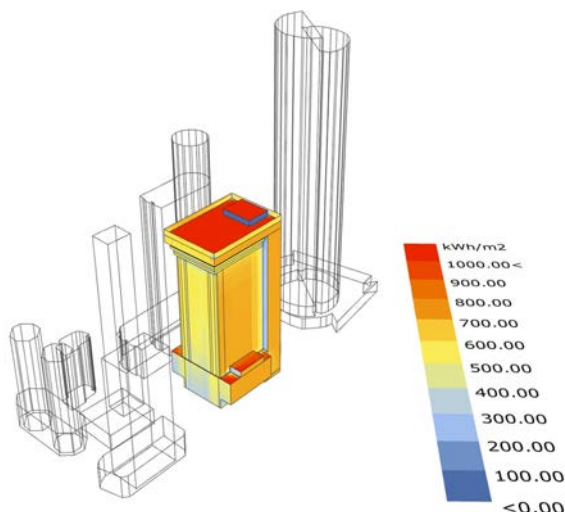
In parallel, the group also further evolved its activities in the area of predictive maintenance of solar PV systems ("smart O&M"). Using its own dedicated test installation, the developed algorithms enable feature extraction from I-V curve scans after deliberately injected faults (e.g. partial shading or potential-induced degradation, PID), with an accuracy that is higher than the built-in function from the inverter manufacturer. This work is being expanded to also detect and project anomalies by typical voltage and current profiles. This aims to make the "smart O&M" algorithms applicable to systems where the inverters do not have the ability to carry out I-V curve scans.

The group also strongly supported the SolarNova programme of the Singapore government, by providing pre-feasibility and glare studies for hundreds of government-owned buildings.

BIPV Centre of Competence

Solar Potential Assessment and Façade Retrofit with Coloured Building Integrated Photovoltaics (BIPV)

The team conducted a high-level technical and financial analysis for potential deployment of innovative coloured BIPV solutions at the Monetary Authority of Singapore (MAS) building. The total in-plane solar irradiation was colour-mapped on the building surfaces, illustrating how the irradiation profile is affected by the surroundings, self-shading, and architectural design. The BIPV façade was found to provide significant savings of almost 6000 tonnes of CO₂ emissions and generate about 15120 MWh of clean electricity over the lifetime of the BIPV system. This indicates a great potential and impact for adoption of BIPV technologies in Singapore.



 Façade areas with their annual solar irradiation profile

Investigations on BIPV Fire Safety

The team continues to work closely with the relevant authorities in Singapore to review and establish a reliable framework for successful integration of PV modules into buildings, especially for façade integrations. In collaboration with the Singapore Civil Defence Force (SCDF), the team carried out extensive assessments on the compatibility of BIPV junction boxes and materials suitable for C-channel cable trays to improve the fire safety and protection of BIPV façades. While the cable trays presently available in the market for BIPV cladding applications cannot avoid dripping of burning/melting plastic parts (or collect drips), one possible stainless-steel based solution is proposed in the Figure below, whereby a detachable aluminium foil casing is added to encapsulate the module's junction box within the C-channel itself. This provides a cost-effective solution to collect drips within the insulation case if the junction box melts. By investigating even minor possibilities of fire occurrences, the team aims to propose a strong integration framework for BIPV façades with adequate protection and fire mitigation strategies, which is expected to improve the reliability of the systems and accelerate BIPV adoption in Singapore.

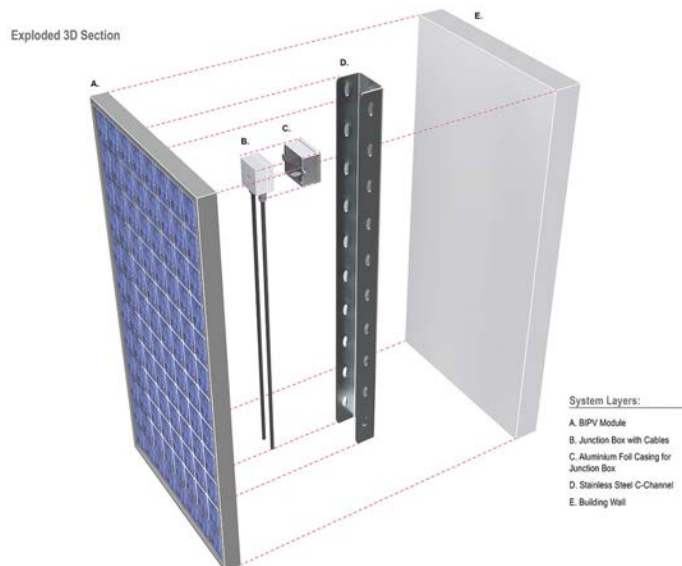


 Illustration of a possible C-channel solution for enhanced fire safety

Evaluation of thermal performance of innovative BIPV modules for Green Mark Certification in Singapore

Green Mark (GM) certification is an important benchmark for attaining building energy efficiency in the tropics. To examine the role of BIPVs in achieving GM certification, the team has experimentally evaluated the thermal performance of five innovative BIPV modules and performed an Envelope Thermal Transfer Value (ETTV) analysis to assess their feasibility to be integrated as building envelopes, in compliance with the green building regulations of Singapore. The results showed that the thermal performance of BIPV modules is significantly better than that of standard aluminium cladding or conventional fenestration systems. Also, the combination of BIPV cladding with Low-E glass windows was identified as the most feasible option to achieve Gold, Gold Plus and Platinum GM certifications in Singapore's tropical climate.

2. Plans of SES Cluster for 2022

- Further expand the activities in the Floating Solar flagship project, especially for near-shore areas.
- Design and test novel deployment options, e.g., for over-building existing infrastructures.
- Set-up a real-world testbed for solar-powered urban farming in Singapore.
- Finalise the trial of the operational solar forecasting system at EMA 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.

References

- [1] <https://energy.sandia.gov/programs/renewable-energy/photovoltaics/pv-systems-and-reliability/pv-camper>

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

Thin-film on silicon tandem solar cells

Dr LIN Fen, Asst Prof HOU Yi, Dr HO Jian Wei, Prof Erik BIRGERSSON, Dr Rolf STANGL, Prof Armin ABERLE

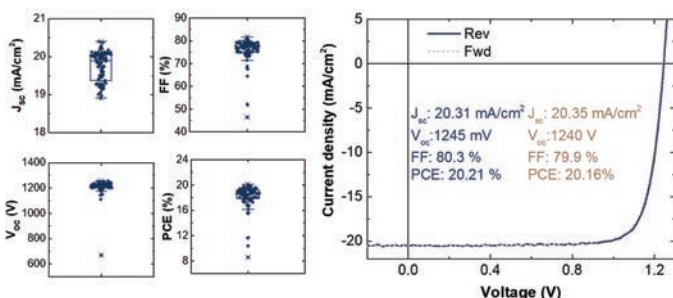
Introduction

Space is limited in Singapore and thus the solar PV systems installed here should have very high energy conversion efficiency, to maximise the amount of generated PV electricity. The efficiency of single-junction silicon solar cells is limited to about 29% under natural sunlight, whereby the world record is 26.7% at present. Much higher efficiencies can be realised by stacking a second solar cell with higher electronic bandgap on top of the silicon cell, forming a tandem solar cell. The fundamental theoretical efficiency limit of a 2-junction tandem solar cell having a silicon bottom cell is 42.5% under 1-Sun illumination (AM1.5G), whereby a practical cell efficiency limit of about 35% seems possible in future mass production (> 2030). Due to their excellent efficiency and cost (\$/W) potential, silicon-based tandem solar cells are of very high relevance for Singapore's solar sector.

In this flagship project, wide-bandgap thin-film materials - in particular organic-inorganic halide perovskites - are being investigated for the top cells. In 2021, the project's research focus was on the development of perovskite/Si tandem solar cells. Despite the difficulties faced due to the COVID-19 pandemic, significant progress was made during the year in various sub-areas of the project.

Perovskite top cells

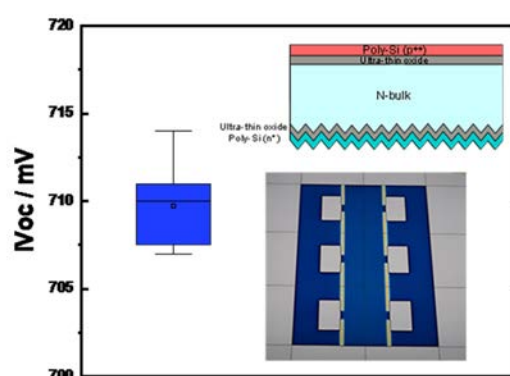
Currently, the most efficient single-junction perovskite solar cells use perovskite absorbers with a bandgap in the 1.49-1.61 eV range, to offer a broad solar spectrum response. However, perovskite/Si tandem solar cells require a wider perovskite bandgap of 1.68-1.73 eV for optimal current matching between the top and bottom cells. In 2021, our Perovskite-based Multijunction Solar Cells Group made rapid progress with wide-bandgap perovskite solar cells, achieving efficiencies of up to 20.2% and average V_{oc} values of more than 1.2 V for 1.71-eV p-i-n perovskite cells.



Electrical performance of solution-processed 1.71-eV perovskite solar cells (1.0 cm²). Left: Statistics of 1-Sun parameters. Right: Measured J-V curves of the best cell.

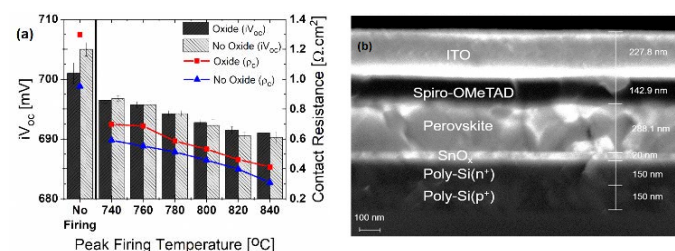
Customised silicon bottom cells

In 2021, the Tandem Solar Cells Group customised the SERIS developed "biPoly™" silicon cell technology for bottom-cell applications in 2-terminal (2T) tandems. The group developed small-area biPoly™ Si bottom cells (0.5-1 cm²) on n-type 4-inch float-zone Si substrates, using SERIS' R&D pilot line for industrial Si solar cells. The cells have a planar front surface and a textured rear surface. Implied V_{oc} values of ~710 mV were achieved for these biPoly Si cells before being integrated into perovskite/Si 2T tandems.



Customised small-area biPoly Si bottom cells: Schematic structure, photograph of a silicon wafer with 6 individual biPoly cells (each 0.5 cm²), and iV_{oc} statistics.

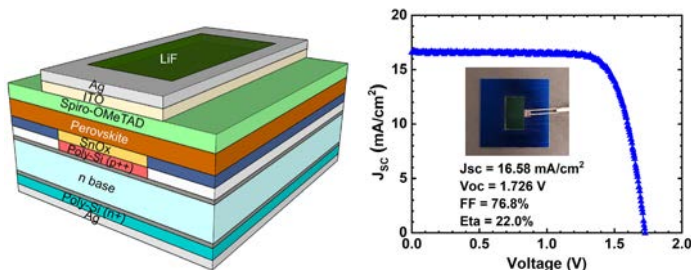
The group also developed an n^+ polysilicon/ p^+ polysilicon tunnel junction for integration of biPoly Si bottom cells into 2T perovskite/Si tandems. The tunnel junction functions both as a front passivated contact of the silicon bottom cell and an interconnection layer with a low tunnelling resistance. The tunnel junction shows excellent thermal stability and is compatible with conventional screen-printing and fast-firing of metal contacts. With an additional SiO_x interlayer between the oppositely doped polysilicon layers, the thermal stability of the tunnel junction is further enhanced and dopant inter-diffusion between the adjacent polysilicon layers mitigated. Optically, our developed tunnel junction is less parasitically absorptive in the near-infrared region as compared to ITO. Integration of this tunnel junction into 2T perovskite/Si tandem solar cells is ongoing, with initial experiments resulting in tandem cell efficiencies of up to 15%.



(a) iV_{oc} and contact resistance of n^+ polysilicon/ p^+ polysilicon tunnel junctions upon fast firing at different temperature. (b) Cross-sectional SEM image of the n^+ polysilicon/ p^+ polysilicon tunnel junction for perovskite/Si 2T tandem cells.

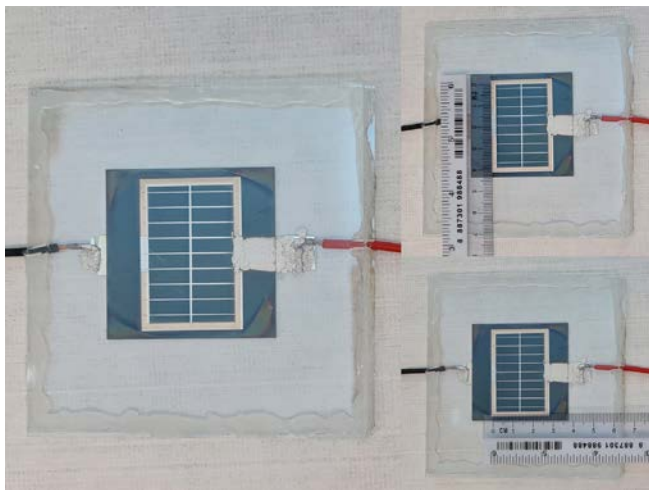
Perovskite/Si 2T tandem cells with biPoly™ Si bottom cells

Using the spin-coated infrared-transparent n-i-p perovskite top cells and the customised biPoly n-type Si bottom cells developed by the Tandem Solar Cells Group, small-area (0.5 cm²) perovskite/Si 2T tandem solar cells with efficiencies of up to 22.0% were achieved in 2021. The short-circuit current density (up to 16.6 mA/cm²) of these devices is primarily limited by parasitic optical absorption in the Spiro-OMeTAD layer. The development of biPoly Si bottom cells allowing the integration of p-i-n perovskite top cells is ongoing and is expected to yield significant tandem cell efficiency gains.



 Schematic structure, photograph and 1-Sun I-V curve of a 22% efficient perovskite/Si 2T tandem cell fully made in SERIS. Top cell = spin-coated n-i-p perovskite cell, bottom cell = n-type biPoly cell with planar front and rear surfaces.

In parallel to the development of small-area tandem solar cells (up to 1 cm²), we have also fabricated perovskite/Si 2T tandem cells in larger sizes. Based on a similar process and the same architecture as used for the above small-area 2T tandem cells, 10-cm² tandem cells using customised biPoly Si bottom cells were demonstrated by the Tandem Solar Cells Group. In 2021, these proof-of-concept experiments achieved tandem cell efficiencies of 12.8% without an anti-reflective coating (ARC).

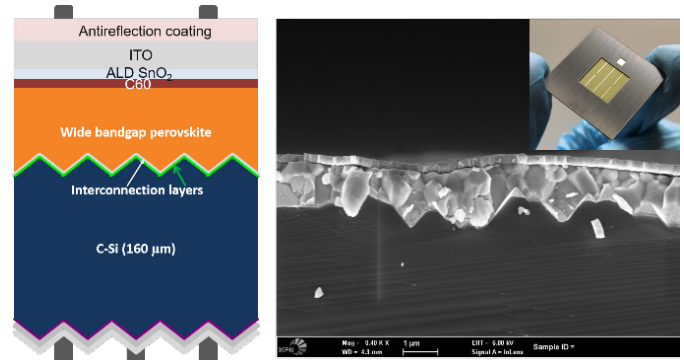


 Encapsulated perovskite/Si 2T tandem solar cell (active area 10 cm²) fully made in SERIS. Top cell = spin-coated n-i-p perovskite cell, bottom cell = n-type biPoly cell with planar front and rear surfaces.

Perovskite/Si 2T tandem cells on heterojunction Si bottom cells

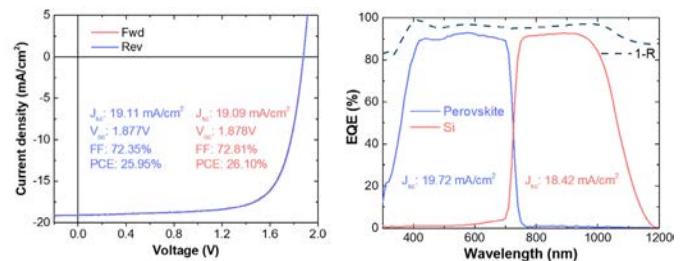
Based on its efficient wide-bandgap perovskite single-junction devices, the Perovskite-based Multijunction Solar Cells Group made perovskite/silicon tandem solar cells using heterojunction silicon cells from an external collaborator. Cell area is 1.0 cm². We selected double-side textured n-type Si wafers 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 (left) and cross-sectional SEM image (right) of a perovskite/Si 2T tandem solar cell made in SERIS. Also shown (top right) is a photograph of one of the fabricated tandem solar cells.

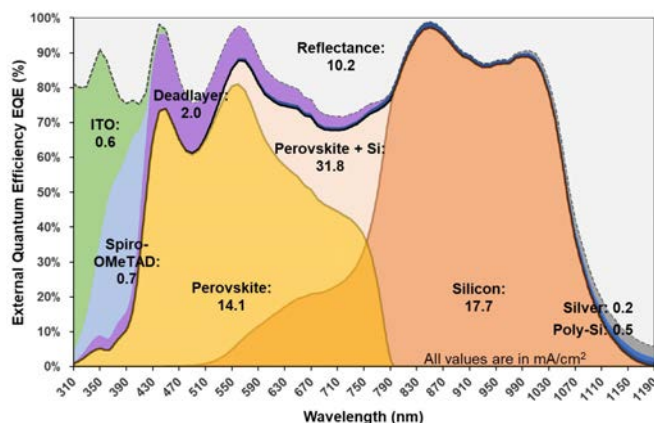
Using this approach, we achieved perovskite/Si 2T tandem cells with efficiencies of up to 26% in 2021, whereby the cell area was 1.0 cm². The champion tandem cell showed a high V_{oc} of 1.88 eV and a J_{sc} of over 19.0 mA/cm². These learnings provide us a clear path towards 30% efficient perovskite/Si tandems.



 J-V curves and external quantum efficiency (EQE) of the best perovskite/Si 2T tandem solar cell (1 cm²) made in SERIS.

Advanced characterisations for perovskite and tandems

Understanding the properties of thin films (e.g. perovskites) and related tandem solar cells is a key step towards improving their performance and reliability. SERIS is equipped with various advanced characterisation tools, and continues to develop new measurement and analysis techniques to provide insights for device optimisation and process control. Advanced loss analysis techniques were developed in 2021. By examining spectral response, reflectance & ellipsometry measurements, the influence of various layers in the solar cell stack on electrical current losses can be delineated for optimising device performance.



Modelling and simulation of perovskite solar cells and tandems

SERIS started the development and evolution of novel mathematical models for perovskite solar cells in 2016. This has led to the successful establishment of a multiscale modelling framework to elucidate the morphology-performance relations and power loss mechanisms that affect the performance of perovskite solar cells. We are now able to model the PV efficiency of any type of single-junction perovskite solar cell, given proper calibration and validation.

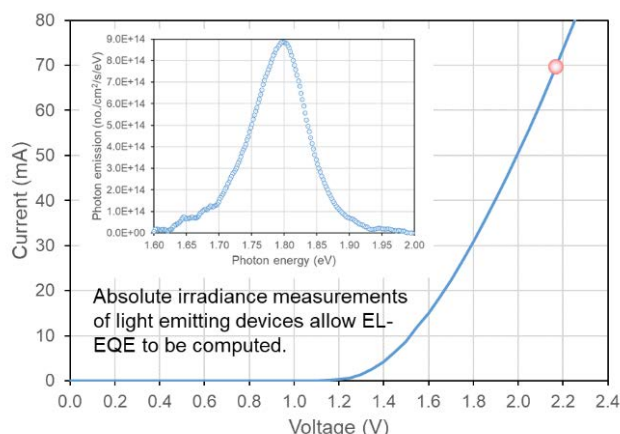
In 2021, SERIS' Thin-Film Modelling Team developed optical codes to account for a mixture of coherent and incoherent structures in all-perovskite tandem device configurations, and modelled the interconnecting layer between the sub-cells in a two-terminal perovskite-perovskite tandem cell. The model allows a combined optimisation of recombination and optical losses. As part of this work, we found that the origin of an S-shaped current-voltage curve of a tandem cell is due to inefficient charge carrier recombination. We are currently extending the model to perovskite/silicon tandem solar cells, and then plan to explore the impact of various parameters (geometrical, material parameters, process conditions) on the PV efficiency of these tandems. These studies are expected to help our device fabrication teams with improving the efficiency of their tandem solar cells.

Plans for 2022

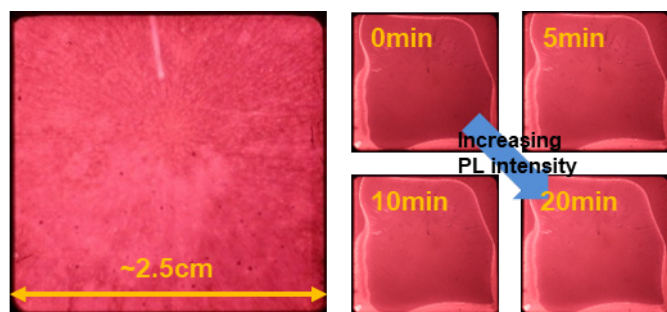
In 2022, SERIS will further strengthen the fabrication, characterisation, modelling and simulation capabilities for perovskite solar cells and tandem solar cells, as well as perovskite and tandem mini-modules. We aim to improve the efficiency of small-area perovskite/Si tandem solar cells beyond 29% and demonstrate perovskite/Si tandem mini-modules with efficiency beyond 20%. 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.

 Delineation of the short-circuit current density J_{sc} losses of a non-optimised perovskite/silicon tandem solar cell by analysing spectral response, reflectance & ellipsometry measurements. Knowing the contributions of various layers towards J_{sc} losses facilitates better solar cell design and optimisation.

Similarly, luminescence imaging and characterisation techniques were also developed and applied to loss analysis, quantifying materials performance, and process metrology. Luminescence quantum yield measurement enables quick material screening, understanding and optimising optoelectronic device performance. For more information on 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 2021.



 Electroluminescence (EL) external quantum efficiency (EQE) measurement of a PV device operated as a light emitting diode (LED) reveals important insights into optoelectronic material and device behaviour.



 Photoluminescence imaging under 625-nm excitation of (left) a perovskite thin film spin-coated onto a glass pane revealing notable process non-uniformity; (right) Evolution of PL intensity over time for an encapsulated perovskite film, indicating changes in material properties under illumination. The measurement of temporal changes is important for device stability studies.

Building-integrated Photovoltaics (BIPV)

Dr TAI Kong Fai, Dr Veronika SHABUNKO

Singapore aims to install at least 2 GW_p of solar PV systems by 2030. With a cumulative installed capacity of 527 MW_p (as of Q2-2021), the solar installation needs to be quadrupled over this decade to achieve the target. According to the “Solar PV Roadmap for Singapore”, the net usable area for solar installations on building façades (9.83 km², including retrofit and new buildings up to 2050) represents 27% of the total area in Singapore that is usable for PV. Therefore, BIPV can contribute significantly to the national solar deployment target. There remain numerous challenges for BIPV such as the requirements on aesthetics, cost, low energy yield due to sub-optimal orientation, integration complexity and building regulations, which this research aims to address.

(i) BIPV Innovations

Dr TAI Kong Fai, SAW Min Hsian, CHEN Tianyi

This project aims to overcome some of the challenges of BIPV, with the following objectives:

- (1) Develop a reliable, cost-effective and high-efficiency BIPV module.
- (2) Develop new and innovative BIPV modules that meet aesthetic requirements for buildings with minimum power loss (< 20% relative loss compared to standard PV modules) and uniform shading to avoid hotspot reliability issues.
- (3) Develop modular PV-integrated building components to ease installation and promote BIPV deployment.

The reducing cost of solar panels makes BIPV more viable than ever before, especially when considering replacing conventional building materials with solar panels which generate clean electricity that pays back the initial extra cost over time. This research approach is publicly funded through the Solar Competitive Research Programme Grant S18-1175-SCRP “Cost-effective high-power density BIPV modules”.

High-performance and colourful BIPV modules

To create aesthetically appealing PV modules, there are various techniques. One solution is the digital printing technology, in which ceramic frit or colour pigments are applied to the front glass pane of PV modules. However due to the combined effects of reflection and absorption by the frit and pigments, the power loss of this technology is relatively high, especially when a high ink density and full ink coverage over the glass is needed to achieve a vivid pattern. Nevertheless, digital printing technology is widely used in the building glass industry due to its ability and flexibility to create any desired aesthetics. Another technology - spectrally selective reflective filters, e.g. interference coating or photonic structural technology - can reflect the specific wavelength of interest with minimal absorption, and hence is able to provide a colour of interest at minimal power loss. However, it produces only plain colours and has limited flexibility in terms of creating complicated patterns/designs.

Given this situation, by combining the best features of these two technologies, we proposed a superimposed method (coined “SERIS-hybrid”) that combines a top digitally printed glass pane with minimal ink density and coverage with a bottom homogeneous base colour layer (a spectrally selective reflective filter) to provide design flexibility with minimal PV power loss. This has been demonstrated with PV modules that emulate building materials. For example, to produce a marble-like appearance, we start with a homogenous white/grey selectively reflective base layer on the encapsulant and then digitally print the marble stripe pattern onto the inner surface of the front glass

pane. Upon lamination of the entire PV module, a marble-like appearance is achieved, see Figure 1. A patent application (PCT/SG2021/050073) has been filed for this invention.

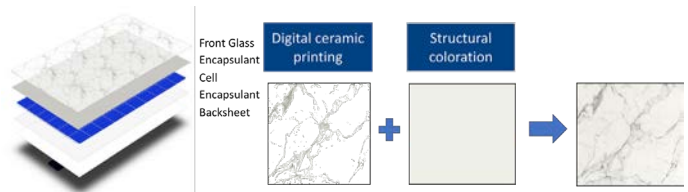


 Figure 1. A superimposed method (“SERIS-hybrid”) that combines digital ceramic printing with spectrally selective reflective filters to provide design flexibility with lower PV power loss.

PV-Integrated building components

Architectural design is always the first step in any building development project. If the architectural consultancy firm is not well versed with solar PV panels or systems, integrating BIPV into the building design may not be their top priority. The most cost-effective and easiest way to deploy BIPV is to integrate the modules during new building construction, by replacing some of the conventional building materials (e.g., a façade cladding) with solar panels. Deploying BIPV onto new buildings also avoids the need for additional construction work to later retrofit with solar panels. Therefore, to equip architects with tools and knowledge of solar integration onto buildings, we set up various demonstration projects for PV-integrated building components.

Often, unitised curtain walls in a commercial high-rise building are made of glass panels covering the vision as well as the non-vision spandrel areas. The non-vision spandrel areas are the areas covering the floor slab and thus do not require transparency. Therefore, the spandrel glass panels can be replaced with PV panels for electricity generation. For highly articulated façades in typical commercial buildings, the non-vision spandrel represents a relatively large area which can generate a significant amount of clean electricity when deploying BIPV. Figure 2 shows a simple prototype of a PV-integrated unitised curtain wall that we developed together with a local curtain wall manufacturer, using a standard black solar module and three other aesthetic solar modules (marble-like, terracotta, and white-colour module). In this case we deployed four different aesthetic modules for comparison and data collection, while keeping prototyping costs at a minimum. We welcome any stakeholders who wish to deploy such BIPV products into their pipeline projects to approach us for further information exchanges.



 **Figure 2.** PV-integrated unitised curtain wall with 4 different types of solar modules (from top left to bottom right: marble-like, standard black module, terracotta, white module) integrated into two unitised curtain walls.

Besides PV-integrated unitised curtain walls, there are other building elements which can be integrated with a BIPV system. For example, we demonstrated a PV-integrated balustrade at the Singapore Sustainability Academy (SSA) located at City Square Mall Level 6, together with our collaborators City Development Limited (CDL) and PvFoundry. Using digital ceramic printing, these aesthetically appealing solar panels can be lined up to form an artwork, while serving as a balustrade and generate clean electricity at the same time. Figure 3 shows the “Solar Artwork” featuring two Singapore iconic landmarks – the Supertrees and the Merlion – as well as the respective company logos, lined up across seven aesthetic modules. The BIPV modules were fabricated using a novel module technology called “bifacial shingling PV modules” which features a higher power density. For comparison, the set-up also has 13 standard bifacial shingling modules with normal PV front glass.



 **Figure 3.** “Solar Artwork” balustrade at City Square Mall

The 20 bifacial panels stretch across a length of 40 metres, with a total capacity of 7.7 kW_p connected to the grid. Solar potential analysis and yield estimation were performed with 3D modelling software and ray-tracing to consider the impact of shading by the surrounding buildings and structures. With a North-West facing vertical installation, the energy yield is expected to be lower compared a conventional rooftop PV system, as the annual in-plane solar irradiation received is only 37% compared to the Global Horizontal Irradiation (GHI). The estimated yield is 4527 kWh per year. This is about 43% of the annual yield of a conventional rooftop PV system with the same capacity, which is slightly higher than 37% due to the rear-side generation of the bifacial modules. The rear-side generation depends on the light (both direct and diffuse) reaching the back of the PV modules (so-called “albedo”). Reflective surfaces such as white

walls would increase the albedo while tall build-ups behind the installation reduce it. This confirms that bifacial PV panels can also be installed vertically (instead of horizontally), provided there is an unblocked front and rear environment, for example as noise barriers along highways or railways.

(ii) BIPV Centre of Competence

Dr Veronika SHABUNKO

The Centre of Competence (COC) for BIPV was established at SERIS in 2017 to testbed innovative BIPV applications in a tropical environment and provide a collaborative platform with relevant stakeholders from the private and public sectors.

The main objectives of the BIPV COC are: i) Test-bedding of innovative BIPV technologies; ii) Acting as an information platform and providing best practices for industry, academia and government bodies; and iii) Developing tools and business models around financing of BIPV.

The BIPV COC aims to work closely with architects, engineers, building developers, façade consultants, and BIPV industry to bring innovation to the Singapore market and conduct training on innovative technologies and implementation. In addition, the BIPV COC is also actively engaged with relevant government agencies such as SCDF, BCA, NEA, HDB, NCCS and EDB to establish regulations for innovative BIPV products and to ensure a smooth future deployment of BIPV solutions in Singapore and the region.



 **Figure 4.** Landing page of the one-stop information portal on BIPV in Singapore: www.bipv.sg

The BIPV COC established the website www.bipv.sg as a knowledge sharing platform about BIPV/BAPV, including latest technologies, BIPV projects worldwide, BIPV publications and events, in order to keep local stakeholders updated on relevant BIPV-related matters (see Figure 4). In addition, the “BIPV SG” community was established with the aim to bring together early adopters, various governmental and regulatory bodies, and relevant stakeholders from private and public sectors to take on a leadership role in advancing and promoting BIPV in Singapore. “BIPV SG” is meant to be an interactive platform to address barriers and find innovative solutions to overcome them in an inter-disciplinary manner, covering the full value chain from design, component selection, construction, installation to operation & maintenance of novel BIPV and BAPV solutions. In December 2021, the “BIPV SG” had over 100 active members and continued to grow.

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. In 2020, despite the COVID-19 pandemic, Floating Solar has continued its expansion, mainly in Asia and Europe. In September 2021, the cumulative installed global capacity surpassed 3 GW_p (see Figure 1). 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). There is a large potential for such hybrid systems in the ASEAN region, especially in Indonesia, Thailand, Vietnam, Laos and Myanmar.

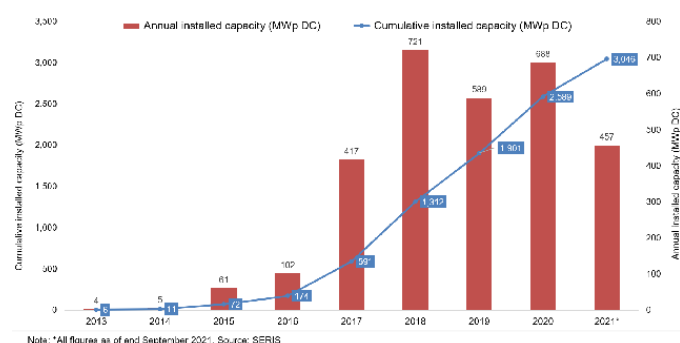


Figure 1. Globally installed FPV capacity

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 2). 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 regularly publishes industry reports (e.g. the “Where Sun meets Water” series, together with the World Bank) and participates in technical consultancy work for large-scale FPV power plants, such as a 60-MW_p system at Singapore's Tengeh reservoir.

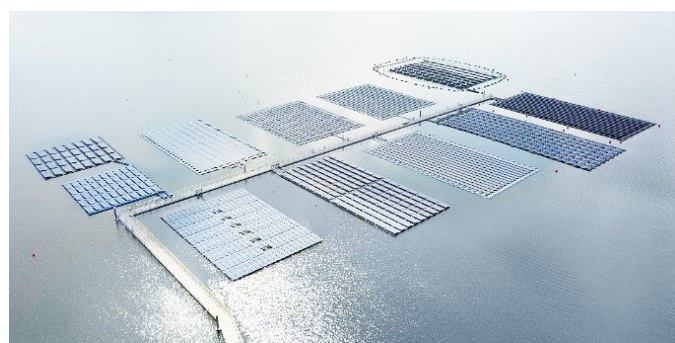
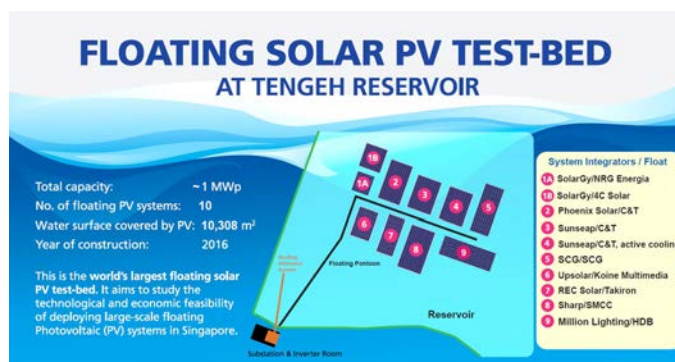


Figure 2. (Top) Schematic of the FPV testbed at Tengeh reservoir with project partners. (Bottom) Photograph (aerial view) of the testbed.

SERIS' Floating Solar flagship project has adopted a holistic approach towards driving various aspects of the FPV industry, which is summarised in Figure 3 and further explained in detail in the following section.

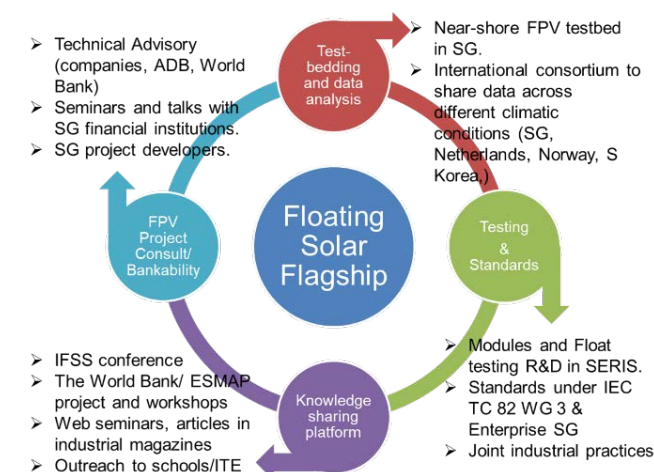


Figure 3. Thrust areas of the Floating Solar flagship project.

1. Knowledge sharing, R&D community building

SERIS aims to continuously grow and support the global FPV community. In October 2021, during the Asia Clean Energy Summit (ACES) and the Singapore International Energy Week (SIEW), SERIS launched the “International Floating Solar Society” (IFS²) website, which intends to nurture and grow the international floating solar community and provide a one-stop shop for anyone interested in Floating Solar, be it from academia, industry, public sector, investors, developers, or financiers. The spirit of the IFS² is to foster continuous exchange of the latest know-how and experiences on Floating Solar.

SERIS also continued to perform analyses on the data from the Tengeh FPV testbed and has published several scientific papers. This included the world's first comprehensive and in-depth analysis of the degradation rates of FPV systems over an extended period of operation (36 months). Also, a cross-climatic comparison of the energy yields of FPV systems in Singapore (tropical) and the Netherlands (temperate) gave insights on the climate-specific benefits of Floating PV:

- Wei L, Isukapalli S., Vinayagam L, Ting S.A., Pravettoni M., Reindl T., Kumar A., “Performance loss rates of floating photovoltaic installations in the tropics”, *Solar Energy* 219 (2021): 58-64.
- Dörenkämper M., Wahed A., Kumar A., Jong M., Kroon J., Reindl T., “The cooling effect of floating PV in two different climate zones: A comparison of field test data from the Netherlands and Singapore”, *Solar Energy* 219 (2021): 15-23.

2. 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) and the Asian Development Bank (ADB) on projects in Singapore, India, Sri Lanka, Vietnam and the Philippines to transfer its knowledge to their real-world projects, be it as part of feasibility studies or the engineering design work. In 2021, SERIS also expanded its technical expertise to the area of hybridisation of floating solar with hydropower stations. This can be in the form of co-location, but has even greater benefits when conjointly operating the solar and the hydropower facilities.

3. FPV standards formation

SERIS is leading the drafting 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) is expected to be published in Q1-2022. In addition, the institute is also leading the efforts on international level as part of Singapore's active membership in IEC TC82 WG3.

4. Near-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. This follows 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.

In 2021, SERIS has expanded its technical leadership role in marine floating solar, leading projects related to near-shore floating PV systems. On the national level, SERIS is involved in a consortium with leading solar developer Sunseap and a subsea marine company in Singapore 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. A comprehensive assessment of 36 float types and 29 PV modules (specifically for FPV applications) was carried out. In addition, a thorough and systematic Failure Mode and Effects Analysis (FMEA) revealed no less than 73 potential failures for near- and off-shore FPV systems, of which 4 have a high and 21 a medium probability of occurrence. Overcoming these challenges is the subject of current ongoing research works.

Plans for 2022

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- or 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 electrolyzers).



SERIS spin-off QE-Labs: The aerial solar solution for PV asset life-cycle management

Dr WANG Yan, Dr KHOO Yong Sheng, Dr Karl BEDRICH, Dr ZHANG Ji, CHAI Jing, Quantified Energy Labs

Quantified Energy Labs Pte Ltd (QE-Labs) is a deep-tech spin-off company from SERIS/NUS. The start-up develops and commercialises aerial solar solutions for the photovoltaic (PV) industry to support its clients in PV asset life-cycle management, which covers PV system design, construction, commissioning, and operation and maintenance (O&M).

The global accumulated PV installations now exceed 700 GW and are growing at a fast yearly pace of more than 100 GW. Similarly, the Singapore government also has announced an ambitious PV deployment target. With large numbers of PV systems installed, life-cycle management is becoming increasingly crucial for ensuring optimal system performance. The typical life-cycle of PV assets consists of the following phases:

- Development (typically 1-3 years)
The development phase is focused on the technical and financial development of the project to ensure its viability and bankability.
- Construction (< 1 year)
The construction phase is typically very short. The major work consists of tracking the adherence to planned milestones and ensuring that the documentation at each stage of construction is in order. Testing and commissioning is performed before moving to the next phase.
- O&M (> 25 years)
Upon successful construction and commissioning, the asset officially enters the Commercial Operation Date (COD). Among all phases, the O&M phase is the longest, up to 25 years or more. Effective routine O&M and troubleshooting is important to ensure that the PV asset is operating optimally throughout its lifetime.
- End of life (a few months)
Once the solar asset reaches its end of life, two options are available for the asset owner. The first is decommissioning and disposal of the asset, according to the legal requirements. The second is repowering of the asset for a new breath of life.

QE-Labs' End-to-End aerial solar solution starts from solar potential assessment and PV system design to support its client in the project development phase. As a city state, Singapore has limited land area for large-scale ground mounted solar power plants, and its high-density built environment poses significant challenges to solar deployment in its urban settings, due to concerns on shading between buildings and glare from PV arrays, not to mention the potential safety hazards that may arise from unoptimised designs. QE-Labs is in the midst of developing drone-based 3D modelling technologies and automated workflow which adopts physics-based simulation engines to generate an optimised PV system design. This product is essential to accelerate the solar PV deployment in Singapore.

One of QE-Labs' core products and services is the use of advanced drone electroluminescence (EL) and artificial intelligence (AI) enhanced quantitative big data analytics for fast and accurate identification of defective PV modules from the field, generating extraordinary insights for PV system commissioning, performance improvement, supporting warranty claims, technical due diligence for asset transaction, etc. The EL camera captures unique signals emitted by solar cells and

hence can detect almost all types of PV module defects. EL is a standard test used in all PV manufacturing for product quality control; all PV modules shipped out by manufacturers would have undergone several rounds of EL measurement at various production stages. While EL is a very powerful tool, it is not widely used in PV system inspection due to following reasons:

- Most of the laboratories take EL measurements manually, which is slow and time consuming, and labour intensive and hence costly;
- There is lack of technology to capture and process large numbers of EL images.

QE-Labs brings EL inspection to a commercially feasible level by enhancing the testing speed from a few hundred manual measurements per night to more than 10,000. Incorporating image normalisation according to IEC TS 60904-13:2018, geo-referenced EL mapping, and the NUS licensed Quantitative EL Analysis (QELA) algorithm for power loss estimation, QE-Labs is able to give a clear answer to the questions of *what* happened in the field and *where* to find the defective PV modules, *how* large is the loss and determine the root cause to answer *why* did it happen.

QE-Labs' unique aerial solar solution has drawn attention of one of Singapore's leading renewable energy firms, Sembcorp. As the launching customer, Sembcorp adopted QE-Labs' aerial solar solution in real-world projects. One example is using a drone 3D model-based PV system design tool in a SolarNOVA phase 5 project in which Sembcorp will build rooftop PV systems on more than 1000 HDB blocks with a cumulative PV capacity of 60 MW. Another example is the integration of full-site drone EL inspection as part of Sembcorp's initial system completion test and commissioning of the 60-MW floating PV system at Singapore's Tengeh reservoir.



 Drone inspection of a solar power plant in Singapore by QE-Labs. Photo credit: QE-Labs

Solar PV is now the cheapest electricity source in the world, with a huge growth potential. With the success in its home market, QE-Labs will bring its unique aerial solar solutions into the global market with the mission to make every solar PV installation count.



SERIS spin-off “PV Doctor”

We listen, we analyse, we cure

Dr Thomas REINDL

The “PV Doctor” is an advanced and comprehensive raft of asset services for PV systems developed by SERIS in recent years that is now being transferred to industry through a newly founded 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” 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 irradiance forecasting.

The graph below provides an overview of the comprehensive services of the “PV Doctor”, which are:

“GP Consultation”

Providing a general analysis of the PV system performance based on a comparison of actual energy generation data with simulations of the theoretically expected annual energy yield.

“Health Check”

Detailed system performance analysis down to inverter and string level. This may include on-site measurements that can be carried out by trained O&M personnel.

“Health Certificate”

Comprehensive PV system assessments, including verification of contractual obligations of suppliers and O&M providers, as well as financial asset performance.

“Ambulance”

In-field assessment of detected under-performance of a PV system. This employs a variety of tools that can range from I-V measurements to IR, EL or UV imaging.

“Cure”

Based on a root-cause analysis a set of rectification measures will be proposed, including their expected impact on the overall business case. Warranty claims will also be considered.

“Medication”

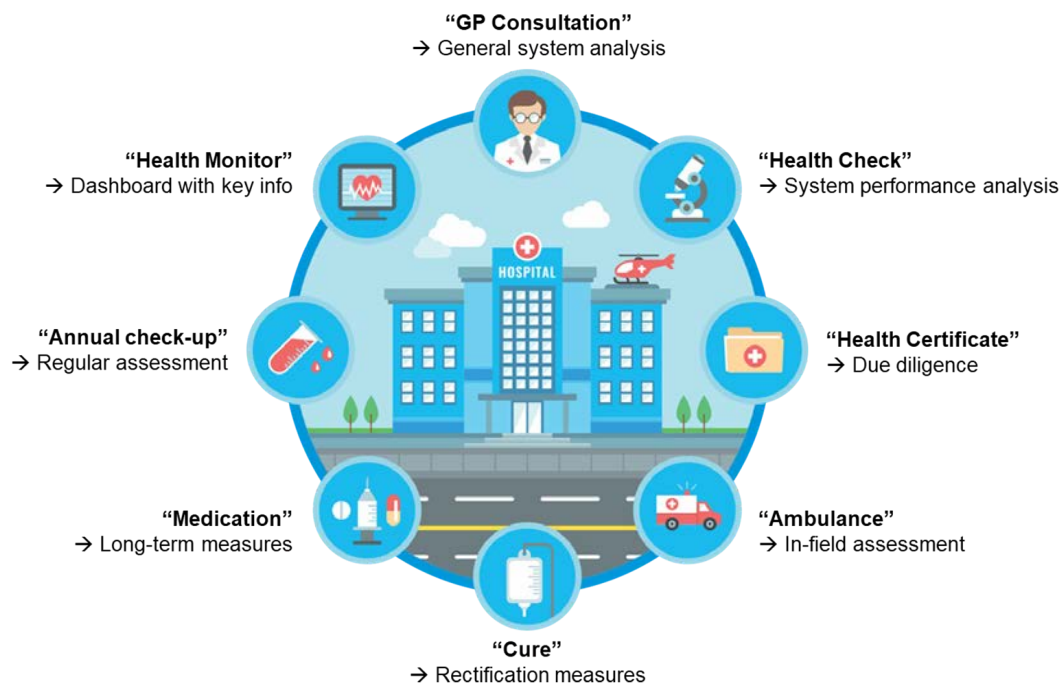
Based on SERIS’ vast experience with PV system monitoring, degradation studies and AI-driven algorithms, smart O&M solutions will be proposed to predict possible future system faults.

“Annual check-up”

Using the existing or a newly deployed PV monitoring system, a regular annual check-up will assess the system performance and benchmark the O&M provider.

“Health Monitor”

A dashboard with key PV system data provides relevant information for a continuous health status update, and also allows to trigger ad-hoc assessments and/or service requests.



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.

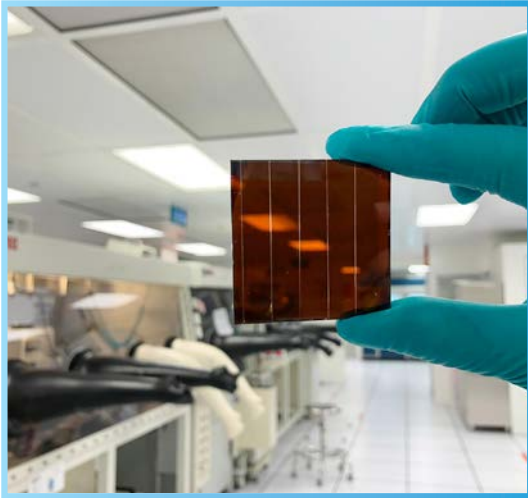


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SELECTED R&D RESULTS 2021



- 1) 23% wide-bandgap perovskite solar cell
- 2) Progress with SERIS monoPoly™ solar cell technology
- 3) Examining process consistency in solar cell fabrication through non-contact external quantum efficiency metrology
- 4) Development of a web-based photovoltaic simulation platform, combining advanced device simulations with machine learning



- 5) Photovoltaic module failures after 10 years of operation in the tropics
- 6) The effect of capacitance on high-efficiency photovoltaic modules: a review of testing methods and related uncertainties
- 7) Assessing Light and Elevated Temperature Induced Degradation (LETID) on commercial solar modules: results from an international interlaboratory comparison
- 8) Building Integrated Photovoltaics (BIPV) on steel based structures



- 9) Full disk Himawari-8/9 satellite imagery from JAXA
- 10) Performance degradation analysis of floating photovoltaic systems in the tropics
- 11) Holistic simulation approach for design and optimisation of agrophotovoltaic systems

23% wide-bandgap perovskite solar cell

Haoming LIANG, Asst Prof Yi HOU

1. Background

The metal halide perovskite solar cell (PSC) is an emerging photovoltaic technology that is attracting a lot of attention from both academia and industry. It took only a few years for the efficiency of single-junction lab-scale PSCs to leap from less than 4% to the current record of 25.5% [1]. The efficiency of lab-scale single-junction PSCs is now approaching that of silicon solar cells as well as the Shockley-Queisser limit. However, it is hard to achieve further efficiency improvements with the composition of the current record device (FAPbI_3) due to its bandgap (~ 1.5 eV) and the resulting limitation of the light-generated current. One of the approaches to boost the efficiency is to pair a wide-bandgap solar cell with a narrow-bandgap one to convert the solar spectrum more efficiently. In this case, by employing PSC's bandgap tunability, the fabrication of a perovskite top cell with a wide bandgap (> 1.6 eV) is of great interest.

Metal oxides, as a common wide-bandgap hole harvesting layer, are widely used in both PSCs and organic solar cells because of their low manufacturing costs, good stability, and industry-compatible deposition process. However, perovskite absorbers deposited on top of a metal oxide layer may suffer from the oxidation of the metal cations. These cations may act as a Lewis acid and de-protonate the amine in the perovskite precursor, leading to the oxidation of the iodide anion (I^-). This, in turn, may lead to the formation of excessive lead iodide and lead bromide ($\text{PbI}_{1-x}\text{Br}_x$) at the interface, which blocks the hole extraction and lowers the device efficiency [2]. The incorporation of a passivation layer realises both faster extraction of holes and effective passivation of the perovskite layer/hole transport layer interface. It also serves as a protection layer to prevent the perovskite absorber layer from reacting with the metal oxide layer [3, 4].

In this work, an efficient 1.62-eV wide-bandgap PSC was fabricated. The device performance was improved via optimising the hole transport layer (HTL), by sandwiching a passivation layer between the metal oxide HTL and the perovskite absorber. On SERIS' I-V tester, the best cell (area 0.055 cm^2) had a power conversion efficiency (PCE) of 23.2%, with an open-circuit voltage (V_{OC}) of 1.21 V, short-circuit current density (J_{SC}) of 22.9 mA/cm^2 , and fill factor (FF) of 83.7%.

2. Scope of project & objectives

The 1.62-eV wide-bandgap PSC was fabricated and characterised with several advanced testing methods. The performance of the device having the passivation layer was compared with the one without it using 1-Sun J-V measurements. Statistics of the device performance parameters were then analysed. The morphology of the top surface and the cross-section was studied with SEM, to have a better understanding of the crystallisation process with and without the passivation layer. Optimisation of the passivation layer coating process was also carried out to push the device performance to a higher level.

3. Significance and impact of project

Unlike the narrow-bandgap PSCs, wide-bandgap PSCs are being developed for applications in multi-junction devices, such as 2-junction ("tandem") and 3-junction cells. By joining a wide-bandgap top cell with a narrow-bandgap bottom cell, a more efficient conversion of the solar spectrum can be realised. Crystalline silicon solar cells, which dominate the terrestrial PV markets, are a narrow-bandgap semiconductor material (~ 1.1 eV). Pairing the wide-bandgap PSC with the narrow-bandgap silicon cell is a promising option to surpass the theoretical efficiency limit of single-junction solar cells, and further lower the cost (LCOE) of solar electricity.

4. Methodology & Results

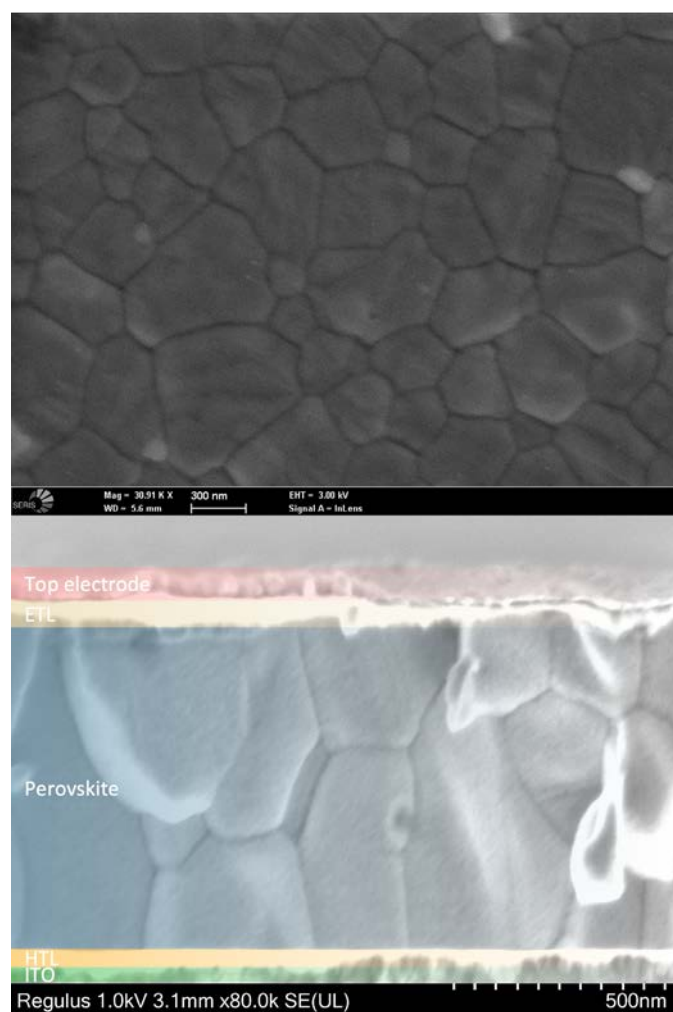


Figure 1. (a) Top-view SEM image of the 1.62-eV perovskite solar cell. (b) Cross-sectional SEM image of the device with the in-house developed HTL.

The wide-bandgap perovskite solar cell was made in the p-i-n configuration, see the scanning electron microscope (SEM) image of Fig. 1(b). The surface morphology of the perovskite device plays an important role for the crystal quality and the device performance. The SEM was used to investigate the effect of the passivation layer on the crystal quality of the perovskite film. As can be seen from Fig. 1, the grain size in the perovskite film is of the order of several hundred nanometres, which is larger than for perovskite films deposited directly onto bare metal oxide HTLs. The passivation layer improved the crystallisation process of the perovskite absorber layer, and also the stability of the PSC. These larger grains facilitate charge carrier transport by allowing them to be transported inside the grains, which reduces non-radiative recombination losses and thus improves the cell efficiency.

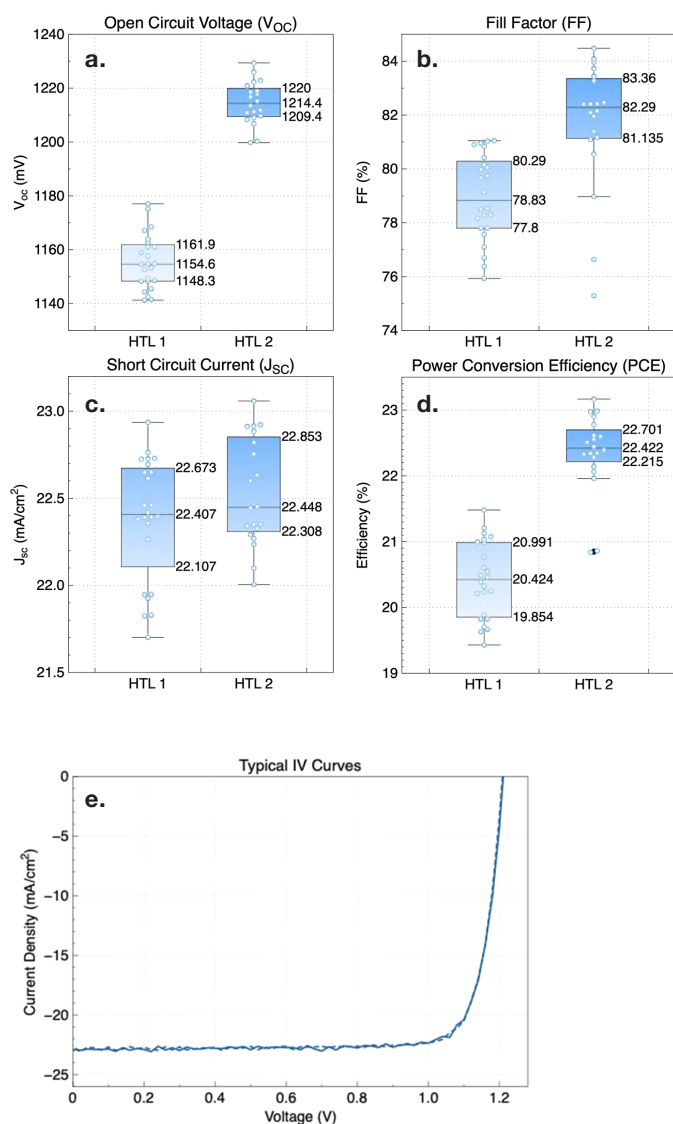


Figure 2 shows a comparison of the 1-Sun performance (AM 1.5G spectrum) of devices with a bare metal oxide HTL (HTL 1) and a passivated metal oxide HTL (HTL 2). As can be seen, the device efficiency improved enormously (by 2 efficiency points) due to the introduction of the passivation layer on the HTL, giving a champion cell efficiency of 23.2% (V_{OC} 1.21 V, J_{SC} 22.9 mA/cm², FF 83.7 %). The efficiency gain was mainly due to improvements of the open-circuit voltage and the fill factor, while the effect on the short-circuit current density was small. The passivation layer improved the average V_{OC} by 70 mV and the average FF by 3.5% absolute. The V_{OC} effect is a solid proof for the passivation effect between the metal oxide and the perovskite.

5. Conclusions

In this work, the effects of passivation of the metal oxide HTL of p-i-n perovskite solar cells was investigated. The role that the passivation plays in the device and the mechanisms of performance boosting was understood better after carrying out the work such that the introduction of a passivation layer was found to reduce interface recombination losses between the metal oxide and the perovskite, improve the crystallisation process of the perovskite thin film, and to boost the open-circuit voltage, the fill factor and the 1-Sun efficiency of the device. It also acts a guide on the design of new passivation materials. Using this approach, a small-area (0.055 cm²) wide-bandgap (1.62 eV) perovskite solar cell with a 1-Sun efficiency of 23.2% was fabricated.

References

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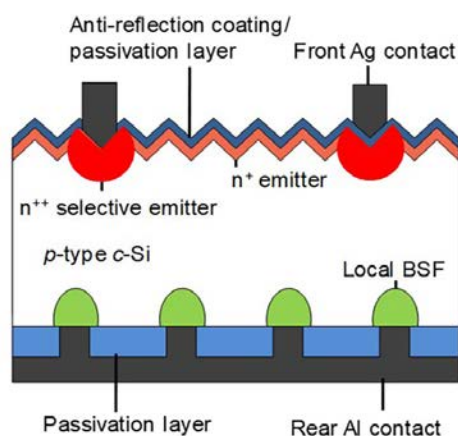
Figure 2. One-Sun performance analysis of p-i-n perovskite solar cells with different hole-selective layers. Comparison of (a) open-circuit voltage, (b) fill factor, (c) short-circuit current density, and (d) power conversion efficiency. (e) J-V curve of the 23.2% champion device (0.055 cm²). Measured on SERIS' I-V tester.

Progress with SERIS' monoPoly™ solar cell technology

Dr YAN Xia, Dr Naomi NANDAKUMAR, Dr Shubham DUTTAGUPTA

1. Background

Global PV manufacturing is dominated by the *p*-type silicon “Passivated Emitter and Rear Cell” (PERC) technology, with a total production capacity of about 200 GW at the end of 2021. PERC modules with above 23% cell efficiency and more than 500 W power output are now in mass production at several companies. With PERC cells approaching their industrial efficiency limit of about 24%, the research focus has shifted towards non-disruptively upgrading from PERC to a higher-efficiency (~25%) cell structure such as TOPCon (“Tunnel Oxide Passivated Contacts”). As one of the leading TOPCon solutions, SERIS has developed the **monofacial** application of **Poly-Si** (i.e., **monoPoly™**) solar cell technology, see Fig. 1. SERIS' monoPoly™ solar cells are made on industrial 6-inch Cz silicon wafers using screen-printed metal contacts, which is well suited for mass production.



Upgradable

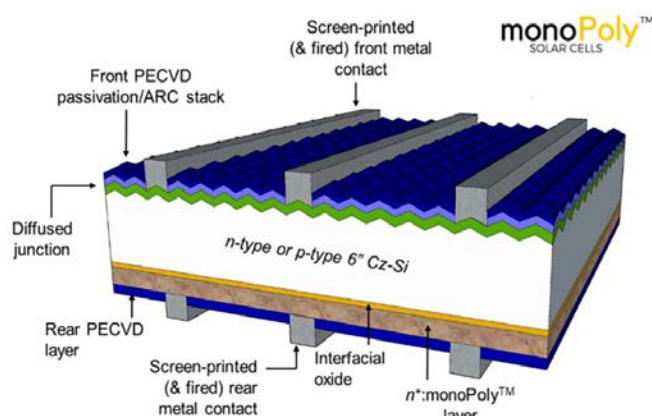


Figure 1. Industrial technology upgrade from 24% PERC solar cells to SERIS' 25% monoPoly™ technology.

2. TOPCon Overview

The TOPCon cell concept was published by Fraunhofer ISE in 2013, and soon demonstrated very high cell efficiency at the lab scale (small cells), excellent high-temperature stability, and good bifaciality. As a result, many research institutes and cell manufacturers started researching TOPCon solar cells. Most of the research institutes focused on conceptual studies and were limited to small-area cells (e.g., $2 \times 2 \text{ cm}^2$) and relied on low-temperature metallisation methods such as physical vapour deposition (PVD). Despite the very high cell efficiencies (~26%) demonstrated in these studies, the used processes cannot directly be transferred to industrial fabrication due to cost (\$/W) and scaling-up issues.

In contrast, from the very beginning of its monoPoly™ research, SERIS has been working on industrial silicon wafers (M2 size) and screen-printed metallisation using conventional high-temperature fire-through metal pastes. To our knowledge, SERIS' monoPoly™ technology has maintained the best TOPCon solar cell efficiency using industrial wafers among all public research institutes, see Fig. 2.

In parallel, several leading PV manufacturers (such as LONGi, Jinko Solar, Trina Solar, Jolywood, etc) have invested heavily in their own R&D pilot lines for TOPCon cell development, giving reported efficiencies of up to 25.25% at Jinko and up to 25.21% at LONGi. These companies have also started early-stage mass production of TOPCon solar cells and modules, with a combined production capacity of 6-8 GW/year.

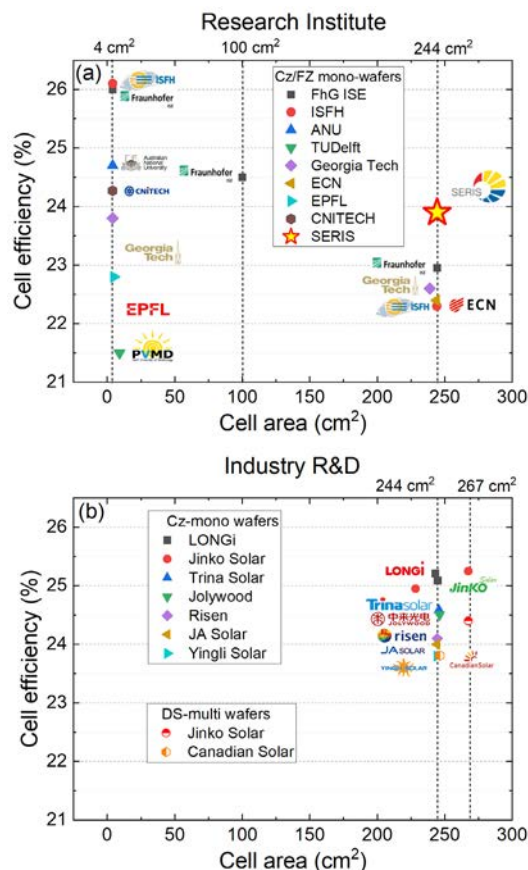


Figure 2. Overview of the best reported TOPCon solar cell efficiencies achieved by (a) public research institutes and (b) companies.

3. Methodology & Results

In TOPCon cells, a passivated contact is achieved with a heavily doped poly-Si layer on a very thin interfacial SiO_x (iO_x). So far, there is no consensus in the PV industry on what the best method is for making the poly-Si layer. The monoPoly™ technology is compatible with both plasma-enhanced and low-pressure chemical vapour deposition (PECVD, LPCVD). Figure 3 shows the process flow of SERIS' monoPoly™ solar cells using either the PECVD or the LPCVD approach. In contrast to PECVD, the industry mainstream LPCVD technology has an unavoidable and severe wrap-around issue during poly-Si growth. To remove this wrap-around, we have developed and optimised an alkaline single-side etch (SSE) process (coined the 'pClean process') that does not require any extra masking step. Table 1 summarises the best monoPoly™ solar cell results recently achieved by SERIS, with champion cell efficiency of 23.9% for the PECVD method and 23.1% for the LPCVD method.

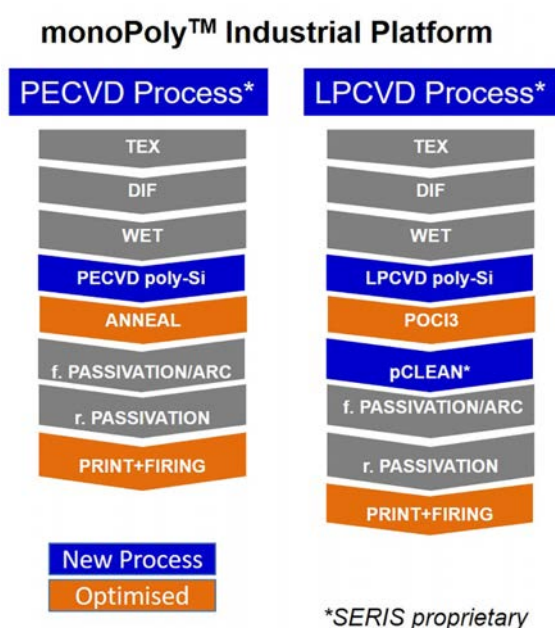


Figure 3. Process flow of SERIS' monoPoly™ solar cells using either the PECVD or the LPCVD approach.

In addition to the solar cell results, we also demonstrated that the monoPoly™ technology is well suited for PV module fabrication. Combining monoPoly™ cell technology with the SmartWire Connection Technology (SWCT®) of our industry partner Meyer Burger in Europe, in 2018/19 we have jointly achieved a monoPoly™ PV module prototype with 60 cells and more than 350 W power (TUV certified).

Method	Group	V_{oc} (mV)	J_{sc} (mA/cm ²)	FF (%)	(%)
PECVD	Batch median	701	41.04	82.5	23.7
	Best cell	703	41.17	82.5	23.9
LPCVD	Batch median	694	40.30	82.1	23.0
	Best cell	695	40.35	82.3	23.1

Table 1. Summary of I-V results of recent best monoPoly™ solar cells fabricated via either the PECVD or LPCVD approach.

4. Conclusions

SERIS' monoPoly™ technology is an extremely promising process for industrial mass-produced TOPCon solar cells, compatible with both PECVD & LPCVD platforms for poly-Si deposition, and high-temperature metallisation based on screen printing. Compared to other public research institutes, SERIS has maintained the highest TOPCon cell efficiency on industrial large-area (6") wafers. We have achieved 23.9% and 23.1% champion cell efficiencies via the PECVD and LPCVD paths for poly-Si deposition. We are targeting to further improve the monoPoly™ cell efficiency to ~25% in the near future. With an adapted structure and process, the monoPoly™ technology could also be used as the bottom cell of perovskite/silicon tandem solar cells.

Selected publications:

1. J.W. Rodriguez, N. Nandakumar, S. Duttagupta; 'SolarEYE' loss analysis of screen-printed, n-type silicon solar cells with 'monoPoly' PECVD rear passivated contacts; Solar Energy Materials and Solar Cells 233, p. 110961 (2021)
2. N. Nandakumar, N. Nampalli, P. Padhamnath, A.G. Aberle, S. Duttagupta; "monoPoly™ silicon solar cells: Status, progress and outlook towards 25% efficiency"; Progress in Photovoltaics: Special Issue article (in press)
3. A.H.T. Le, R. Basnet, D. Yan, W. Chen, N. Nandakumar, S. Duttagupta, J.P. Seif, Z. Hameiri; Temperature-dependent performance of silicon solar cells with polysilicon passivating contacts; Solar Energy Materials and Solar Cells 225:7 (2021)
4. P. Padhamnath, A. Khanna, N. Nandakumar, A.G. Aberle, S. Duttagupta; Impact of firing temperature on fire-through metal contacts to P-doped (n^+) and B- doped (p^+) poly-Si; Solar Energy Materials and Solar Cells 230, p. 111217 (2021)
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Examining process consistency in solar cell fabrication through non-contact external quantum efficiency metrology

Dr Keng Siew CHAN, Ming Xuan HENG, Dr Jian Wei HO

1. Background

Quantum efficiency (QE) measurement is one of the most widely used techniques to measure the spectral response of finished solar cells. QE is often deployed to investigate fabrication process consistency, to troubleshoot poor solar cell efficiencies, and/or to study improvement in fabrication processes. However, conventional QE measurements are slow as compared to other in-line measurement tools such as current voltage (*I*-*V*) and electroluminescence imaging (EL). Additionally, the requirement for good direct electrical contact to solar cells also induces extra stress that can damage them. As a result, QE is currently still limited as an off-line tool, especially for fault finding during solar cell mass production.

The aim of this project is to provide solutions to the above pain points. This is achieved by developing a fast and mass production feasible method for external quantum efficiency (EQE) measurements. In particular, we investigate the use of “non-contact” EQE, a method to measure the spectral response of a solar cell without direct electrical contact to it. This is several times faster than the conventional contacted EQE measurement, thus making it suitable as an in-line mass production analytics tool. Furthermore, the contactless approach enables the measurement of the spectral response of non-metallised cells. This research is supported by the National Research Foundation Singapore (NRF) and the Singapore Economic Development Board (EDB), under the Solar Competitive Research Programme grant S18- 1173-SCRP, project Solar CRP01-018 “Future-Ready Solar Cell Manufacturing: Model Driven Process Control to Maximise Efficiency and Consistency”.

2. Scope of project & objectives

We deploy the aforementioned non-contact EQE (nc-EQE) technique to study the spectral response of industry-grade silicon solar cells. The performance of the samples at different stages of the solar cell fabrication process is investigated and correlated. This is especially useful to gain detailed insights on the limiting factors of achieving higher efficiency of solar cells through fabrication process control improvements. A manufacturing environment is simulated where contactless EQE is measured for a batch of 200 bifacial PERC silicon solar cells. Initial results on passivated and non-metallised diffused silicon wafers are also reported.

3. Significance and impact of project

The non-contact nature of nc-EQE measurement allows on-the-flight inspection of the spectral response of solar cells during mass production. This opens up new possibilities of integrating QE measurements as an in-line inspection tool for high-throughput solar cell manufacturing. In particular, the nc-EQE technique can be inserted after *I*-*V* measurement, without significant impact to production throughput and the need to re-contact the solar cells.

Additionally, the nc-EQE can also be inserted prior to the metallisation processes. In Si solar cell manufacturing, metallisation constitutes significantly (~25%) to the total

cell fabrication process costs due to the use of Ag pastes [1, 2]. As a result, the ability to measure the EQE before the metallisation process may assist in the detection and removal of defective wafers before metallisation. This has the potential to significantly reduce the cost of solar manufacturing.

4. Methodology & Results

The samples investigated in this work comprise 200 large-area (244.3 cm²) p-type monocrystalline Si bifacial passivated emitter and rear cell (PERC) devices fabricated in SERIS' R&D pilot line. To ensure the same bulk properties, the as-received Si wafers were chosen from the same wafer supplier batch. The information of wafer position during texturing, POCl₃ diffusion and PECVD processes were recorded. In this work, a PulseQE apparatus supplied by Tau Science Corporation (USA) is used to acquire the nc-EQE. The nc-EQE tool is calibrated with the EQE of a similar PERC solar cell measured with the traditional contacted EQE method. The contacted EQE of several cells sampled from the experimental batches show a good match to the nc-EQE curves.

Figure 1 shows the short- and long-wavelength nc-EQE as a function of wafer position during (a) PECVD processes, and (b) R_{sheet} measured after diffusion. Despite some noise at wave lengths < 365 nm and 1050 nm, noticeable patterns of process variation can be discerned. Specifically, for PECVD processes, wafer position in the tray is found to influence the nc-EQE values from 325 to 450 nm and 980 to 1050 nm. In particular, wafers located at the edge of the tray (R zone in Figure 1 (a)) show lower average nc-EQE values at ~0.75, ~0.77 and ~0.69, compared to ~0.79, ~0.80 and ~0.71 for the wafers located at the middle of the tray, at wavelengths of 325, 340 and 1050 nm, respectively.

Figure 2 shows cell *I*-*V* parameters of the samples versus the measured nc-EQE values at wavelengths of 325, 385 and 1050 nm. Both V_{oc} and I_{sc} appear to exhibit a strong correlation with the EQE. On the other hand, FF is more sensitive to the nc-EQE at 385 nm.

The results in Figures 1 and 2 reveal an interesting observation for the spectral response of the investigated solar cells, particularly in relation to the POCl₃ diffusion and the PECVD processes. Specifically, the nc-EQE values at < 385 nm and 980-1050 nm are found to fluctuate noticeably with respect to wafer position in the PECVD tray. In particular, samples of low nc-EQE are observed for wafers located at the edge of the tray (position R in Figure 1(a)) during the silicon nitride and aluminium oxide deposition processes. This could originate from poorer surface passivation during the PECVD processes. The poorer passivation also produces a lower V_{oc} and I_{sc} at 325 and 1050 nm, as is noticeable in Figure 2. As a result, this indicates that PECVD is a substantial limiting factor to more consistent solar cells made in this work. PECVD recipes can be optimised in future works to produce more uniform films across the entire wafer tray. This will improve the overall efficiency of the solar cells, with nc-EQE at < 385 nm and 980-1050 nm acting as suitable indicators to gauge the surface passivation quality of the deposited films.

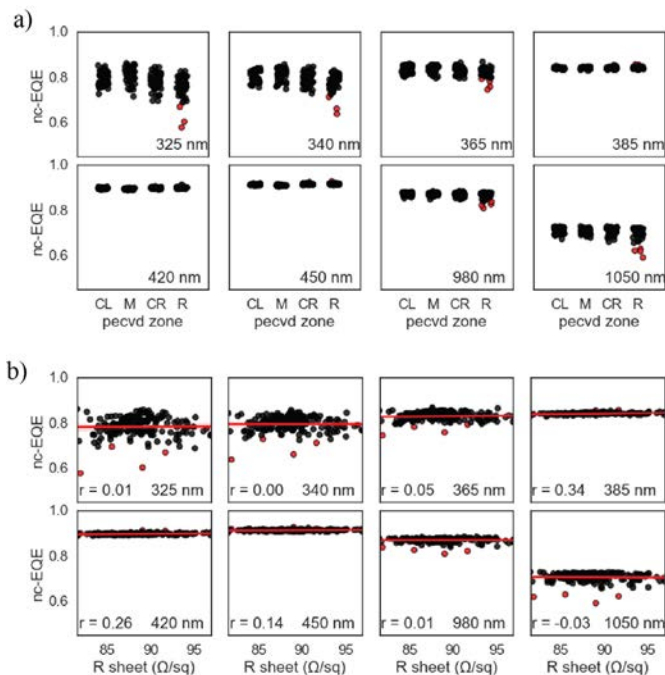


Figure 1: Short- and long-wavelength nc-EQE with respect to (a) wafer position during PECVD processes. (b) R_{sheet} of diffused wafers. Samples with nc-EQE values < 0.65 at 1050 nm are marked as red.

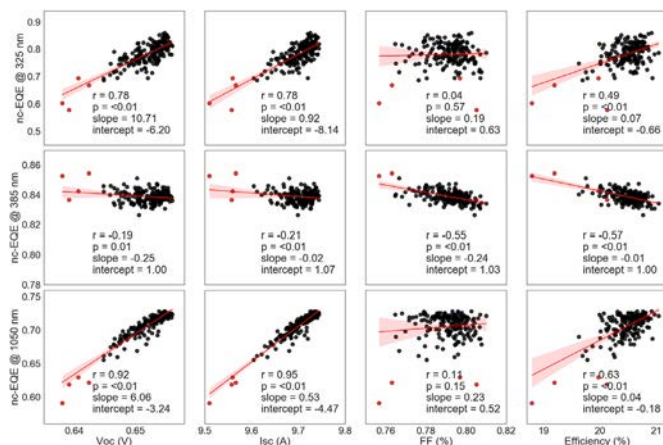


Figure 2: Cell current-voltage parameters versus nc-EQE at wavelengths of 325, 385 and 1050 nm.

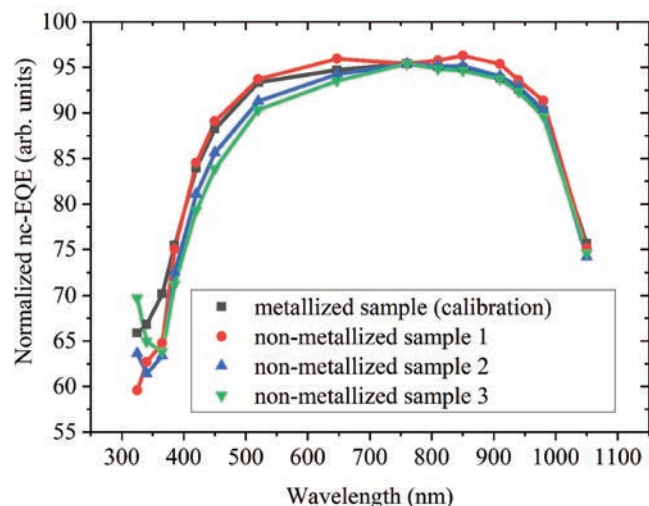


Figure 3: Non-contact EQE curves of p-type monocrystalline Si bifacial PERC solar cells before and after the metallisation process.

In addition, as shown in Figure 1 (b), R_{sheet} shows the strongest linear relationship with nc-EQE at 385 to 420 nm, where the highest r values are found. Figure 2 also shows that FF is the most sensitive to nc-EQE at 385 nm. FF values are negatively affected by the cells' series resistance, to which R_{sheet} and the corresponding doping characteristics contribute. As a result, this suggests that the nc-EQE from 385 to 420 nm may be used to gauge the uniformity and process control of the diffusion process.

Figure 3 shows the nc-EQE of monocrystalline p-type bifacial PERC wafers, prior to cell metallisation, in comparison to the metallised cell from the same fabrication batch. For clarity, the curves are normalised to the value at 760 nm. A close congruence between non-metallised and metallised samples is observed, in the form of the expected EQE shape. The slight differences in the long- and short-wavelength regions could be attributed to variation in cell processing and wafer condition. Additionally, the absence of metal contacts may also impact the flow of photogenerated charge carriers. This application will be investigated in a future work.

5. Conclusions

In this work, analysis of the spectral response of solar cells using non-contact EQE techniques is demonstrated in an R&D pilot line. The nc-EQE measurement is capable of shortening the measurement time of conventional contacted EQE from the range of minutes to the order of seconds for the same measurement steps and size. This allows statistical analysis to be carried out on a large dataset. The results reveal that non-contact EQE at 385 - 420 nm is sensitive to the $POCl_3$ diffusion process, while at < 385 nm and in the 980 - 1050 nm range it is sensitive to the PECVD processes. As a result, these wavelengths, or other wavelengths depending on cell designs, may be used as quality tracers for the respective processes during cell manufacturing.

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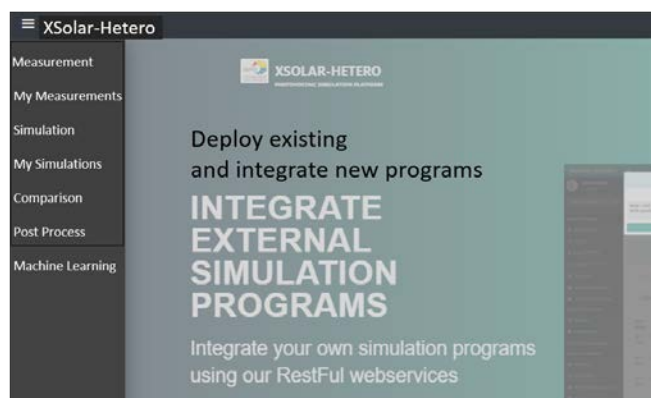
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Development of a web-based photovoltaic simulation platform, combining advanced device simulations with machine learning

Rolf STANGL, Mehul GARK, Aniruddhan MURALI, Rahul JAISWAL, Hansong XUE

1. Background

We describe the current status of XSolar-Hetero, a web-based photovoltaic simulation platform which is being developed at SERIS. This platform is intended for uploading & simulation of measurements, thereby continuously collecting curated data suited for machine learning. It can integrate all kinds of device simulation programmes, provided they can be executed from a command line interface (CLI). A common standard output (using the JSON format) is to be provided for each measurement implemented in the platform, thus allowing to inter-compare different programmes. The easy-to-use platform shall enable researchers (1) to upload, simulate and compare measurements, (2) to process curated data for machine learning (post-processing, batch execution), and (3) to upload, deploy and re-train machine learning models which have been developed by our data scientists using the processed data for training artificial neural networks.



2. Motivation

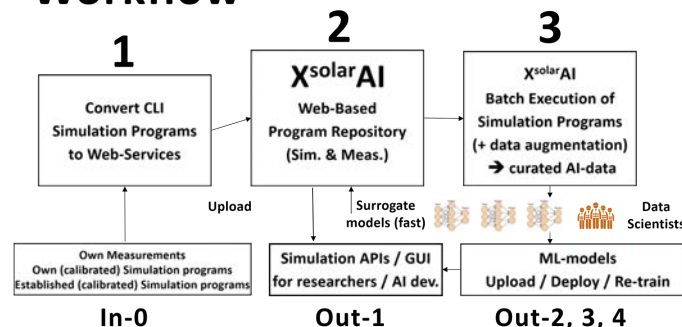
In order to use machine learning for process and device optimisation, curated data are needed. This means that the actual measurements have to be saved together with measurement parameters, information on the sample's architecture and, ideally, the process parameters used in its fabrication. Aiming at machine learning applications, the actual model development and evaluation consumes less than 20% of the time needed for the total development cycle, i.e. the collection of curated data and the model deployment consume more than 80% of the time. Our currently developed web-based simulation platform is intended in the future to automate the data collection as well as the model deployment part, in order to free up time for advanced data science.

The training of artificial neural networks (ANNs) for machine learning usually requires to acquire a huge amount of data points (measurements). This, however, is extremely expensive in the context of solar cell R&D (which is typically conducted in expensive cleanroom laboratories). By simulating measurements, a huge amount of initial training data can be generated in order to pre-train the ANN (thus significantly saving on processing cost needed for machine learning model development). The ANN can then be re-trained with (constantly incoming) real measurements, requiring a significantly lower amount of data and computation power. Last but not least, time consuming device simulations itself can be substituted by trained ANNs (so-called surrogate models), which can be executed within a few seconds.

3. Current scope of project & methodology

Currently, it is possible to directly upload the most important measurements from our characterisation instruments, like current-voltage (I-V), quantum efficiency (QE), injection dependent lifetime (QSSPC), diffusion profile (ECV), reflectance/transmittance (UV- VIS-NIR) and photoluminescence imaging (PL). Common simulation programmes (externally or internally developed) have already been integrated into the platform, like current-voltage and carrier lifetime from Griddler, SentaurusDevice or PC1D, diffusion profile (BBR3 tube diffusion) from SentaurusProcess, reflectance & photogeneration from SentaurusOptics, Matlab or Mathematica, and photoluminescence from Griddler. Uploading such programmes to the platform allows to specify those input parameters which can be varied in the front-end, while all other parameters are fixed or hidden.

Workflow



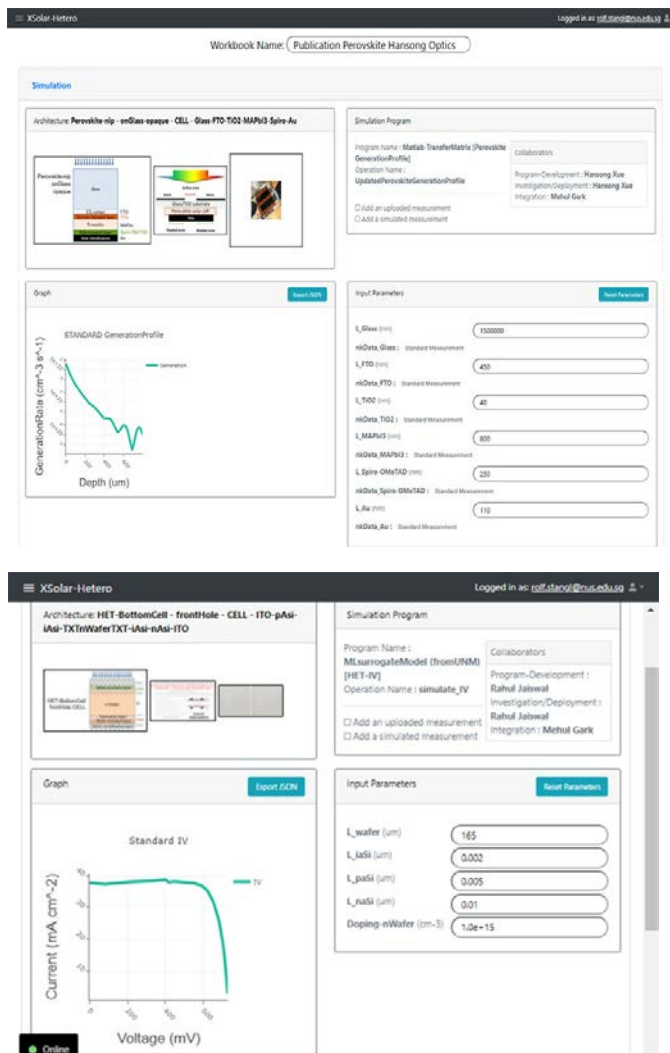
Having demonstrated a silicon solar cell simulation environment [1], we are currently establishing a corresponding perovskite solar cell simulation environment. This includes perovskite cells on glass substrates and perovskite/silicon tandem cells.

Using a (well calibrated) device or process simulation programme, an ANN can be trained with simulated measurements (simple supervised learning), by varying the most relevant input parameters in specified ranges (surrogate modelling). Using the free software Tensorflow-Serving, the corresponding surrogate models can be directly uploaded and deployed within the platform. In contrast to some advanced device simulations (which, depending on their complexity, may take several hours to finish), the corresponding surrogate models are executed within a few seconds. Thus, using ANN based surrogate models, further device optimisations and more advanced machine learning (like "reverse modelling", i.e. predicting device parameters from measurements) will be possible.

Several simple machine learning applications have so far been investigated: (1) Mimic a 3-dimensional optical and electrical Sentaurus device simulation for heterojunction silicon solar cells (surrogate models, supervised learning), (2) predict tube diffusion process parameters in order to get a desired diffusion profile (supervised learning, reverse modelling), (3) predict metal recombination device parameters from PL imaging (supervised learning, reverse modelling).

4. Selected results

The platform's programme upload capability has been improved by allowing the output of other simulation programmes to be used as input parameters for a new simulation programme to be uploaded. Thus, simulation chains can now be implemented. As an example, the photogeneration profile within a perovskite solar cell absorber can be calculated (transfer matrix calculation using a Python/Matlab simulation chain), by taking measured ellipsometry results (n & k data of the layers involved) as an input.



In order to execute current-voltage simulations of perovskite solar cells, a Python/Matlab/COMSOL simulation chain has been established.

A surrogate model, calculating the I-V characteristics of a heterojunction silicon solar cell (using 3D SentaurusDevice calculations) has been developed and uploaded, in collaboration with the University of New Mexico, USA. This reduces calculation times from close to 4 hours to less than 2 seconds.

A first prototype machine learning deployment has been integrated within the XSolar-Hetero platform (by executing a trained artificial neural network (ANN) within a specifically designed web page, using the software Tensorflow-Serving). By providing two (simulated) PL images generated by Griddler device simulations (for light intensities of 1 and 0.1 Sun), the metal recombination rates (j_0) can be predicted with an accuracy of > 96%. However, to be useful for actual solar cell research, this ANN still needs to be re-trained with real measurements.

Prediction of metal recombination

Using simulated PL, training an ANN (Tensorflow).
PL imaging: → get metal j_0 fast and non-destructive!

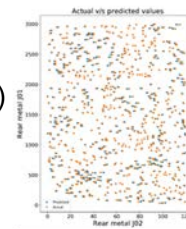


Input:

- PL image (1 sun)
- PL image (0.1 sun)

Output:

- j_{01} -MetalRear
- j_{02} -MetalRear



Accuracy:

for sim. PL
> 96%

But:

ANN to be re-trained with measurements

5. Outlook

The XSolar-Hetero platform is currently in a proof-of-concept development stage and still needs some further improvements in order to guarantee a stable deployment. This is planned by internal (and external) stress testing and improvements (via external research collaborations).

Reference

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Photovoltaic module failures after 10 years of operation in the tropics*

Dr Wei LUO, Carlos Enrico CLEMENT, Dr Yong Sheng KHOO, Dr Yan WANG, Aung Myint Khaing, Dr Thomas REINDL, Dr Abhishek KUMAR, Dr Mauro PRAVETTONI

1. Background

The economics of photovoltaic (PV) electricity depends heavily on the reliability and durability of PV modules. A lower failure and degradation rate for PV modules translates directly to a higher lifetime energy yield and lower levelised cost of electricity (LCOE). PV devices and components are commonly required to comply with the International Electrotechnical Commission (IEC) standards to maintain manufacturing quality. For instance, the IEC 61215 series qualifies PV modules for operations in different climates so that they will not fail prematurely. PV modules are typically warranted for over 20 years, raising concerns about their performance beyond infancy. However, it is difficult, if not impossible, to accurately predict the service life of PV modules in real-world applications. Knowledge of the performance of fielded modules after long-term exposure is thus valuable in many aspects. This article presents a case study of PV module failures after more than 10 years of operation in Singapore. The South-East Asia city-state has a tropical rainforest climate that presents unique challenges to the reliability of PV modules.

2. Scope of project & objectives

Three types of modules, including multicrystalline silicon (multi-Si), monocrystalline silicon (mono-Si), and copper indium selenide (CIS), are thoroughly characterised with various techniques to understand the degradation/failure modes and the underlying mechanisms. These modules were selected randomly from a roof-mounted PV system in Singapore that had been in operation outdoors for over 10 years.

3. Significance and impact of study

This study identifies the dominant degradation/failure modes of various types of PV modules operating in the tropics. These results highlight the future research efforts needed to achieve 25 to 30 years (or more) of service life for different PV module technologies. Furthermore, this study may contribute to the development of climate-specific accelerated stress test standards, where close attention should be devoted to certain degradation/ failure modes to ensure the long-term performance stability of PV modules in the tropics.

4. Methodology & Results

The modules investigated in this project were selected randomly from a roof-mounted PV system in Singapore. The PV system (commissioned in early 2010) deployed three different types of modules, which were all installed at a tilt angle of about 10°. Shading was minimal at the site and air ventilation of the modules was good. These modules had been in operation outdoors for over 10 years before the final indoor characterisation. Table 1 summarises the details of the modules sampled.

Method type	Multi-Si	Mono-Si	CIS
No. of samples	2	2	2
Nominal power (W)	160	160	160
Construction	Glass/ backsheet	Glass/ backsheet	Glass/ backsheet
Framed	Yes	Yes	Yes
Certification	IEC 61215	IEC 61215	IEC 61646

Table 1. Specifications of the three investigated PV module types (total six modules sampled), based on the datasheets from the manufacturers.

The modules were thoroughly cleaned with both water and detergent prior to any measurements. First, visual inspection was conducted on them to identify visible defects. Next, current-voltage (I-V) characteristics at standard testing conditions (STC: 1000 W/m² total irradiance, AM1.5G spectral irradiance and 25 °C cell temperature) were measured with a class A+A+A+ 100-ms pulsed solar simulator (h.a.l.m cetisPV). In addition, to determine the lumped series and shunt resistances, dark I-V measurements were performed. The CIS modules were stabilised with over 2 kWh/m² of light exposure before the measurements. Furthermore, electroluminescence (EL) images at both high and low injected currents were captured to detect cell-level defects.

Figure 1 shows an example of visual defects in the silicon modules. Encapsulant discoloration is seen in the centre of the cells for the multi-Si modules (Figure 1a), whereas for the mono-Si modules, the entire cell area appears to be brownish (Figure 1b). Furthermore, the extent of the colour change is also much more severe for mono-Si modules. Other visual defects include backsheet yellowing (cell side), a permanent soiling band at the lower module end (in reference to the actual installation), corrosion of cross-connectors and metallisation, and delamination.

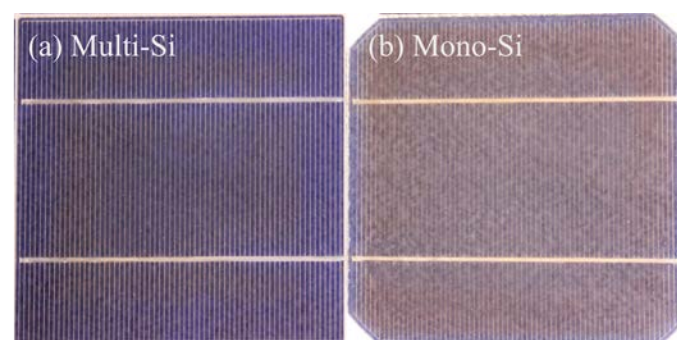


Figure 1. Example of encapsulant discoloration in the (a) multi-Si modules and (b) mono-Si modules.

Table 2 summarises the STC performance of the silicon modules, compared to the nameplate rating. The maximum power at STC (P_{mpp}) of multi-Si modules degraded by more than 9% on average, largely due to loss in fill factor (FF). The short-circuit current (I_{sc}) remained nearly the same, whereas the open-circuit voltage (V_{oc}) dropped by about 1%. The mono-Si modules had already failed at the time of the measurement (> 40% power reduction). They suffered catastrophic losses in FF (> 30%) and I_{sc} (> 10%), while V_{oc} was relatively the least affected.

Method type	P_{mpp}	I_{sc}	V_{oc}	FF
Multi-Si 1	-8.5%	0.1%	-0.7%	-7.9%
Multi-Si 2	-10.2%	-0.1%	-1.1%	-9.1%
Mono-Si 1	-41.7%	-12.3%	-1.6%	-32.4%
Mono-Si 2	-42.8%	-14.8%	-1.4%	-31.9%

Table 2. Summary of the STC performance of the silicon modules, compared to their initial rating.

The I_{sc} loss of the mono-Si modules is largely a result of the encapsulant discolouration (see Figure 1b) that leads to transmittance losses. As for the FF drop, a decrease in shunt resistance (R_{sh}) and increase in series resistance (R_s) are likely the culprits. As shown in Table 3, the R_{sh} values of mono-Si modules are over 20 times lower than that of the multi-Si modules, whereas their R_s is significantly larger. Comparing the parasitic resistance changes to the multi-Si samples is reasonable because they had the same initial electrical ratings (i.e., P_{mpp} , I_{sc} , V_{oc} and FF).

	R_s (Ω)	R_{sh} (k Ω)
Multi-Si 1	0.31	24.8
Multi-Si 2	0.32	23.8
Mono-Si 1	0.60	1.1
Mono-Si 2	0.71	1.1

Table 3. Summary of the R_s and R_{sh} values of the silicon modules.

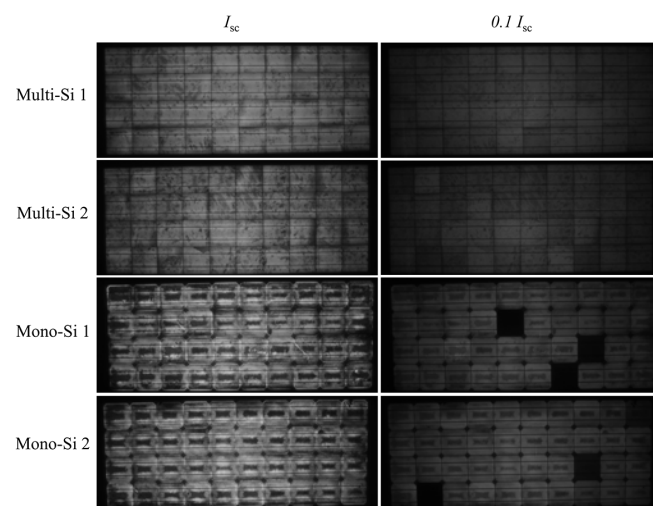


Figure 2. EL images of the silicon modules at $0.1 I_{sc}$ and I_{sc} .

EL images of the silicon modules are shown in Figure 2. At high injected current, reduced performance along the cell edges is visible for the multi-Si modules. This leads to an increase in R_s and thus FF loss, which agrees with the I-V results. For the mono-Si modules, severe corruptions were also observed in the central regions of the cells, which could be due to reactions with the trapped by-products (e.g., acetic acid) of encapsulant deterioration. Moreover, EL at the low injected current revealed heavily shunted cells in the mono-Si modules. This result is consistent with the low R_{sh} values shown in Table 3. It is therefore believed that potential-induced degradation (PID) was the cause of the significant reduction in R_{sh} . PID-shunting also affected V_{oc} , which may explain the slightly higher V_{oc} loss of the mono-Si modules.

Table 4 shows the STC performance of the CIS modules, compared to the nameplate rating. The two samples exhibited a huge difference in STC performance. One CIS module lost roughly 45% of its power, with significant reductions in I_{sc} , V_{oc} and FF. The relatively less-affected sample retained ~85% of the initial power, and the I_{sc} change was the dominant factor for the power loss.

	P_{mpp}	I_{sc}	V_{oc}	FF
CIS 1	-45.3%	-14.3%	-16.3%	-23.8%
CIS 2	-15.7%	-12.0%	-1.6%	-5.8%

Table 4. Summary of the STC performance of the CIS modules, compared to their initial rating.

The I_{sc} loss of both CIS modules is closely associated with the encapsulant discolouration and soiling. The significant reductions in the V_{oc} and FF of CIS 1 are likely caused by PID. The R_{sh} of CIS 1 is estimated to be about 5 times lower than that of CIS 2 (about 5000 Ω). Its EL signature (almost entirely dark in Figure 3a) also resembles the behaviour of PID. Corrosion very likely also contributed to the FF loss of CIS 1, but it is difficult to differentiate this from the PID effects. As for CIS 2, the FF loss is probably a result of corrosion that increased the R_s . Its EL signal suggests corrosion along the perimeter of the module (Figure 3b). The EL defect in CIS 2 that starts from the right corner and extends diagonally to the centre (Figure 3b) should be a manufacturing issue.

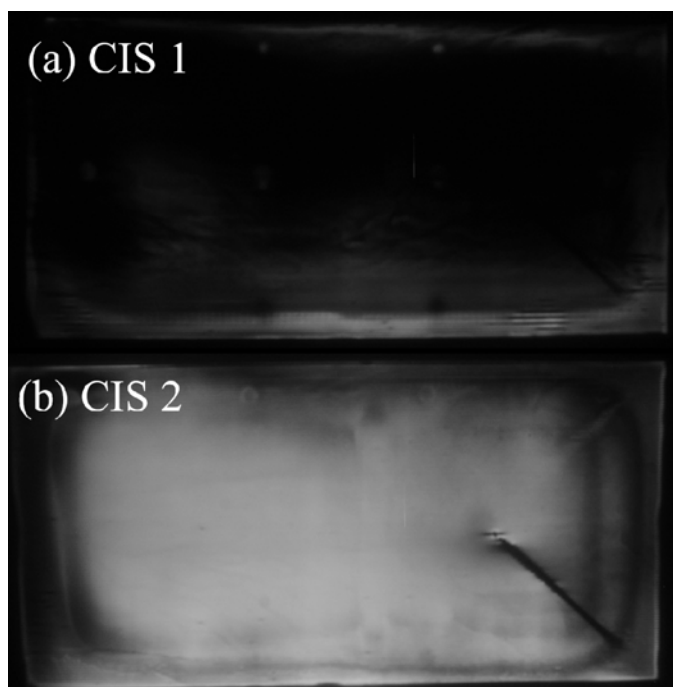


 Figure 3. EL images of the CIS modules at I_{sc} .

5. Conclusions

In this study, three different types of modules (multi-Si, mono-Si and CIS) were investigated with various characterisation methods after more than 10 years of outdoor operation in tropical Singapore. PID, corrosion and encapsulant degradation were identified to be the most detrimental degradation processes for PV modules in Singapore's hot and humid climate. Close attention should therefore be paid to these issues in future research developments, to ensure more reliable PV modules for the tropics. Furthermore, stricter stress test standards need to be adopted specifically for these degradation processes to ensure good long-term performance in tropical climates.

*This article is the extract of a more comprehensive work published in Renewable Energy 177, pp. 327-335, as W. Luo et al., "Photovoltaic module failures after 10 years of operation in the tropics", Copyright Elsevier (2021).

The effect of capacitance on the electrical characterisation of high-efficiency photovoltaic modules*

Dr Mauro PRAVETTONI

1. Background

The effect of solar cell capacitance in the electrical characterisation of photovoltaic (PV) modules at Standard Test Conditions (STC) is known since the 1990s. With the efficiency of new solar modules increasing over the years, the corresponding measurement artefact in 1-Sun laboratory tests has been generally resolved with long-pulse solar simulators, from a few milliseconds in the early 2000s up to 100 milliseconds today. With the recent improvements in module technology, and the growing interest in n-type silicon and silicon heterojunction (HJT) cells, and with the increasing wafer and cell sizes, it can be demonstrated that even 100-ms simulators are no longer capable of accurate I-V measurements. The need for innovative measurement methods is therefore becoming more urgent for accurate measurement of full-size PV modules. This article is a review of today's best practices in advanced testing laboratories of silicon PV modules, and it represents a contribution addressed to metrologists, researchers and module manufacturers.

2. The single-diode capacitive model

The electrical behaviour of solar cells and modules can be described in classical physics terms with the *single-diode capacitive model*. In its simplest form, the model includes a capacitor in parallel to the photodiode, where the current source is the semiconductor material that generates in short-circuit ($V=0$) the maximum amount of current available (I_{sc}).

The capacitor represents the accumulation of charges in the PV device. The capacitance of a PV device is attributed to both junction capacitance and diffusion capacitance, both of which are voltage dependent. In the single-diode capacitive model, we assume that the total transient current of charge (or discharge) of the capacitor is

$$I_C(V) = \frac{dQ(V)}{dt} = \frac{d[C(V) \cdot V]}{dt} \quad (1)$$

which represents a possible loss (or gain) in output current, hence a loss (or gain) in maximum power P_{mpp} . If, for the sake of simplicity, we ignore the effect of parasitic resistances (assuming negligible series resistance and infinite shunt resistance i.e. the *ideal diode* approximation), the I-V characteristic equation describing the electrical performance of the PV cell in the ideal single-diode capacitive model is

$$I(V) = I_{sc} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{N_P}{N_S} C_{eff,cell}(V) \frac{dV}{dt} \quad (2)$$

where I_0 is the reverse saturation current, q the elementary charge, n the ideality factor, k the Boltzmann constant, T the cell temperature, N_P the number of submodules in parallel (typically 1 for full-size cell modules, 2 for half-cut cell modules) and N_S is the number of cells in series in each submodule (typically 60, 66 or 72). $C_{eff,cell}(V)$ is introduced here as an *effective cell capacitance*, which is function of V and a combination of the drift and diffusion capacitance at cell level.

Let us now consider an I-V measurement with a pulsed solar simulator. During the flash pulse, a voltage ramp $V(t)$ is applied to the module terminals and the module generates the current as in Eq. (2). In the experimental practice this usually occurs either in direct I-V mode (from $V \leq 0$ to $V \geq V_{oc}$, in which $\frac{dV}{dt} = \left(\frac{dV}{dt} \right)_{dir} > 0$) or in reverse I-V mode (from $V \geq V_{oc}$ to $V \leq 0$, when $\frac{dV}{dt} = \left(\frac{dV}{dt} \right)_{rev} < 0$). Thus (2) can be written for the two cases as:

$$I_{dir}(V) = I_{sc} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{N_P}{N_S} C_{eff,cell}(V) \left(\frac{dV}{dt} \right)_{dir} \quad (3)$$

$$I_{rev}(V) = I_{sc} - I_0 \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{N_P}{N_S} C_{eff,cell}(V) \left(\frac{dV}{dt} \right)_{rev} \quad (4)$$

and this pair of equations can be combined to calculate the cell effective capacitance

$$C_{eff,cell}(V) = \frac{N_S}{N_P} \frac{I_{rev}(V) - I_{dir}(V)}{\left(\frac{dV}{dt} \right)_{dir} - \left(\frac{dV}{dt} \right)_{rev}} \quad (5)$$

Figure 1 shows the values of $C_{eff,cell}(V)$, derived from Eq. (5) and plotted per unit cell area as a function of the applied voltage (normalised to V_{oc}) for 10 different commercial PV modules. The different dash types refer to the different cell technologies. In order of decreasing peak value of effective capacitance, HJT modules show the highest peak cell capacitance at approximately $190 \mu F \text{ cm}^{-2}$; the n-type Interdigitated Back-Contact (IBC) module has a value of peak effective capacitance ($138 \mu F \text{ cm}^{-2}$) that lies between the HJT modules and the n-type PERT modules ($\sim 50 \mu F \text{ cm}^{-2}$); p-type PERC modules show the lowest capacitance ($12\text{--}15 \mu F \text{ cm}^{-2}$ for mono-Si; $5 \mu F \text{ cm}^{-2}$ for multi-Si).

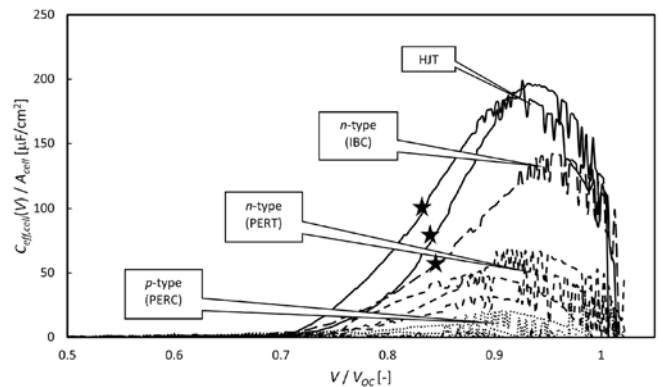


Figure 1. Effective cell capacitance per unit cell area (in $\mu F \text{ cm}^{-2}$) derived from equation (5) for 10 different commercial modules and plotted as a function of voltage V (normalised to V_{oc}). The different dash types refer to the different cell technologies. The star symbol (*) indicates the effective cell capacitance at the maximum power point for the three modules with largest capacitance (two HJT modules and an n-type IBC module).

The figure shows that the effective cell capacitance at the maximum power point (labelled with the star symbol) is at about half of the peak value and at a voltage well below V_{oc} , showing a similar trend as the solar cell's diffusion capacitance (see Monokroussos et al., 2006, Proc. 4th IEEE World Conference on Photovoltaic Energy Conversion, Waikoloa, Hawaii, pp. 2231-4).

3. The effect of module capacitance

Module power is $P(V) = I(V) \cdot V$. In the ideal diode approximation, multiplying Eqs. (3-4) by V gives:

$$P_{dir}(V) = I_{sc}V - I_0V \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{N_P}{N_S} C_{eff,cell}(V)V \left(\frac{dV}{dt} \right)_{dir} \quad (6)$$

$$P_{rev}(V) = I_{sc}V - I_0V \left(e^{\frac{qV}{nkT}} - 1 \right) - \frac{N_P}{N_S} C_{eff,cell}(V)V \left(\frac{dV}{dt} \right)_{rev} \quad (7)$$

If we define $P(V) = I_{sc}V - I_0V \left(e^{\frac{qV}{nkT}} - 1 \right)$ as the power in stationary conditions (i.e. when $\frac{dV}{dt} = 0$, in which by definition the effect of a capacitance is absent), then these two equations become:

$$P_{dir}(V) = P(V) - \frac{N_P}{N_S} C_{eff,cell}(V)V \left(\frac{dV}{dt} \right)_{dir} \quad (8)$$

$$P_{rev}(V) = P(V) - \frac{N_P}{N_S} C_{eff,cell}(V)V \left(\frac{dV}{dt} \right)_{rev} \quad (9)$$

Equations 8 and 9 describe the gain and loss of power that can be observed in direct and reverse I-V mode due to the effect of capacitance, when the duration of the voltage ramp $V(t)$ (also referred to as *sweep time* Δt) is not long enough to mitigate it. Solving Eq. (8) for $\frac{P_{dir}(V)}{P(V)}$ at the maximum power point gives

$$\frac{P_{mpp,dir}}{P_{mpp}} = 1 - \varepsilon \quad (10)$$

where $P_{mpp,dir}$ and P_{mpp} are the maximum power points measured in direct I-V mode and in stationary mode, respectively. The parameter ε can be written as

$$\varepsilon = \frac{N_P}{N_S} \frac{C_{eff,cell}(V_{mpp})}{I_{mpp}} \frac{V_{OC,dir}}{\Delta t} \quad (11)$$

and defines the level of accuracy of the measured $P_{mpp,dir}$ compared to the “true” P_{mpp} value, in terms of percentage deviation between the two values.

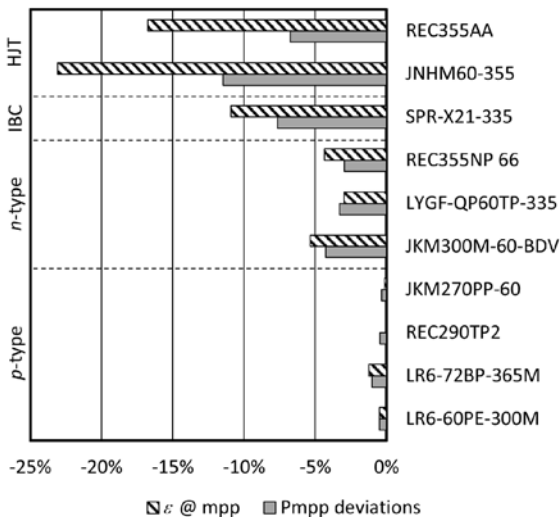


Figure 2. Comparison between the calculated level of accuracy ε defined in Eq. (11) and the % deviation between the measured value of P_{mpp} and the “true value” on direct I-V curves with a 10-ms solar simulator.

The measured deviations of the maximum power for the 10 modules of Figure 1 and the values of ε are shown in Figure 2 for direct I-V measurements with a sweep time $\Delta t = 10$ ms.

Equation (11) shows that the level of accuracy in direct I-V measurement of capacitive modules is directly proportional to the effective cell capacitance at maximum power $C_{eff,cell}(V_{mpp})$ and reversely proportional to the sweep time Δt . In Figure 3 the minimum values for the level of accuracy ε that are achievable with direct I-V curves are plotted as a function of Δt , based on a range of values for $C_{eff,cell}(V_{mpp})$ for the various c-Si cell technologies under investigation in Figure 1.

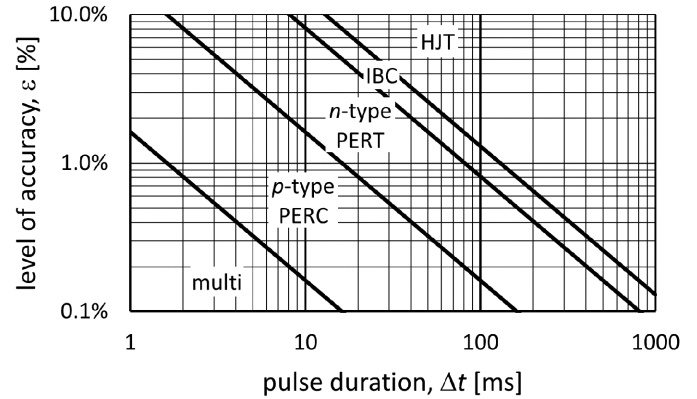


Figure 3. The various regions of the graph are delimited by the minimum level of accuracy ε achievable with direct I-V measurements for the selected technologies with the given value of sweep time t .

4. How to mitigate the effect of capacitance: Practical methods

The eight most significant measurement techniques available nowadays to lower the capacitive effect of PV modules to defined levels of accuracy are:

- **Long pulse** – with a long-pulse solar simulator, capable of a voltage sweep as slow as needed, the capacitive effect can be made negligibly small. This is also the case for continuous solar simulators and for outdoor I-V measurements under natural solar irradiance.
- **Stationary I-V** – performing several current-voltage measurements at fixed voltages, gives $\frac{dV}{dt} = 0$ by definition and the capacitive effect is absent, although data points need to be interpolated to reconstruct the continuity of the full I-V curve.
- **Dragonback™** – it is a combination of direct and stationary I-V methods, in which after a fast initial sweep the voltage ramp is shaped by successive short steps of constant voltage (where $\frac{dV}{dt} = 0$).
- **Section I-V** – overcoming the limitations of interpolation in the stationary method, the full I-V is split into N shorter voltage ramps, each of duration Δt , so that the full I-V is equivalent to a measurement on a simulator of arbitrarily long pulse duration $N \cdot \Delta t$. It may require a large number N of measurements.

- **Direct + section I-V** – a variation of the section method. In fact, sometimes the first and last sections can be as fast as the direct I-V method.
- **“Shaped” I-V** – the operator can manually “shape” the profile of the voltage ramp, to make $\frac{dV}{dt}$ as slow as needed at voltages close to the maximum power point.
- **Hysteresis™** – based on the single-diode capacitive model and on the assumption that the *current loss* due to the capacitor charging in direct I-V mode at the given voltage V is equal and opposite to the *current gain* in reverse I-V mode at the same voltage due to discharge. The arithmetic average of the direct and reverse I-V is an approximation of the “true” I-V, which can be accurate with long values of Δt .
- **Capacitance compensation (CAC™)** – the method is based on the calculation of the effective capacitance $C_{\text{eff, cell}}(V)$ from Eq. (5), and subsequent correction of the measured direct I-V curve.

5. Uncertainty considerations

The deviation in P_{mpp} of a PV module due to the effect of capacitance is a systematic measurement bias that, if uncorrected, represents an uncertainty contribution to be quantified and considered in the measurement uncertainty analysis.

The circles in Figure 4 give an overview of realistic values for ϵ , from which it is possible to derive the uncertainty ($u(P_{\text{mpp}}) = \pm \epsilon$ for symmetric uncertainty distribution; $-0/+2\epsilon$ or $-2\epsilon/+0$ for asymmetric distributions), as a function of the pulse duration (in ms) and of the number of flashes needed on pulsed solar simulators. The graph summarises all the testing methods reviewed for measurement of commercial HJT silicon modules. The size of the circles represents the typical values of ϵ that are possible to achieve in the given conditions of measurement. The data shown are estimations based on the definition of ϵ in Eq. 11, on the experimental evidence of the module under investigation in this work and on the laboratory best practice as of today.

The direct I-V method used on 10-ms simulators shows, as expected, the largest values of ϵ and therefore of measurement uncertainty, as high as $\pm 17\%$ for HJT modules. The uncertainty contribution on P_{mpp} is large in direct I-V measurements even with 100-ms simulators ($\pm 2\%$), but the graph shows how it can be minimised to less than $\pm 0.2\%$ with the methods reviewed in this work.

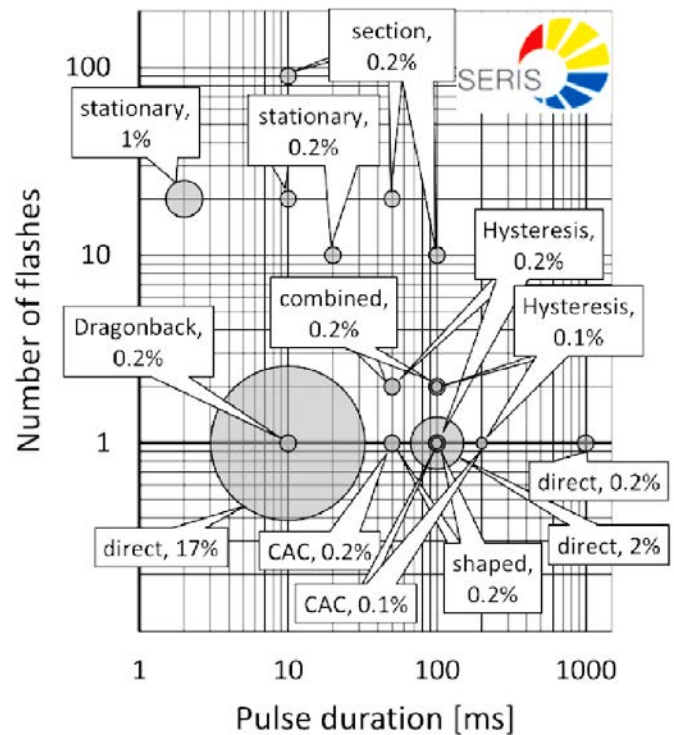


Figure 4. Level of accuracy ϵ for P_{mpp} measurements due to the effect of capacitance, as a function of the pulse duration (in ms) of a solar simulator and the number of flashes required. Example of a typical HTJ module, with effective cell capacitance at maximum power of $80 \mu\text{F cm}^{-2}$.

6. Conclusions

The effect of cell capacitance in the high-efficiency Si PV modules available today can, if uncorrected, cause a severe underestimation of P_{mpp} in direct I-V measurements. The effect is known in the literature for decades, but has recently gained more attention due to the commercialisation of new generations of high-efficiency c-Si products, like n -type PERT and HJT, and due to the expected further increase in solar cell size. The single-diode capacitive model allows to quantify the level of accuracy ϵ with which direct I-V measurements can predict the “true” P_{mpp} values of PV modules with capacitive effects.

Eight methods to address and mitigate the effect of cell capacitance in the measurement of P_{mpp} in the experimental practice were described. The measurement uncertainty for the various methods was evaluated. The analysis confirmed that uncertainties from $> 1\%$ to $> 10\%$ can occur when measuring HJT modules with direct I-V methods and pulse lengths of 100 ms or less.

*This article is an extract of the work published as M. Pravettoni et al., “The effect of capacitance on high-efficiency photovoltaic modules: A review of testing methods and related uncertainties”, J. Phys. D: Appl. Phys. 54 (2021) 193001.

Assessing Light and Elevated Temperature Induced Degradation (LETID) of commercial solar modules: Results from an international interlaboratory comparison

Dr Mauro PRAVETTONI and Henry LIM

1. Abstract

Light and Elevated Temperature Induced Degradation (LETID) is a recently discovered degradation mechanism in silicon PV modules that is different from the well-known boron-oxygen related Light Induced Degradation (LID) effect. LETID occurs during years of outdoor exposure, rather than weeks for the boron-oxygen LID, and supposedly involves hydrogen as a precursor. The International Electrotechnical Commission (IEC) will publish a dedicated Technical Specification to define the correct measurement method, allowing to quantify the amount of LETID degradation and its potential recovery in the modules under test. To validate this new standard, an interlaboratory comparison was organised with the participation of several international research centres and PV module manufacturers. This article presents the results of SERIS' measurements, and confirms the reproducibility of the LETID degradation and regeneration tests.

2. LID and LETID

LID is one of the best-known “infant” degradation modes, as it starts as soon as the module is exposed to sunlight. LID of silicon modules is mainly due to boron-oxygen defects in the silicon wafers (BO-LID): Oxygen atoms in *p*-type silicon wafers combine with boron dopant atoms, forming BO complexes that are recombination active, thus reducing the solar cells' short-circuit current and maximum power. Sunlight provides enough energy to generate the B-O defects. Therefore, LID of affected silicon modules takes place even at mild temperatures and the effects are clearly visible after only a few kWh/m² of sunlight exposure.

In 2015 researchers from Hanwha Q-CELLS and the Technische Universität Bergakademie Freiberg in Germany proposed a new degradation mechanism, which they coined “*Light and Elevated Temperature Induced Degradation*” (LETID, [2-4]). According to their preliminary studies, for certain multicrystalline silicon modules, relative power losses of up to 10% can occur over a time scale of a few years in the field and at high temperatures. LETID was also shown to feature a regeneration phase. This severe power degradation level, and the slow kinetics, could not be explained by the B-O or other known degradation processes.

In 2017 the same authors reported further evidence of up to 7% degradation in maximum power with LETID-sensitive multi-Si PERC modules. The result was verified on the Mediterranean island of Cyprus after the first 3 years of outdoor operation [5].

Although research is still ongoing to provide a fully satisfactory physical and chemical explanation, the most convincing precursor for LETID presently seems to be hydrogen (hence, often, the reference to Hydrogen Induced Degradation, or HID), and may affect both *p*-type and *n*-type silicon [6]. Deceglie *et al.* [7] also presented a detailed case study of degradation from the field in a utility-scale PV power plant in the United States. The authors stressed the importance of a quality programme for module reliability, indicating the path to a new sequence in the qualification standard.

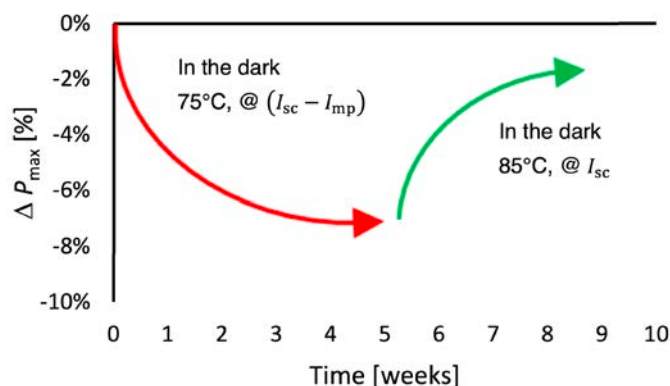


Figure 1. Scheme of the draft IEC test for LETID degradation (red arrow: current injection of $I = I_{sc} - I_{mp}$ at 75°C in the dark) and regeneration (green arrow: current injection of $I = I_{sc}$ at 85°C in the dark).

3. Normative activity and the interlaboratory comparison

Soon after the 2015 report on LETID, the standardisation community started developing a robust test procedure to identify LETID-sensitive modules. In the 2017 Neuchatel meeting of the Technical Committee 82 (“Solar photovoltaic energy systems”) Working Group 2 (“Modules, non-concentrating”) of the IEC, a new test sequence was proposed in IEC 61215 (the module qualification standard series). A Project Team was formed and a draft test scheme was prepared, with the test steps shown in Figure 1:

- **LETID degradation test:** The module under test is subjected (in the dark and at 75°C) to the injection of a small current intensity $I = I_{sc} - I_{mp}$ (I_{sc} and I_{mp} are the short-circuit current and the current at maximum power, respectively, both measured at Standard Test Conditions, STC). The test is repeated with several thermal cycles of 162 hours each, until the module stops degrading.
- **LETID regeneration test:** After degradation has stopped, the module under test is subjected (in the dark at 85°C) to the injection of $I = I_{sc}$ until it stops recovering.

The urgency to publish the new edition of IEC 61215, and the lack of time for an appropriate and systematic method validation, later led to the decision to delete the LETID section from the qualification standard, and to work on a dedicated Technical Specification. This new document is expected to be published in 2022 as IEC TS 63342.

Meanwhile, an international interlaboratory comparison was organised, coordinated by the National Renewable Energy Laboratory (NREL) in USA [8], with the scope to evaluate the reproducibility of LETID degradation and recovery procedures and better define the stop criteria in both phases, thus avoiding excessively long tests. In this exercise (a “simultaneous scheme” in which randomly selected homogeneous sub-samples are distributed simultaneously to participants for concurrent testing) the following laboratories participated: NREL and PVEL (USA), PI Berlin, CENER, JRC, SUPSI, Fraunhofer-ISE and Fraunhofer-CSP (Europe), TÜV-Rheinland (Europe and China), NISE (India) and SERIS. The modules to be tested (full-size commercial multicrystalline silicon modules) were kindly provided by Mitsubishi Solar, Solaria, Trina Solar, REC, Canadian Solar and Hanwha Q-Cells.

4. Results and reproducibility

ISO/IEC 17025 (the standard stating the general requirements for the competence of testing and calibration laboratories) indicates interlaboratory comparison as one of the techniques to validate non-standard procedures. The basic idea is that a robust measurement method should be *reproducible*, i.e. should give comparable results (within the stated measurement uncertainty) when replicated on the same or similar samples in different locations, and by different operators and/or measuring systems. Under this framework, the manufacturers involved in the interlaboratory comparison were asked to provide three types of test samples: i) purposely designed LETID-sensitive modules (referred to as “type P” modules); ii) expected LETID-free modules (“type T”); and iii) modules of unknown or unexpected LETID behaviour (“type S”).

These samples (all multi-Si modules) were distributed among the participating laboratories in homogeneous subsets. SERIS received two “type P”, two “type T” and two “type S” modules in total, from Canadian Solar and Mitsubishi.

Figure 2 shows the comparison between SERIS’ results (in light green lines, indicated by the black arrows) and the other anonymous labs that measured the homogeneous sub-samples from the same manufacturers. The degradation tests for all modules measured at SERIS were aligned with the average of the results from other participants, thus positively assessing the reproducibility of the degradation testing procedure. Furthermore, apart from an outlying laboratory showing power increment after the first cycle (P and S modules, red curves in Figs. 2a and 2c), the degree of reproducibility between the laboratories was very good, as is also confirmed in the type-T LETID-free modules (Fig. 2b).

More critical was the reproducibility of the regeneration phase, as most of the laboratories skipped this particular test, and generally there was no agreement on when the degradation phase had stopped, resulting in a biased timeline. However, the only available comparison on type-P modules confirmed a good agreement in the partial regeneration at ~1000 hours after the end of the degradation phase, whereby the module power had recovered to about 98% of its initial maximum power before the test (Fig. 2a).

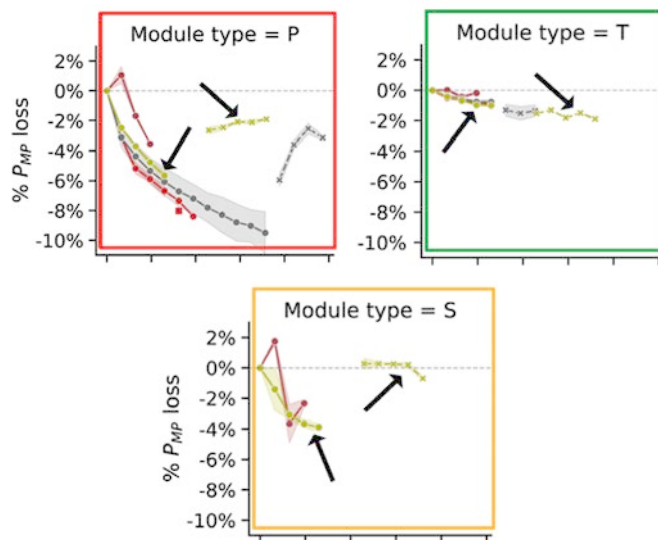


Figure 2. Interlaboratory comparison: (a) LETID-sensitive modules (“type P”); (b) LETID-free modules (“type T”); and (c) unknown LETID behaviour (“type S”). SERIS’ results are plotted in light green and are indicated by black arrows. With LETID-sensitive modules, the degradation test was followed by the regeneration test (first cycle of 500 hours, followed by subsequent cycles of 162 hours each). Source: [8].

5. What happens to a LETID-sensitive module?

Figure 3 shows the degradation of the electrical 1-Sun parameters of a LETID-sensitive module (one of the two type-P modules of Fig. 2a measured at SERIS). The graph also shows the EL images of the same module, measured after each of the 162-hr degradation cycles.

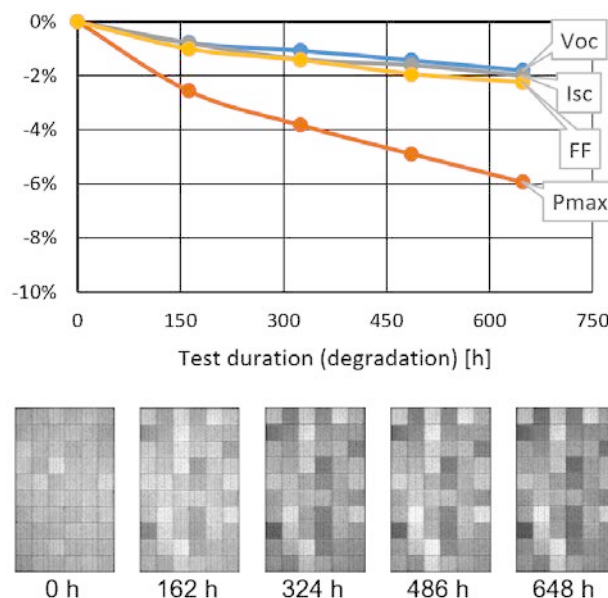


Figure 3. LETID degradation: Power degradation and corresponding EL analysis. In LETID-sensitive modules, V_{oc} , I_{sc} and FF degrade nearly equally, contributing one third each to the overall degradation in P_{max} .

The degradation effect varies from cell to cell, but is about equally split between the short-circuit current (I_{SC}), the open-circuit voltage (V_{OC}) and the fill factor (FF). The resulting total 6% degradation in maximum power (P_{max}) from the initial STC value is the combination of the degradation of all 3 parameters.

Figure 4 shows the regeneration test for the same module. The original EL is almost recovered after 1148 hours of annealing, although a -2% deviation was still observed, mainly due to lower I_{SC} and FF.

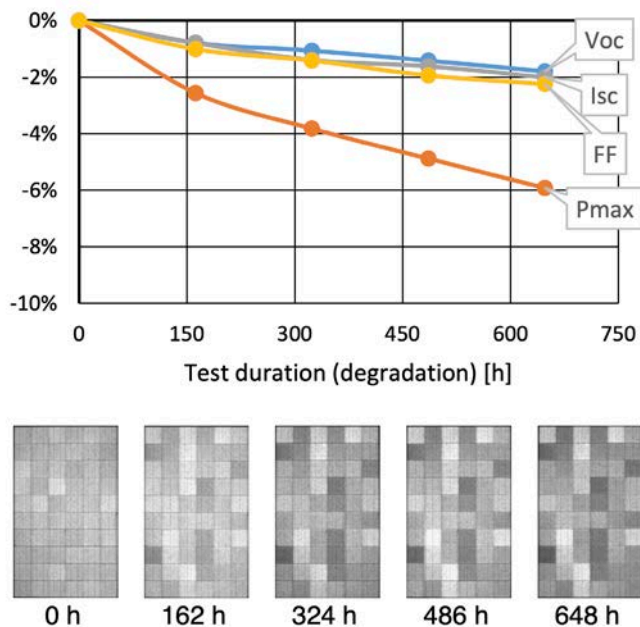


 Figure 4. LETID regeneration: Power recovery and corresponding EL analysis. The regeneration of V_{OC} occurs faster than that of I_{SC} and FF. After ~1000 hours the original V_{OC} is recovered, while the lower I_{SC} and FF still cause a 2% relative loss of P_{max} from its initial value.

6. Conclusions

LETID is a new challenge in silicon PV module reliability, probably caused by the formation of hydrogen bonds and potentially affecting all silicon modules, although originally detected mainly in multicrystalline silicon modules. The degradation process is much slower than the boron-oxygen related LID effect, and the design of a test method to assess the LETID sensitiveness of commercial silicon PV modules is fundamental to avoiding unexpected power losses in fielded modules, particularly in hot climates. Results from an inter-laboratory comparison showed that the currently proposed method, which is planned to be published in the near future as a new dedicated IEC standard, has shown good reproducibility among the participating laboratories. SERIS took part in this exercise and will be ready to adopt the new standard to better serve the industry in the development of LETID-free PV modules.

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Building integrated photovoltaics (BIPV) on steel based structures

Dr TAI Kong Fai, Prof HENG Chye Kiang, CHEN Tianyi, Gavin RAHARJO

1. Background

Buildings account for 30-50% of humankind's annual energy consumption, representing a significant contribution to greenhouse gas emissions [1, 2]. Thus, many countries around the world have gradually been implementing different policies to adopt zero energy buildings (ZEB). However, there is a lack of BIPV design related information for architects to integrate BIPV systems in the early design stage [3]. Therefore, there is a need for modular unitised BIPV façade elements that offer an easy integration solution [4]. As a game-changing construction method, "pre-fabricated and pre-furnished volumetric construction" (PPVC) has great advantages in reducing costs, enhancing quality, and improving productivity. Integrating photovoltaics (PV) into the PPVC method could significantly reduce the cost of BIPV integration. Working with architects, PV engineers and building contractors, SERIS and NUS' Department of Architecture (DOA) have developed a PV-integrated "modular pod" using steel based PPVC technology. The modular pod consists of various prefabricated modular BIPV building elements, including a panelised wall, a wall with monsoon windows, a unitised wall, and a fixture wall. Each of these elements serves as a proof-of-concept which can be deployed into other actual building developments.

2. Scope of project and objectives

To promote BIPV and equip design architects with knowledge and information about BIPV, the research scope of this project includes:

- (1) to explore the design principles of modular BIPV facades;
- (2) to develop modular BIPV prototypes and integrate them into an actual building for field testing;
- (3) to monitor the electrical and thermal performance of various BIPV facades and find the correlation with various build parameters.

The objective of the modular pod is to facilitate the merging of PPVC and PV technologies, including the design of prefabricated BIPV prototypes for the tropics, gaining construction experience, and data collection for further design improvement. The following sections introduce the modular pod, including the design concept and refinement of each prefabricated element, provide a solar potential analysis of the hosting site in Singapore, and present preliminary electricity production results for each type of wall.

3. Significance and impact of project

We try to conduct holistic research as much as possible to provide a complete BIPV solution to the community. Our research team comprises of front-end architects that consider building design and aesthetics, scientists and engineers to develop BIPV modules, to back-end BIPV system developers and integrators. With competitive BIPV prototypes and actual demonstrations, we strive to lower the entry barrier for BIPV deployment, thereby promoting Super Low Energy Buildings (SLEBs) or even Positive Energy Buildings (PEBs), in line with Singapore's green building movement.

4. Methodology & Results

The modular pod measures 3.40 x 3.36 x 3.40 metres, with a roof tilted 3.3° towards the south. The modular pod is made of various prefabricated BIPV elements (roof, panelised wall, monsoon windows, unitised wall, and fixture wall) to mimic the different real-world building components.

Figure 1 shows the exploded view of the modular pod with various prefab BIPV elements attached to the structural openings, which can flexibly adapt to different construction requirements and scenarios. The development of such prefabricated BIPV elements would allow architects and developers to easily adopt BIPV into their buildings.

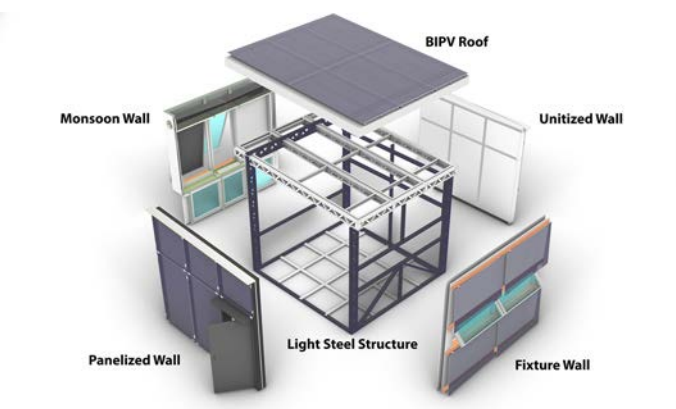


 Figure 1. Exploded view of the modular pod. Each side of the wall is designed to be modular to fit into the openings of the main structure.

The design concept for each prefab BIPV element is as follows:

- (i) Monsoon window: PV-integrated window with openable ventilated device at level position to allow natural ventilation even in rainy days, suitable for the tropical climate and helping to reduce the cooling load. Two different configurations were built to study the impact of ventilation mechanisms on indoor thermal comfort and PV performance.
- (ii) Prefab unitised wall: Similar to the typically unitised curtain wall systems, but opaque in this case to replace a continuous concrete wall. The modular unit with floor height dimension allows installation from the building interior, without the need of hoisting or scaffolding. Three configurations were built to study the impact of various air cavities and insulation layers.
- (iii) Fixture wall: PV modules on the external prefab wall with adjustable mounting angles to create dynamic patterns on the façade.
- (iv) Prefab panelised wall: Large-scale prefab panelised wall with integrated PV modules. Installation to be done from building exterior by hoisting. This enables quick installation over a large façade area. An open system to integrate windows and doors.
- (v) Prefab BIPV roof: A fully integrated solar roof with thermal insulation and waterproofing elements.

Design element and orientation	Simulated irradiation (kWh/m ² /yr)	H1-2021 simulated irradiation (kWh/m ²)	H1-2021 actual irradiation (kWh/m ²)	PV capacity (kW _p)	H1-2021 estimated PV energy yield (kWh)	H1-2021 actual PV energy yield (kWh)
Monsoon window (N)	796.7	416.0	287.9	0.68	226.3	163.9
Unitised wall (E)	917.2	470.2	434.5	1.02	354.6	312.4
Fixture wall (S)	690.5	346.6	-	1.36	377.1	277.1
Panelised wall (W)	787.5	406.9	-	0.82	266.9	159.2
Roof	1588.9	822.1	733.2	2.46	1617.9	1160.5
Total				6.34	2842.8	2073.1

Table 1. Simulated irradiation, estimated PV energy yield (assuming a PV system performance ratio (PR) of 0.80) and actual PV energy yield for the walls and roof of the modular pod. Deviations between simulation and actual data are likely due to unusually heavy rainfall in the first half (H1) of 2021.

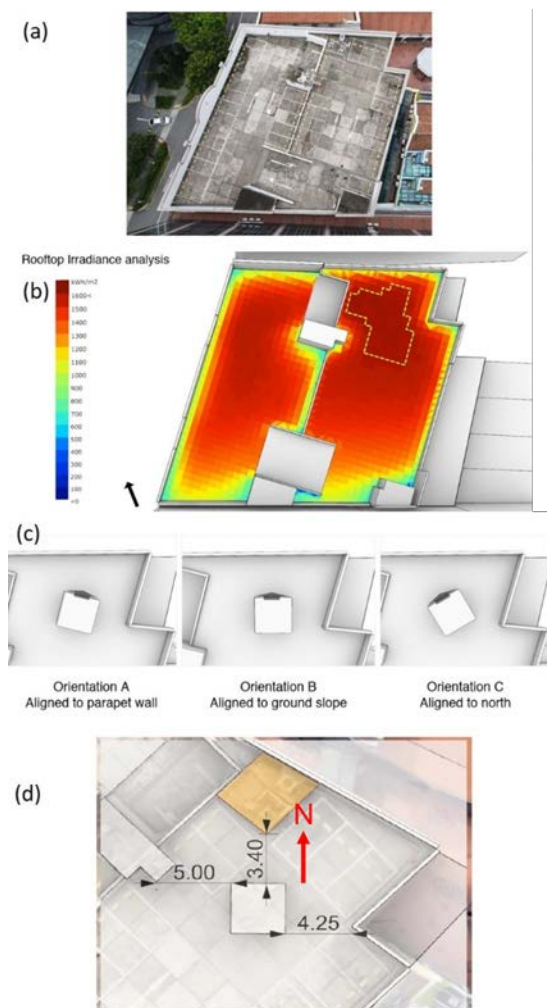


Figure 2. Solar potential analysis for the pod's location

To test the real-world performance of different BIPV configurations, the prototype pod should receive good solar irradiation. Thus, in the planning stage of the pod's construction, a solar potential analysis was conducted for the site (rooftop of multi-storey carpark at Central Mall in Singapore), as shown in Fig. 2. From the annual solar irradiation analysis, the area receiving the highest solar irradiation was identified (Fig. 2b). Once the area was narrowed down, several iterations of pod placement were tested within the boundaries and with different orientations (Fig. 2c). From all these iterations, the final location of the pod was decided as shown in Fig. 2d. A photo of the actual constructed pod is shown in Fig. 3.

The annual irradiation for each sidewall of the pod was also simulated, as shown in Table 1. Note that the simulation model includes reflection by the parapet wall and ground surfaces. Reflection by the white parapet wall with > 2 m height is quite significant. This explains a rather high simulated irradiation for the vertical surfaces, with over 57% relative irradiation level for the East-facing façade compared to the roof. This is further verified by the actual irradiation data collected thus far for the East-facing wall, which also shows a relatively high irradiation level (59%) compared to the roof. Therefore, although a high building density in urban environments can result in cross-shading, reflections from neighbouring buildings can contribute positively to solar electricity generation. This is especially beneficial for the top few floors of tall buildings, which have no cross-shading effect but enjoy the benefit of sunlight reflections from neighbouring buildings. This compares favourably to a standalone East-facing surface, which typically receives ~51% of the global horizontal irradiance (GHI) [5]. The deviation between the simulated irradiation (with historical weather data input) and actual irradiation measured for the first half of 2021 could be explained by the unusually large number of rainy days and more severe rainfall as observed from historical government weather data [6, 7]. As the pod's unitised wall is facing East, receiving direct sunlight mostly in the morning, the simulated and actual irradiation values deviate less compared to the pod's roof and monsoon window wall, as rainfall in the tropics typically happens in the afternoons.

The PV energy yield was estimated based on the simulated irradiation and the PV capacity installed on each wall. The actual yield recorded for each module (and hence each façade) was obtained via our module level power electronics. Typically, it is advisable to collect a full year of data to account for seasonal changes and sun position variation. However, since data collection only started in early 2021, we can only report results for H1 of 2021. Nevertheless, we are already seeing a significant generation from the pod's vertical facades, even without including the generation from the roof. A total generation of 913 kWh from the pod's vertical facades with a PV capacity of less than 4 kW_p for H1 2021 alone is already sufficient to power a 4-room HDB flat for 2.5 months with an average consumption of 359 kWh/month [8], even with little generation on the West-facing façade due to a tall building blocking the western Sun in the afternoon, and a lower than usual irradiation level due to an unusually high number of rainy days. From our estimated energy yield based on historical irradiation data, 1225 kWh (excluding the rooftop PV) will be sufficient to power a typical 4-room HDB flat for more than 3.4 months.

Regarding the impact of build parameters such as the ventilation cavity, we already observed some beneficial effects behind the solar panel in the unitised wall during a clear sunny day, in terms of PV performance and indoor thermal comfort. Further improvements will be performed through modelling and simulation before building the next-generation prototypes. For the monsoon window wall facing North, June to July of the year will be the most important months for the study of the build parameters as the Sun is in its northern-most position during these months. The effect of build parameters like the ventilation mechanism will be amplified when the surface receives more direct sunlight, resulting in elevated temperatures. A detailed study and experimental investigation of various build parameters will be reported in the future when the data of at least a full year are recorded and analysed.



Figure 3. Actual constructed modular pod located on the rooftop of the carpark at Central Mall, Singapore.

5. Conclusions

Several design concepts for modular BIPV prototypes were presented and realised by integrating selected BIPV elements into a modular pod for field testing in Singapore. This demonstration indicates that BIPV integration into buildings can be realised easily when it is considered during the building design stage. Various BIPV configurations were integrated into the monsoon window wall and unitised wall to study the impact of the build parameters on the PV performance and indoor thermal comfort. Preliminary results from H1 2021 show that a total of 913 kWh of solar energy was generated from the pod's vertical facades alone, sufficient to power a 4-room HDB flat for 2.5 months even with a lot of rainy days. Furthermore, we have observed some beneficial effects in terms of PV performance and indoor thermal comfort for the various build parameters in the unitised wall. A more detailed study will be published when a full year of data is collected and analysed. We are also planning to build a simulation model and tools for indoor thermal comfort and PV performance to facilitate further BIPV designs in the future.

This work is supported by the National Research Foundation of Singapore through the Singapore Economic Development Board under a Solar Competitive Research Program Grant (S18-1175-SCRP), City Development Limited (CDL) which provide the modular pod's hosting site and infrastructure support, and Photovoltaic Foundry Pte. Ltd. (PvFoundry) by providing the PV panels for the vertical facades.

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Full disk Himawari-8/9 satellite imagery from JAXA

Xixi SUN, Sasikala GNANAMUTHU, Nilesh ZAGADE, Peng WANG, Dr Jamie M. BRIGHT

1. Background

Today, the world leading approach to estimating solar irradiance anywhere on the planet is by using geostationary satellite imagery. With geostationary satellites, each image perfectly overlays the Earth of the image underneath it, meaning the only thing we can see that moves are clouds, atmosphere, and changes to the Earth's surface. This feature means that placing one image next to the other essentially shows a time lapse of the Earth.

Geostationary satellite imagery typically takes measurements across different scanning bands, each with a specific wavelength, in addition to visible imagery. Every wavelength can have a particular use in meteorological applications, for example detecting smoke, albedo, surface temperature or water vapor. Typically, satellite-derived irradiance datasets rely heavily on the visible channel to provide information about clouds during the daytime, leaning on infra-red channels to be able to work during the night. Most commonly, satellite solar resource estimation techniques employ semi-empirical techniques which typically operate on deriving two distinct properties: clear-sky irradiance and cloud attenuation [1].

Over Asia, the Japanese Meteorological Agency (JMA) launched the Himawari-8 and -9 satellite series that take scans of the Earth every 10 minutes. They can be on our computers with a delay as short as 10 minutes behind real time. With some algorithmic approaches, it is possible to instantaneously estimate the current solar irradiance anywhere within the satellite image. Himawari-8/9 satellite imagery covers a geography containing 51% of the world's population. Furthermore, using a sequence of imagery, we can estimate the cloud motion to forecast future solar energy production.

2. Scope of project & objectives

The aim of this work is to introduce a recently released Python package from the SERIS forecasting team to the world that takes advantage of a brand-new dataset by the Japanese Aerospace Exploration Agency (JAXA), who release the images free of charge to researchers. The python package can be found at <https://pypi.org/project/ftp-himawari8-hsd/>.

A companion paper named "Data article: Full disk real-time Himawari-8/9 satellite AHI imagery from JAXA" was published by the authors in JRSE (see reference at the end of the article). Researchers can now have real-time access to full disk Himawari-8/9 satellite imagery to make estimates of the available solar energy at the Earth's surface.

3. Significance and impact of project

This work enables researchers to access and use the Himawari-8/9 satellite imagery in a simple and easy-to-use manner. A lot of research work and future explorations can be achieved based on this work.

4. Methodology & Results

Here we do not detail how to use the package. Users can easily find documentations for the package in the companion JRSE paper. An example of the Himawari-8/9 full disk imagery is displayed in Figure 1 to prove the potential of the package. This image is an example of the enormous potential of multi-spectral

bands of satellite imagery. An issue observed in the figure is that taller clouds can cast shadows on other clouds, which causes a reduced reflectance value. This is particularly prevalent at pixels with low sun values.

With satellite imagery as displayed in Figure 1, a fundamental component of converting satellite imagery to solar irradiance is to leverage machine learning models or to perform physical radiative transfer models. At the PVSC-48 conference, SERIS demonstrated for the first time the power of using a purely statistical model to convert all wavelength images of the Himawari-8-9 satellite imagery from the JMA and JAXA to arrive at solar irradiance.

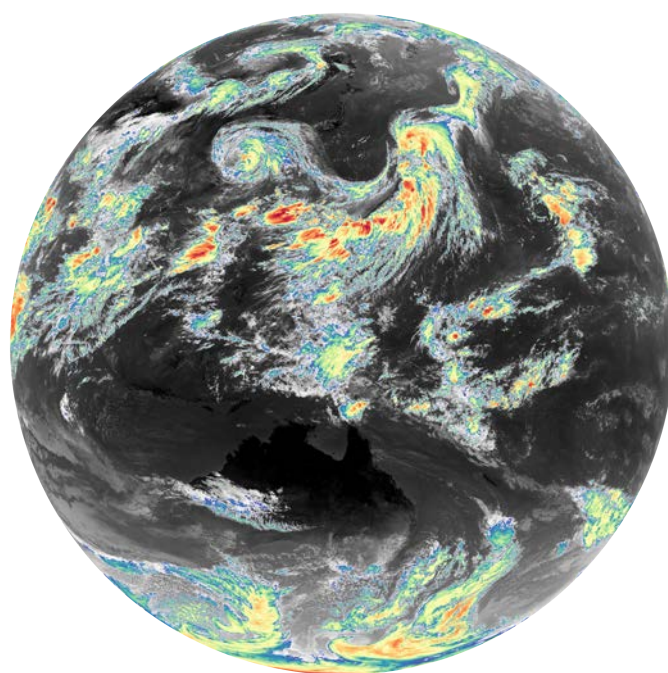


Figure 1. Example of the Himawari-8/9 full disk imagery, showing the infrared cloud masses, indicative of water and rainfall

The new technique of deriving gridded irradiance from the Himawari-8 satellite imagery - specifically from 7 bands provided by the Meteorological Services of Singapore (MSS) - is part of a research collaboration. Our aim is to understand the usefulness of satellite-derived data for very short-term solar forecasting timescales, i.e. 5-min intervals, which could provide support of energy markets with high share of variable renewables. We wish to explore how the 7 bands of satellite imagery in conjunction with dynamic cloud and surface albedos (derived from the same imagery) can be combined to yield improved clear-sky index estimations, using ground pyranometer measurements as truth. This can be seen as both a site-adaptation principle as well as a novel experiment into statistically blending these different available variables in a non-physical manner. Success in this approach would open a door to fast full-disk forecasting from any satellite such that the training and parameterisation stage are replicable. A critical objective is to keep the approach generalised so that it could be more broadly applied to any satellite and band combination, if given identical training practices. Issues of site adaptation can be mitigated by parameterising regions or domains, as is done in some operational cases.

The approach was illustrated using the 25 ground sensors that SERIS has installed across Singapore. By extracting the pixel value of each of the 16 types of images and combining them in a machine learning optimisation approach on training data, we demonstrated the power of combining all available bands of satellite imagery with a basic scaling and weighting function per band, combined in an ensemble. This approach is far from advertised as the best in class, however, it served to demonstrate the power of including more and more data into the calculation and derivation of the clear-sky index. The pixel information from Himawari-8/9 of Singapore is displayed in Figure 2.

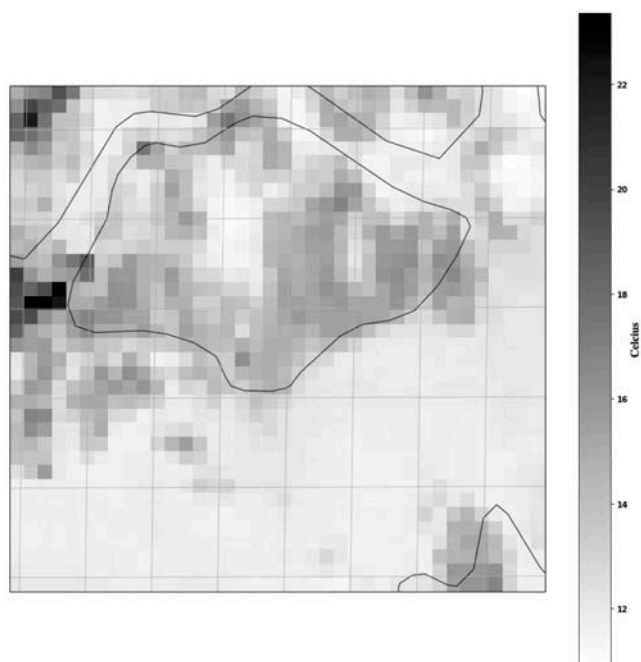


 Figure 2. Zoomed-in Himawari-8 satellite image of Singapore. Each pixel represents an area of about 2 km by 2 km.

Each of the 16 satellite imagery bands is created at a specific wavelength. This means that each image sees a different quality or feature within the atmosphere. Some of those wavelengths interact differently with the different molecules that exist in the atmosphere. For example, some are absorbed by ozone whilst others pass right through ozone but instead react to water vapor. The combination, then, of all these different features enables an improved estimation power of the model.

The results of our work challenge the status quo of using just the visible imagery in a long-standing statistical relationship. Figure 3 shows a validation on identical blind testing data using all satellite bands and a standardised approach for optimisation.

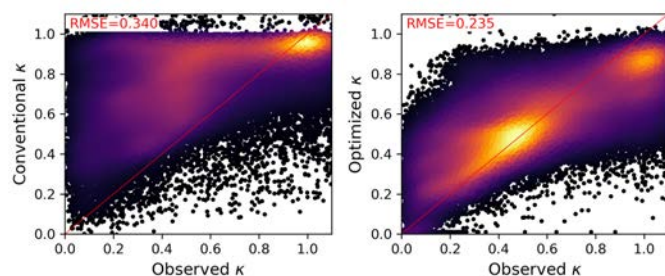


 Figure 3. Scatter density plot showing the combination of all hours of clear-sky index calculation from using the conventional method on the left plot, and for the optimised method on the right.

5. Conclusions

The key result from this work is that there is a wealth of untapped potential from geostationary satellite imagery that can potentially unlock ground-breaking changes in solar forecasting. SERIS has provided the tools to access this fantastic dataset to researchers and demonstrated a benchmarking approach to estimating the clear-sky index from the imagery. We intend to drive this forward and foster world-leading solar resource estimation techniques from satellite imagery for the whole of Asia.

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Performance degradation analysis of floating photovoltaic systems in the tropics*

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1. Introduction

Floating photovoltaic (FPV) concepts unveil many new opportunities for scaling up worldwide solar deployments and meeting renewable energy targets. FPV systems, as the name suggests, are PV installations on floating structures on top of waterbodies. The global FPV potential is estimated to be approximately 400 GW-peak (GW_p) if only one percent of man-made reservoir surfaces is used, and the market opportunity could reach terawatt scale if sea surfaces are also taken into consideration.

FPV concepts offer numerous benefits such as:

- No competing land-use
- Hybridisation of FPV with hydropower plants
- Energy yield gains due to the cooling effect

Despite the advantages of FPV technologies, many challenges and issues need to be addressed to unlock the full potential. One of the crucial questions is the long-term performance of FPV installations, or perhaps more specifically, whether it will be similar to that of land-based PV systems over their operational lifetime.

Here, we investigate the performance stability of FPV systems in one of the world's largest FPV testbeds, located in Singapore's Tengeh Reservoir, during the operation period of April 2017 to March 2020. The performance stability of a nearby rooftop reference system is also analysed and compared to the FPV installations.

2. PV system description

The 1-MW_p (DC) FPV testbed in Singapore's Tengeh Reservoir (1°20'N, 103°38'E) is an initiative by the Singapore Economic Development Board (EDB) and the PUB, Singapore's National Water Agency. SERIS was responsible for the overall management of the design, construction, testing and commissioning, and is now carrying out the scientific research of the testbed.

The testbed consists of 10 individual FPV systems, featuring different floating platforms, PV module types and inverters, and one rooftop system. The DC capacity of each FPV system is approximately 100 kW_p. The reference rooftop system (~16 kW_p) is rack-mounted on top of a room (on nearby shore land) in which all the inverters, low-voltage and high-voltage switchgear are stationed. The testbed also includes meteorological stations, measuring irradiance, ambient temperature, relative humidity, wind speed and direction and other relevant parameters. Instruments are also deployed to measure the DC and AC outputs, i.e., voltage and current values from the PV strings and systems. Further details of the testbed can be found in [1].

In this analysis, ten PV strings have been selected for performance stability investigation, with eight from several FPV systems and two from the rooftop system located in close proximity. The selection is mainly based on the data availability of the operation period from April 2017 to March 2020. The DC capacity of the selected PV strings is in the range of 5.2–5.7 kW_p. While most of the strings have multicrystalline silicon (multi-Si) PV panels, two strings use monocrystalline silicon (mono-Si) modules. All PV modules are of glass/backsheet type (with frame). Information on the selected PV strings is summarised in Table 1.

String ID	Location	Orientation	PV type
1	Rooftop	7° East	Multi-Si
2	Rooftop	7° East	Mono-Si
3	Floating	7° East	Multi-Si
4	Floating	7° East	Multi-Si
5	Floating	7° East	Mono-Si
6	Floating	7° East	Multi-Si
7	Floating	12° East	Multi-Si
8	Floating	12° East	Multi-Si
9	Floating	12° East	Multi-Si
10	Floating	12° East	Multi-Si



Table 1. Summary of the information on the ten PV strings investigated in this study. All PV module efficiencies are in the range of 16-17%, based on the manufacturers' specifications. The mono-Si modules are of bifacial type, while the others are monofacial.

3. PV performance metrics

Various performance metrics have been proposed for the evaluation of PV systems' health conditions. One of the most frequently used metrics is the performance ratio (PR), which considers the effect of irradiance on the output of PV systems. The performance evolution of the ten investigated PV strings from April 2017 to March 2020 is shown in Fig. 1. The blue data points are the normalised daily PR values, while the red data points represent the monthly median. In general, Strings 1 and 2 from the nearby rooftop exhibit less fluctuation (not the decreasing trend) in the daily PR than the floating ones, where String 6 experiences the most. Although there is little seasonal variation in Singapore's weather conditions, a certain level of seasonal effects in the PR values is observed.

Figure 2 shows the performance loss rate (PLR) of the ten PV strings from the FPV testbed estimated by three different methods: Ordinary least squares (OLS), seasonal and trend decomposition using locally weighted scatterplot smoothing (STL), and year-on-year (YoY) methods. A good agreement in the results from these 3 approaches can be seen. In general, the OLS method produces slightly higher PLRs than the other two, whereas the uncertainty of the YoY approach is relatively larger. To make a fair comparison between the floating and rooftop PV strings, results from different methods are examined separately. Based on OLS, the PLRs of strings 1 and 2 are –0.6 and –1.1 %/year, respectively, where for the floating PV strings (from 3 to 10), the mean and median of their PLRs are –0.7 and –0.6 %/year, respectively. From STL, the annual PLRs of strings 1 and 2 are also –0.6 and –1.1 %/year, respectively, whereas the mean and median PLRs of the floating PV strings are both –0.5%/year. Lastly, the PLRs of strings 1 and 2 from the YoY calculations are –0.5 and –1.1 %/year, respectively, while the mean and median PLRs of the floating PV strings are both –0.5%/year. It should also be noted that the worst FPV string (in terms of PLR) exhibits an annual loss of –1.1%/year (OLS analysis). The durability and reliability of PV modules from different manufacturers and with different bills of materials can differ in the field, which could introduce bias to the comparison.

Overall, there is little distinction in the performance stability between the rooftop and FPV installations in the testbed over the 3-year measurement period, irrespective of the calculation method.

From an industrial perspective, the PLRs (median or mean) of the FPV strings meet the performance warranty from PV module manufacturers, and hence should build confidence in stakeholders for future FPV deployments.

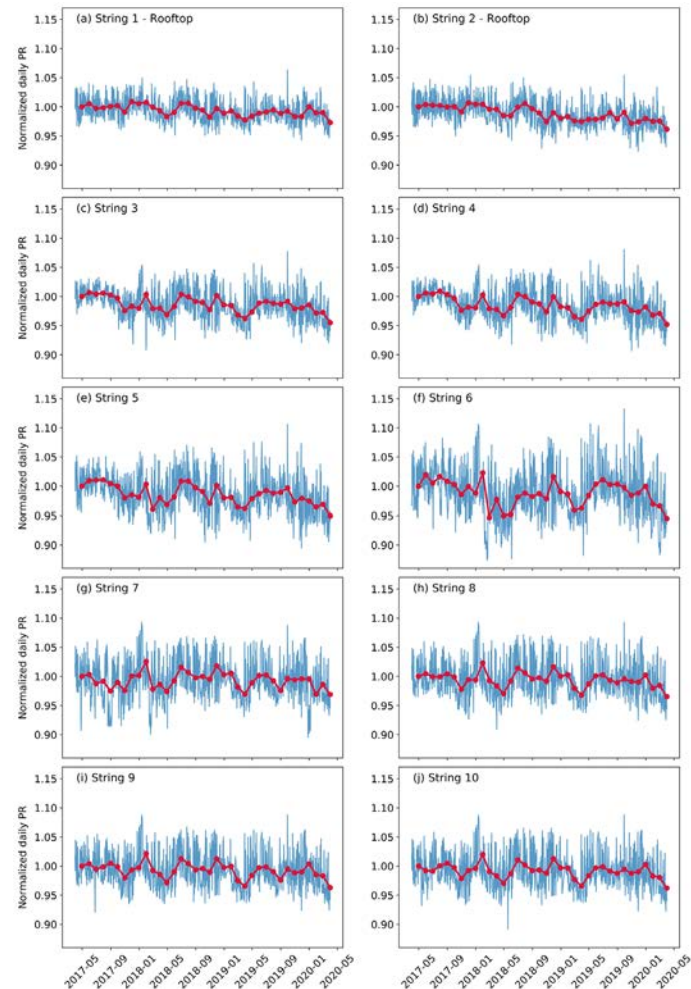


Figure 1. Normalised daily performance ratio of the 10 analysed PV strings.

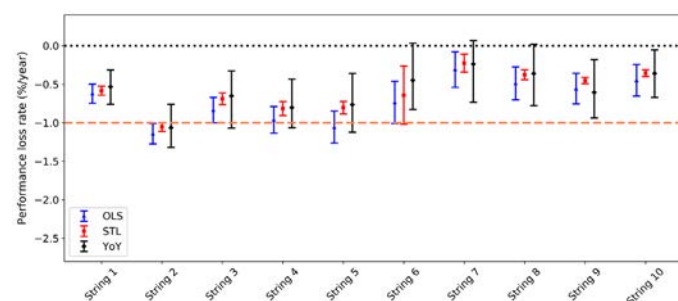


Figure 2. Performance loss rate of the 10 investigated PV strings obtained by 3 statistical methods.

4. Conclusion

In this work, we investigated the performance stability of FPV installations in one of the world's largest FPV testbeds, located in Singapore (tropical rainforest climate), during the operation period April 2017 to March 2020. Three commonly used statistical methods - OLS, STL and YoY - were deployed to estimate the annual PLRs. The mean annual PLRs of eight monitored FPV strings from OLS, STL and YoY are -0.7 , -0.5 and -0.5 %/year, respectively; the median annual PLRs (in the same order) are -0.6 , -0.5 and -0.5 %/year, respectively. These results are in line with the performance warranties from the PV module manufacturers. A comparison is also made with two PV strings from the nearby rooftop reference system. One rooftop PV string exhibits a performance loss in the range of -0.6 to -0.5 %/year, while the other is at -1.1 %/year. In general, the performance stability of the rooftop and FPV installations in the testbed is similar over the first 3 years of operation. This study presented, for the first time, a systematic and detailed analysis of the PLRs of FPV installations. The results are promising at this stage and should boost the confidence of different stakeholders in future FPV applications; however, further monitoring is needed to evaluate the long-term PLR of the installed systems.

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*This article is the extract of a more comprehensive work published in *Solar Energy* 219, pp. 58-64, as W. Luo et al., "Performance loss rates of floating photovoltaic installations in the tropics", Copyright Elsevier (2021).

Holistic simulation approach for design and optimisation of agrophotovoltaic systems

Dr Veronika SHABUNKO, Dr Dhanup Somasekharan PILLAI

1. Background

Agrophotovoltaics (APV) or agrivoltaics is a relatively new and innovative concept in the solar industry, owing to the tangible benefits it offers by transforming agricultural farm land to bifunctional agricultural land. In principle, the aim of APV systems is to provide dual-revenue to agriculturalists by ensuring quality crop yield while generating clean energy from solar panels installed above the harvests, employing raised-rack systems. Thus, an optimally designed APV system enhances the food-energy synergy of the host community, and concurrently expands the global solar installed capacity too. However, each APV system is unique in various aspects that reflect the respective global microclimates. Therefore, in contrast to large-scale solar development, APV systems require a more complex, holistic, and thoughtful design process. Unfortunately, the business models that are presently available for large-scale APV deployment do not guarantee the required viability in the aforesaid facets, which are required for global energy transition and decarbonisation.

To address the above pain points, the team has developed a holistic simulation model to optimally design and deploy APV systems in the ASEAN region and beyond. This simulation model has been developed by combining meteorological data sets, computer aided design and PV system design software platforms such as Rhinoceros3D and PVsyst. In contrary to existing approaches, the proposed solution is capable to take into consideration: climate conditions, orientation, terrain of the location, novel PV tracking systems, high-efficient and transparent PV modules. This is to balance the maximum energy yield and crop yield, including quality of the crop.

2. Scope of project & objectives

By developing a holistic simulation model, the project aims to fulfil the following objectives during the planning and design phases of an APV project: a) to evaluate the feasibility of the project location pertinent to the annual weather portfolio, b) to identify suitable crops that could generate maximum profit with respect to the illuminance (Lux value) available at the ground, c) to select a suitable type of PV system that can provide uniform illuminance distribution to satisfy crop's illumination requirement (based on further optimisation of system orientation, tilt angles, module transparency and assessment between fixed tilt and tracking systems), d) to optimise the ground coverage ratio (GCR) to ensure adequate light intensity required for the photosynthesis process by performing row-row shading analysis, and e) to predict and optimise the annual energy yield in accordance with various GCR values as well as the type of PV system selected for deployment.

3. Significance and impact of project

The proposed solution assesses how well an APV system could perform to achieve the desired outcomes in the intended microclimate prior to its deployment itself. Thus, the developed tool will be pivotal for landowners, farmers, and energy investors to develop successful APV business models, which could accelerate the future energy transition by means of modern agriculture. The project also has equal capabilities to meet both the investor and end user requirements, thereby inheriting a strong potential to improve the public perception towards agrivoltaics.

The project also has a strong impact on bringing marginal lands into agricultural production by identifying high value crops suitable for farming in combination with appropriate PV systems that would guarantee a profit. Thus, APV can be made more practical, and transform it as an alternative to large-scale solar, especially for rural economic development. Additionally, the solution has considerable application to urban agriculture and roof-top farming, which could benefit countries like Singapore to increase its access to locally grown food and simultaneously achieve an optimised trade-off between food and energy production.

4. Methodology & Results

The holistic simulation model performs sequential tasks to optimise each design parameter of an APV system. The results attained during each step are utilised as inputs to proceed further to the subsequent stages. The findings are then consolidated and co-related to provide the final optimal design recommendation. These steps include: 1) microclimate study, 2) site geography analysis, 3) PV system orientation optimisation, 4) shading analysis, 5) location specific high-value crop identification, 6) PV system impact assessment on photosynthesis process, 7) site GCR optimisation, and 8) collective energy-crop yield estimation.

The microclimate study is performed for an initial APV feasibility assessment, which considers peculiar factors of the host community including weather conditions, irradiance distribution and daylight hours. Furthermore, to guarantee reliable results and prediction, the monthly average climate data utilised in the proposed model is acquired from Meteonorm database. Once the project is found to be initially feasible, a site geography analysis is performed to derive the mathematical coordinates meant for actual site modelling in an integrated software platform combining PVsyst and Rhinoceros3D. The incident in-plane irradiance and optical losses are then calculated to optimise the tilt and azimuthal angles to ensure maximum energy yield.

The key challenge in any APV system design is to identify the net ground illuminance available for plant photosynthesis process, especially when the PV panels are installed overhead. To understand its significance, Figure 1 illustrates the relation between photosynthetic volume and ground illuminance (expressed in terms of kLux/hr). The minimum illuminance requirement of certain high value crops is also indicated. The analysis exemplifies that crop selection and ground illuminance optimisation are important design parameters for successful APV deployment.

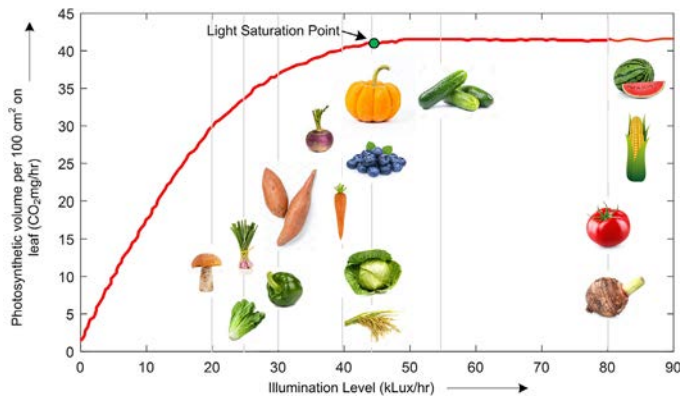


Figure 1. Light saturation point (LSP) curve, and minimum LSP requirement of different high value crops.

In this context, the proposed computational model assesses a potential PV panel arrangement that can be deployed on-site to meet the requirements discussed above. For this, a system model has been developed using Rhinoceros3D, by considering the actual site data (latitude, longitude, and total available area) imported to the Rhinoceros software. Illuminance analysis is

However, single and dual-axis tracking (SAT and DAT) systems used to enhance the PV power generation can reduce the direct irradiance on the ground. Therefore, evaluating the feasibility of fixed tilt, horizontal SAT, tilted SAT, and DAT options becomes obligatory to derive the most performing APV system. This is accomplished by integrating the PVsyst modelling data to Rhinoceros model to calculate the percentage reduction in Lux values per square metre, which subsequently provides the optimal GCR and the type of PV system.

Once the system is optimised, yield prediction is carried out using PVsyst, establishing a reliable trade-off between crop and energy yields. It is worthwhile to mention that the developed model also takes the bifaciality, module transparency and ground albedo factors into account while performing the shading analysis. Overall aim is to achieve an optimal GCR to satisfy the required ground illuminance for best plant growth.

5. Conclusions

This report has demonstrated a new modelling approach to optimise the design of APV systems for deployment in the ASEAN region and beyond. Furthermore, the compatibility of the developed computational model to meet the preliminary APV design requirements was also exemplified with a summary of simulation results. The investigations carried out clarified that pertinent to the planned microclimate, the proposed approach is efficient to identify suitable high value crops and optimise the GCR value as well as the type of PV system to ensure adequate light intensity required for the photosynthesis process of crops underneath. Overall, the model allows to maximise the combined yield of farmers by concurrently optimising the annual solar energy yield and the quality of the crop. This tool will be applied to support building owners, and developers to conduct feasibility study of urban solar roof farms and agrivoltaic projects.

Reference

- [1] Tazawa, S. (1999). Effects of various radiant sources on plant growth (Part 1). Japan Agricultural Research Quarterly, 33, 163-176.

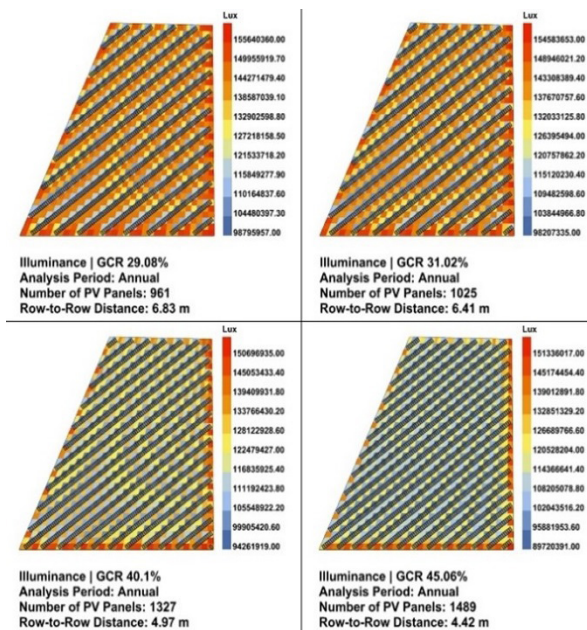


Figure 2. Example of results obtained for shading analysis showcasing annual ground illuminance achievable for a range of optimal GCR values (with bifacial PV modules).

concurrently carried to determine a range of optimal GCRs to maximise the energy output and crop yield. The orientation of the panels to maximise incident irradiation incident on the plane-of-array is also optimised using the Galapagos optimiser.

Shading analysis is then performed using environmental modelling plugin to determine the Lux values available at the ground. The model evaluates multiple GCRs by varying the pitches, and a typical example for the result obtained via shading analysis on an annual basis is presented in Figure 2. As can be seen, the total site area is divided into a number of small sections, and the annual average ground illuminance is separately analysed for each section for precise computation.



SERIS Facilities and Laboratories



PEROVSKITE SOLAR CELL LABORATORY

This 190 m², 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 Lab dedicated to various processes such as synthesis, deposition, metallisation and characterisation of perovskite materials and solar cells.

Glovebox Workstations (Danvec & Mikrouna)

The multi-compartment glovebox systems with controlled N₂ environment (less than 1 ppm O₂ 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. A dedicated glovebox is used for encapsulating and testing of samples, and houses 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 × 166 mm (M6 wafers). The depositions are carried out either via the thermal resistive sources or thermal furnace sources (RADAK sources), depending on the material's evaporation or sublimation properties. In order to achieve high-quality films with low contamination levels, a very low base pressure is required in the vacuum chamber, and this 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 N₂ environment (less than 1 ppm of O₂ 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.



AERIS X-Ray Diffraction Bench-top Unit (Malvern Panalytical)

This XRD unit is a material characterisation equipment to analyse thin films and powdered samples for properties such as chemical composition and phase crystallinity. Closed-cabinet setup and powerful software provide a rapid, easy and safe technique for quantitative and qualitative analysis of samples.

Other equipment for processing and device integration:

- Semi-automated wafer bonding system (EVG)
- Chamber furnace (Protherm)
- UVO Cleaner (Jelight)
- Fume hoods
- Humidity chamber for sample testing (Mettmert)

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SILICON SOLAR CELL LABORATORIES

The silicon solar cell processing 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

Manual Batch Wet-Benches (MediaMac, Singapore)

SERIS' batch wet-chemistry tools were custom-built by MediaMac. They include process baths for standard silicon wafer cleaning sequences, various etching processes, and alkaline silicon texturing processes. The tools are compatible with M2 and M4 size silicon wafers and process 50 wafers per batch via manual handling. The tools are used for standard wet-chemical processing as well as testing of new chemical processes and additives.

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

The BatchTex tool from RENA Technologies is a high-throughput system (> 250 wafers per hour) for wet-chemical etching, alkaline texturing, and cleaning of crystalline silicon wafers (up to M6 wafer size). It consists of a saw-damage removal bath, 3 rinse baths, a texturing bath, 2 cleaning baths with O_3 -based cleaning and etch back, a hot water and warm air dryer. The robotic arms enable automated 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 wafer size). This is a semi-automated 1-lane machine for inline wet-chemical etching and cleaning. It has a heated HF bath, an alkaline bath and an acidic bath for single-side etching with water rinses separating each chemistry.



Automated batch tool for wet-chemical processing



Inline wet-chemistry tool for single-side processing of silicon wafers

Tube furnace #1

(Quantum / Tempress Systems, Netherlands)

The Quantum tube furnace from Tempress Systems is a 5-stack high-throughput furnace featuring two separate HD (high density) $POCl_3$ (phosphorus oxychloride) diffusion tubes, two BBr_3 (borontribromide) diffusion tubes, and one thermal annealing tube for dry and wet oxidations. The furnace has an integrated lift shuttle system for automated wafer handling. The furnace configuration allows all five process tubes to operate independently, with dedicated temperature and process controllers. With this furnace SERIS has the capability to perform industrial high-quality $POCl_3$ and BBr_3 diffusions for mono-Si wafers of up to M4 wafer size, dry and wet oxidation processes, and oxide assisted drive-ins.



Tube diffusion furnace with integrated lift shuttle system



View into the load station of the furnace

Silicon Cleanroom Lab 1B

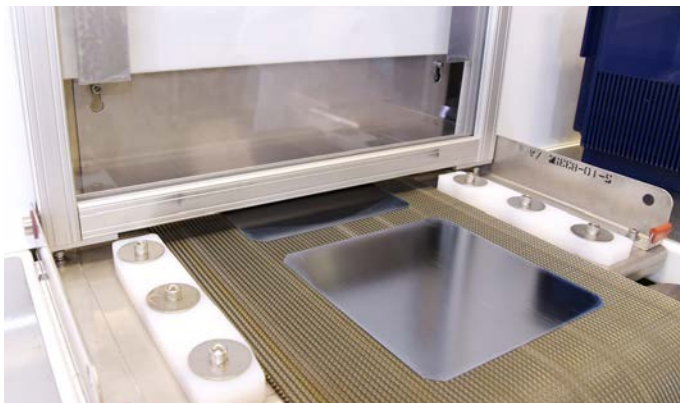
APCVD

(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 silicon wafers, in a single-sided process. The R&D scale 3-chamber APCVD system installed at SERIS is capable of depositing BSG, PSG and SiO_x layers. The tool is highly flexible and enables precise control of the film thickness and dopant concentration. Production systems using belt transport (see photo) have a capacity of 1800 wafers per hour.



 Atmospheric pressure CVD (APCVD) tool in cleanroom lab 1B



 Silicon wafers entering the APCVD tool for thin-film deposition

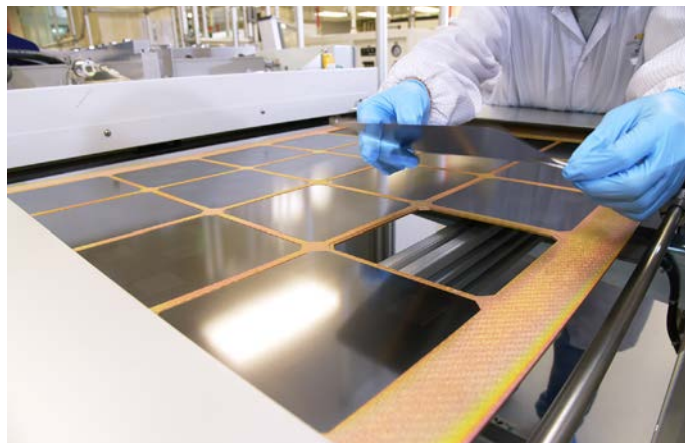
Inline dynamic PECVD tool

(MAiA 2.1 / Meyer Burger, Germany)

The R&D inline plasma-enhanced CVD (PECVD) machine MAiA 2.1 from Meyer Burger, Germany provides a range of functional thin-film coating options required for implementing new technological approaches to increase the efficiency of c-Si solar cells. It is a quasi-continuously operating high-throughput PECVD reactor (> 1000 wafers/hour for some processes). The c-Si wafers are transported through the machine in a flat carrier. The deposition process uses a 'remote' plasma energised by 2.54-GHz microwaves, inducing lower damage to the Si wafers than the conventional parallel-plate approaches. The tool consists of three modules: load/buffer module (LM/BMI), process module (PM), and buffer out/unload module (BMO/UM). The loading module is equipped with an infrared lamp array for rapid substrate heating to the process temperature (350-550°C). The buffer module is equipped with radiation heating plates. The process module with deposition zone includes an array of identical linear plasma sources.



 MAiA PECVD tool in cleanroom lab 1B for the deposition of AlO_x , SiO_x and SiN_x films



 Twenty 6-inch silicon wafers can be deposited per run

Spatial ALD tool

(InPassion LAB / SoLayTec, Netherlands)

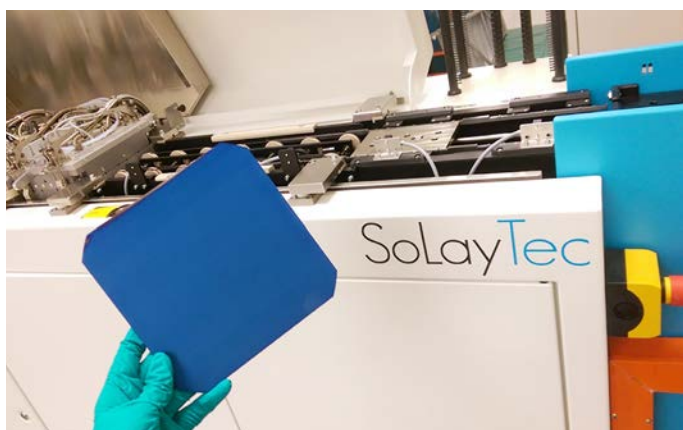
The InPassion LAB ALD tool from SoLayTec is a pioneering R&D system developed for the deposition of Al_2O_3 films using spatial atomic layer deposition (ALD) technology, where precursors are separated in space rather than in time. The deposition of Al_2O_3 films aims to improve surface passivation of c-Si solar cells to boost cell efficiencies as well as pave the way for new and advanced solar cell concepts. Further, SERIS and SoLayTec jointly implemented an upgrade of this tool to include the deposition of intrinsic ZnO, Ga-doped ZnO and Al-doped ZnO thin films by spatial ALD for the development of transparent conductive oxides or transparent metal oxide applications in high-efficiency silicon solar cells. The spatial ALD system features two gas cabinets for the liquid precursors, a process deposition tool and an external abatement system. The deposition tool uses N_2 for wafer transport by a double floating principle at atmospheric pressure and boasts a throughput of up to 100 wafers/hour (for film thicknesses of 10 nm). Deposition rates of up to 35 nm/min can be achieved with low precursor consumption. Cassette to cassette loading is integrated into the system. For single-sided depositions, the film thickness can be adjusted for each wafer. This enables ultrafast ALD growth of functional thin films for industrial implementation in c-Si solar cells.



 Spatial ALD tool



 Close-up view of the load station showing all four process tubes



 Al₂O₃ coated Si wafer

Tube furnace #2 (TS81254 / Tempress Systems, Netherlands)

The tube furnace TS81254 from Tempress Systems is a 4-stack R&D high-throughput furnace featuring various process options: low-pressure chemical vapour deposition (LPCVD) of doped and intrinsic poly-Si films for passivated-contact solar cell applications (double-sided deposition), doped and intrinsic silicon nitride deposition, oxidation for surface passivation applications, as well as co-annealing of implanted samples. The furnace has an integrated lift shuttle system for automated wafer handling. The four process tubes of the furnace operate independently, with dedicated temperature and process controllers.



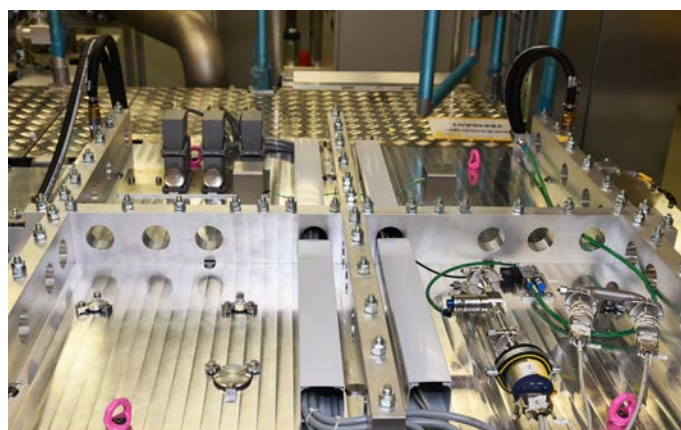
 Tube furnace #2 in cleanroom lab 1B for low-pressure CVD deposition of intrinsic and doped poly-Si and SiN_x films

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.



 CAiA Lab tool for single-sided plasma deposition of doped Si layers and transparent metal oxides



 Close-up view of the CAiA's first process chamber

Silicon Cleanroom Lab 2A

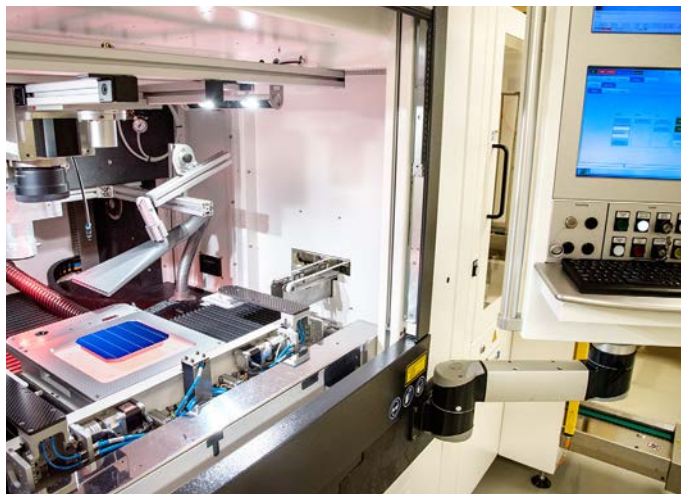
Versatile Laser System

(ILS LT 124 / Innolas Solutions, Germany)

The ILS LT is an R&D laser processing workstation designed for high-precision applications in the PV sector. The machine features three individual 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 silicon solar cell applications, including contact opening, selective mask processing or edge/junction isolation, wafer drilling, wafer cutting, and laser marking for tracking purposes. An automated loading system enables a high throughput of 500 wafers/hour.



 Innolas ILS LT laser system with cassette loading and unloading station



 View inside the laser process station, with either fixed optic and x-y table movement or scanner optics for M2/M4 silicon wafers

Pilot-scale Inkjet Printer

(IP410 / Meyer Burger, Netherlands)

The IP410 at SERIS is a versatile pilot-scale inkjet printer for solar cell masking and patterning applications. The printer supports a wide range of functional inks, including hotmelt inks, UV curable inks, solvent-based metal inks, and chemical precursor inks (example for perovskite cells applications). Multiple printing modules are available at SERIS to quickly switch between different ink types while avoiding cross contamination. An ink evaluation module with disposable cartridges is also available to test small volumes of experimental inks. Printing patterns are digitally defined and therefore can be quickly updated, which makes the inkjet printer ideal for process development and rapid prototyping. The tool is fully automated and includes cassette loading and unloading. Cassette loading and unloading is combined in a compact module with an innovatively designed robotic arm. This compact module allows the tool to maintain a relatively small footprint.

Hybrid scribing machine (MPV-LMM / MDI, Japan)

The hybrid scribing system from MDI, Japan is used for P1, P2 and P3 patterning and preparing of thin-film and tandem mini-modules of sizes up to 30 cm x 30 cm. The machine features both laser and mechanical scribing methods to prepare thin-film mini-modules and mimics the scribing processes commonly used in CIGS PV module production. The system is equipped with a laser source for metal scribing (P1 step) and two dedicated mechanical heads for thin-film diode scribing (P2 step) and front TCO scribing (P3 step). Both laser and mechanical scribe line widths can be varied from 30 to 60 µm. The system is capable of handling both glass substrates and flexible substrates.



 Pilot-scale inkjet printer for masking with hotmelt wax or direct metal printing on silicon wafers



 Hybrid scribing system for P1, P2 and P3 patterning of thin-film and tandem PV mini-modules

Silicon Metallisation Lab 2B

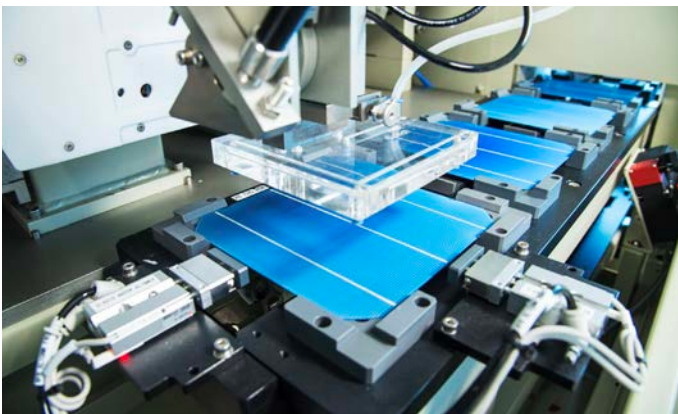
Inline Plating Tool

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

The Meco inline plating tool at SERIS is a versatile system for pilot-scale (throughput > 100 wafers/hour) R&D on plated metallisation of solar cells. The tool 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 electroplating. The tool is also equipped with process channels for inline resist removal and seed layer etch back to pattern plated metallisation on advanced cell structures like heterojunction cells and all-back-contact cells. Additionally, by exploiting the vertical transport mechanism, the Meco tool at SERIS can be used for simultaneously plating both surfaces of bifacial solar cells.



 Inline plating tool



 Wafer loading from a horizontal cassette loading belt to the vertical wafer transport system used for the inline plating process

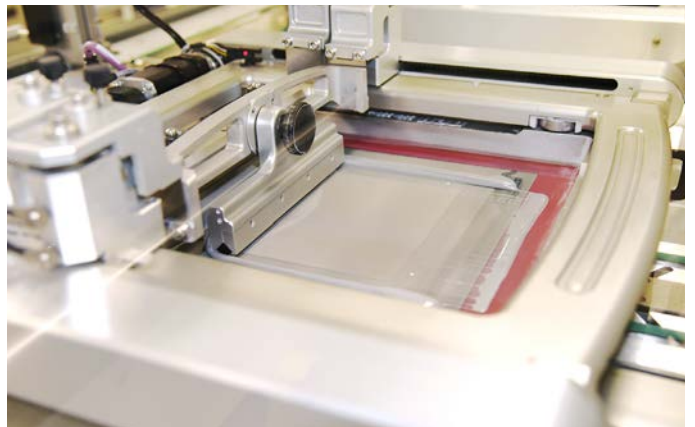
Industrial screen printing line (Eclipse / DEK, UK)

SERIS' industrial screen printing line 'Eclipse' from DEK/ASM Assembly Systems has a throughput of 1200 wafers/hour 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 line has three individual print stations. Station 1 is used for printing of silver pastes, station 2 for printing of aluminium pastes, and station 3 for printing of copper and

masking pastes. Each print station includes an automated weighing station that measures the weight of the metal paste printed onto each wafer (without the need to handle the wafers manually for weight measurements). The print stations have an alignment accuracy of $\pm 10 \mu\text{m}$ and the prints can be aligned to the wafer edges or specific patterns on the wafer. This enables print-on-print applications and the metallisation of selective-emitter solar cell structures.



 Eclipse screen printing line



 Screen printing process

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. The firing furnace has 6 zones with infrared lamps for heating c-Si wafers within a temperature range of 300-1000°C. The furnace uses a belt with edge support for the wafers. This minimises belt marks on the wafers after firing. The furnace has the capability to independently control power to the top and bottom lamps of the high-temperature firing zones, which is beneficial for high-efficiency c-Si solar cell architectures like PERC solar cells and n-type bifacial solar cells. 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 depositing metal and other functional thin films (Al, Ag, etc) onto various substrates (silicon wafers, glass sheets, etc). The deposition chamber uses a cryogenic pump and can achieve very low pressure ($< 10^{-6}$ Torr), ensuring high-purity metal films. The evaporator features dual resistively heated sources and a rotating substrate table to ensure uniform depositions across large-area substrates.



 Fast firing furnace



 Thermal evaporator for metal films

Inline multi-chamber sputter machine #1 (SV-540 / FHR Anlagenbau, Germany)

The physical vapour deposition (PVD) sputtering platform is designed for medium-throughput applications like silicon solar cells and architectural glass. The machine was designed for depositing transparent conductive oxide (TCO) and transparent metal oxide (TMO) films onto M4-size silicon wafers (6 per run) or glass substrates of sizes up to 30 cm x 40 cm. This state-of-the-art machine has dedicated chambers for the sputtering of metallic, dielectric and TCO/TMO layers. The processing chambers are equipped with planar magnetron sources for DC and RF sputtering of metals, oxides and oxynitrides in the reactive mode, and with a cylindrical dual-magnetron source and planar sources for pulsed DC ("DC+") sputtering of dielectrics

and TCOs/TMOs, with substrate heating up to 500°C. It is also possible to deposit graded layers, or multi-layer stacks of up to six different materials, without breaking the vacuum conditions. As the platform is comparable with large-scale production machines, the processes developed in this machine can easily be scaled up to industrial production lines. 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.

Inline multi-chamber sputter machine #2 (Line-540 / FHR Anlagenbau, Germany)

This inline sputtering tool from FHR Anlagenbau, Germany has three planar magnetron sources, whereby two sources are connected to a DC power supply for DC sputtering of metal layers, while the third source is connected to an RF power supply for the deposition of dielectric films such as ZnO. Substrates of sizes up to 30 cm x 40 cm or up to six M4-size silicon wafers per run can be processed at substrate temperatures of up to 200°C. The tool is also used for deposition of Cu and other metal seed layers onto silicon wafers for subsequent plating.



 Inline multi-chamber magnetron sputtering machine for the deposition of metals, dielectrics and TCOs



 Close-up view of the vertical load carrier, here for 6 silicon wafers per run

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PHOTOVOLTAIC DEVICES CHARACTERISATION LABORATORIES

The PV Devices Characterisation laboratories at SERIS are equipped with a comprehensive suite of measurement tools to examine both material and device properties. The characterisation of optical and passivation layers, bulk materials, and solar cell metallisations provides better understanding of their influence on the PV efficiency. This complements device level measurements of silicon wafer 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



 Materials Characterisation Laboratory

Contactless corona-voltage (C-V) measurement 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 technique uses incremental corona charging of dielectrics and subsequent measurement of the surface potential with a vibrating capacitive electrode ('Kelvin probe'). 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.

μ -PCD lifetime mapping tool (SEMILAB, PV-2000)

Microwave-detected photoconductance decay (μ -PCD) is a time-resolved method to determine and map the effective carrier lifetime of silicon samples with a spatial resolution of 5 mm. Differential carrier lifetime measurements at up to 20 Suns of bias light intensity can be performed in this tool.

Eddy current based carrier lifetime measurement (Sinton Instruments, WCT-120)

The Sinton Instruments WCT-120 system is a standardised

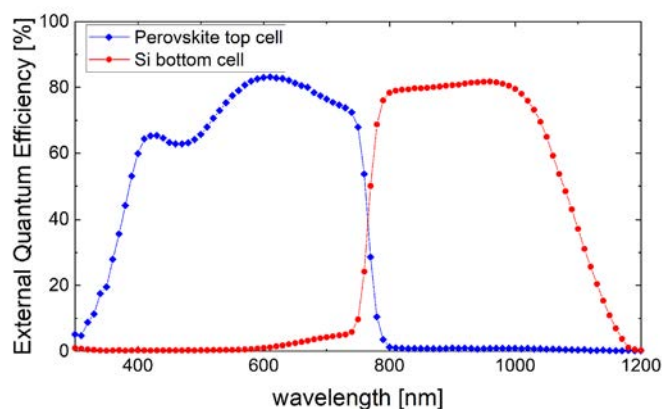
carrier lifetime tester for silicon samples. The system measures the effective carrier lifetime of a silicon sample from its impedance and the incident light intensity from a flash lamp. From the measured effective carrier lifetime, the system also provides the sample's implied V_{oc} and the emitter saturation current density J_0 . The sample temperature can be controlled in the range of 30-190°C.

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. PL and EL images are maps of the excess charge carrier densities, which in turn are influenced by the local junction voltage and effective carrier lifetime. These maps can be obtained in the order of seconds, on both partially processed silicon wafers as well as finished solar cells. For cells, combinations of images enable the separation of factors that influence device voltage, such as series resistance and the saturation current density. Because PL can be applied to a wafer at any stage of processing, it is also an ideal tool to track the evolution of the cell voltage potential as the sample goes through the individual processing steps.

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

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



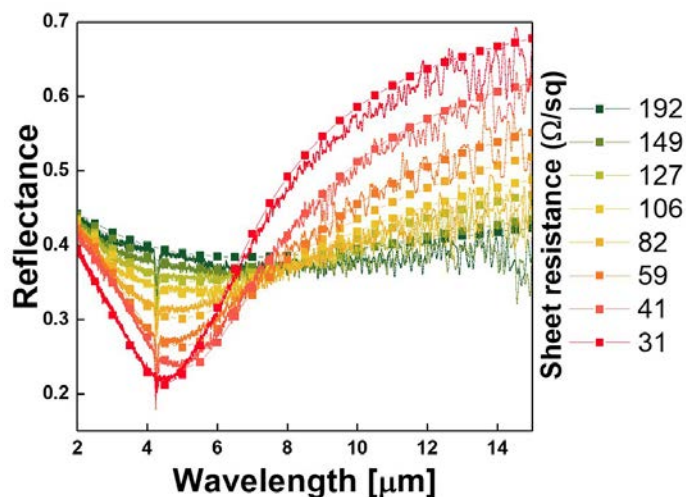
Measured EQE of a monolithic perovskite/Si tandem cell. (Courtesy of A/Prof Hou Yi and Dr. Liu Shunchang for providing the sample).

Fourier transform infrared (FTIR) spectrometer (Thermo Scientific, Nicolet iS-50)

An FTIR spectrometer measures the amount of infrared light a sample absorbs at each wavelength due to change in dipoles of molecules during vibration. It is ideally suited for the analysis of the composition of materials, including thin films like amorphous silicon, silicon oxide, silicon nitride and aluminium oxide. The instrument can be further equipped with a gold-coated integrating sphere configured with a high-performance mercury cadmium telluride (MCT) detector for hemispherical diffuse reflectance and transmission measurement.



FTIR spectrometer with gold-coated integrating sphere installed for hemispherical transmittance and reflectance measurements in the mid-IR range. ATR and mapping accessories are also shown.



Measured hemispherical reflectances (lines) of boron diffused n-type Si wafers with different sheet resistances. The smooth lines with squares are the corresponding simulated curves.

Non-contact bifacial sheet resistance measurement (Aurora, DM-121)

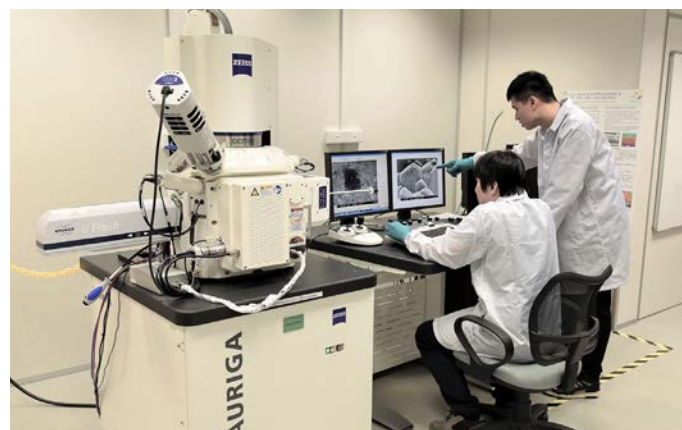
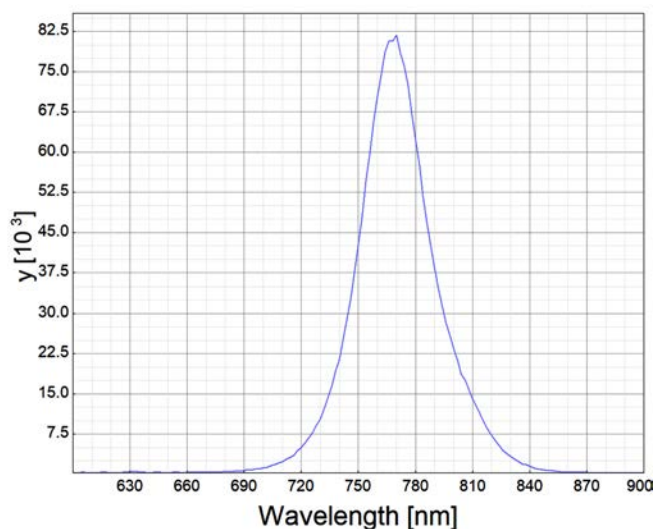
Measurement of the emitter and back-surface-field sheet resistance of solar cells is essential for process control. The DM-120 system performs this contactlessly using infrared light at high speed at a series of discrete points along the centreline of each wafer.

Solar cell metal line and contact resistance measurement (IVT)

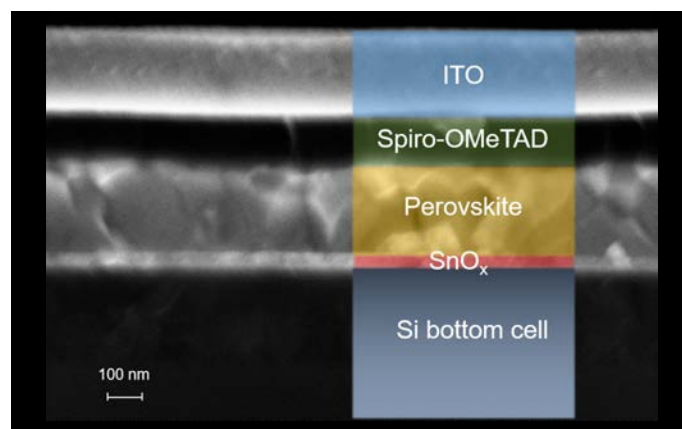
The transmission line method (TLM) enables metal-semiconductor contact resistance measurements down to $1 \text{ m}\Omega\text{-cm}^2$. Different probe heads are available for a wide range of metallisation finger pitches, for measuring both screen-printed cells as well as evaporated metal contacts on test structures. Busbar-to-busbar resistance and line resistance measurements are complementary techniques to determine metal grid resistance.

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.

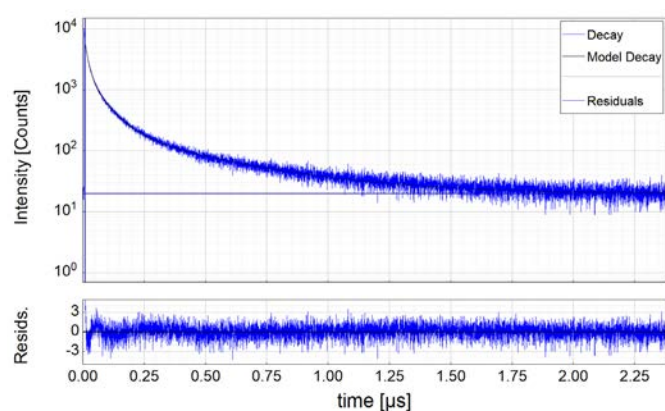


 Scanning electron microscope



 An cross-sectional SEM image of a monolithic perovskite on Si tandem cell (Courtesy of the Tandem Solar Cells group for providing the sample)

 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 allows 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 $10^{12} - 10^{21} \text{ cm}^{-3}$ can be detected with a depth resolution of 1 nm.

Microscopy Laboratory

Scanning electron microscope (SEM) (Carl Zeiss, Auriga)

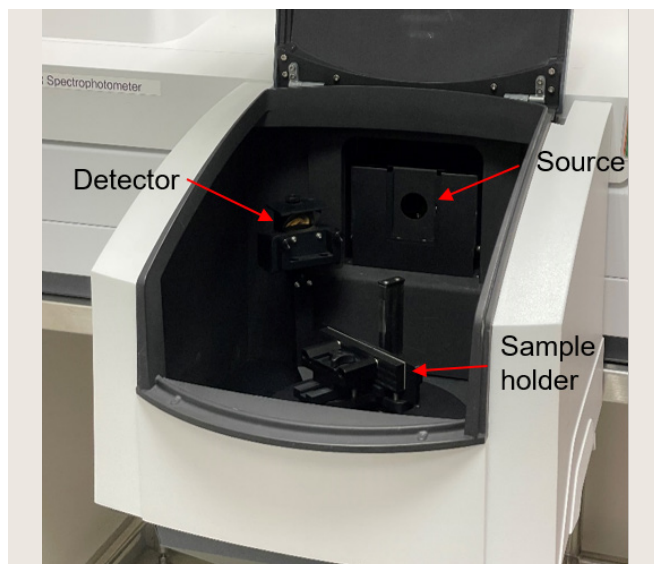
This field emission SEM can achieve a resolution of 1 nm at low acceleration voltages of less than 1 kV. It is ideal for imaging sub-micron morphologies, cell front textures, and micro- and nanopatterned structures. The SEM is also equipped with electron back scatter diffraction (EBSD) (Bruker, e-Flash), electron beam induced current (EBIC) (Kammrath & Weiss) and energy dispersive X-ray (Oxford Instruments, Aztec X-MaxN) features.

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

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 uniform illumination intensity across an area of 300 mm × 300 mm, making it well suited for the measurement of silicon cells, single-cell modules, and small thin-film modules under standard test conditions.

LED solar simulator 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. The built-in spectrometer and photodetector are designed to give real-time feedback to maintain intensity and spectral stability. The LED intensity can be changed over a very large range, enabling I-V and Suns- V_{oc} measurements to be performed from 1.2 Suns down to 0.1 Suns. Together, these solar simulators are capable of measuring solar cells with metallisation grid patterns ranging from traditional H-patterns to newer busbarless designs.

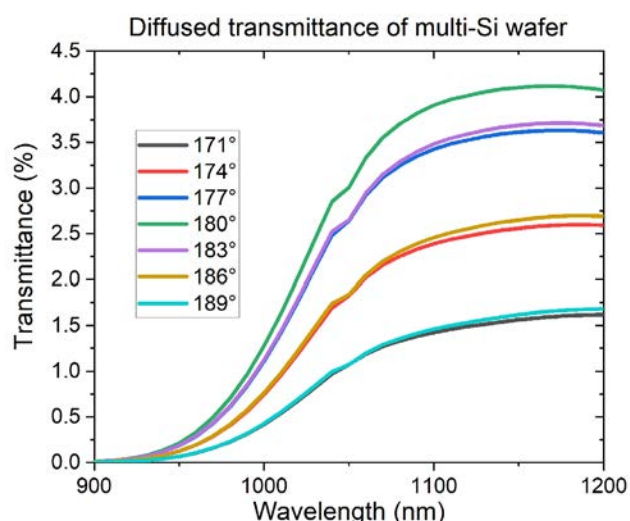
Large-area spectral response analyser (Enlitech, SR-156)

This system projects a large monochromatic beam which overfills the silicon wafer area for differential spectral response measurement up to 1-Sun bias light intensity. Solar cells with an area of up to 160 mm × 160 mm can be measured. The external quantum efficiency (EQE) extracted from the measured spectral response curve enables the determination of the spectral mismatch correction factor to refine the prediction of a test solar cell's short-circuit current under the AM1.5G spectrum.

Light soaking system (SOLARONIX, Solixon A-70)

The system is able to conduct light soaking at an intensity of 1 Sun and at 25°C device temperature prior to device testing. In some cases (for example amorphous silicon thin-film solar cells), a higher light intensity and a higher temperature may be used. Light soaking is important for solar cells that suffer from light-induced degradation (LID) effects, such as amorphous silicon thin-film solar cells ('Staebler-Wronski effect'), boron-doped Cz silicon wafer solar cells (boron-oxygen related defects), and other degradation modes found in multicrystalline silicon solar cells.

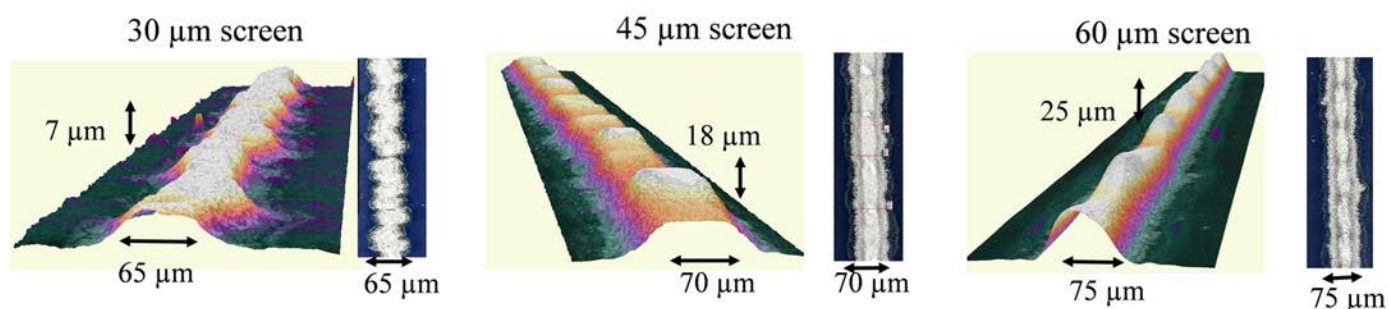
 The universal measurement accessory for measuring angular resolved reflectance and transmittance.



 Measured diffused transmittance of a multi-Si wafer.

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 on silicon wafer solar cells.



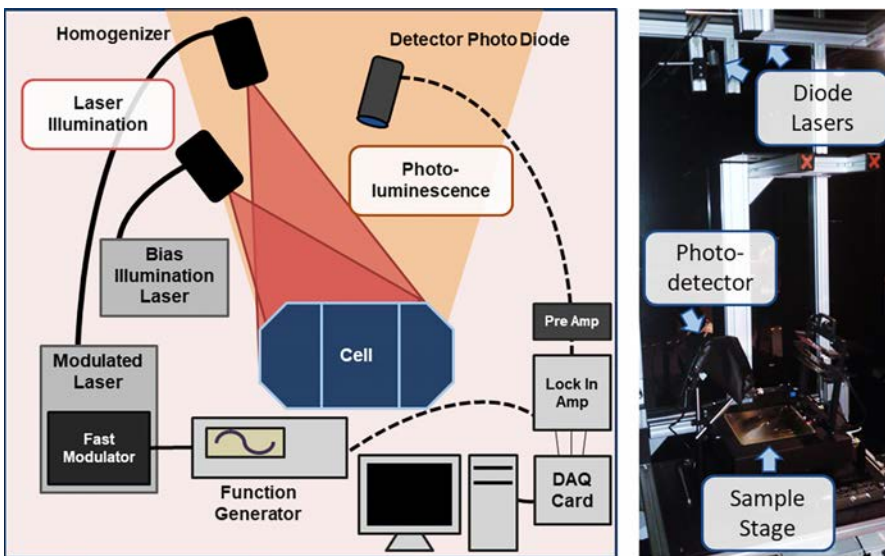
 The Zeta optical profiler is capable of obtaining detailed topographic information of structures on a solar cell, for example printed metallisation lines.

Advanced LED light soaking system (SERIS)

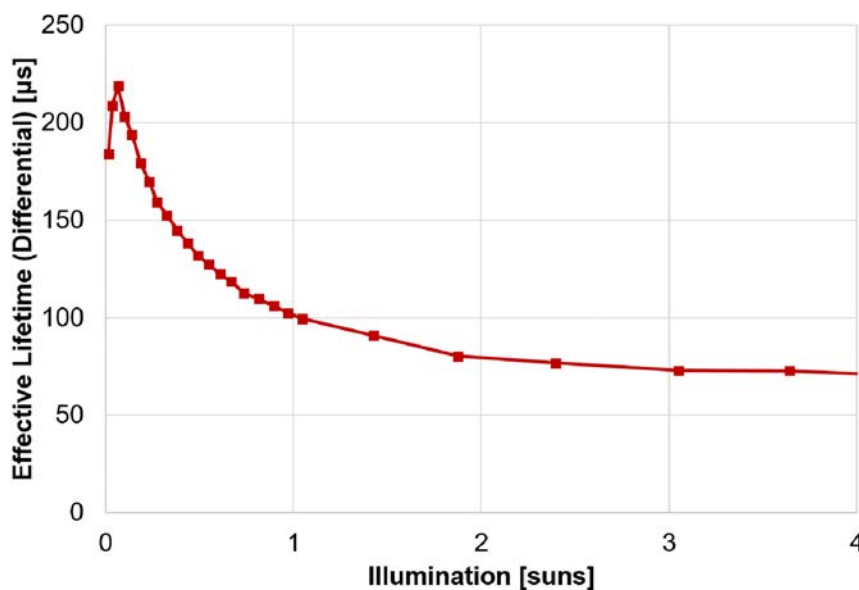
A SERIS-built LED-based light soaking system extends the capabilities of light soaking up to 5 Suns intensity and up to 300°C device temperature. These functionalities are particularly relevant for studying light and elevated temperature induced degradation (LeTID) - also known as carrier-induced degradation.

Modulated photoluminescence (SERIS)

Modulated PL is capable of measuring the effective charge carrier lifetime as a function of injection level for a variety of silicon wafer samples, including midstream processed samples, carrier lifetime samples, metallised cells, and even single-cell modules. It is a versatile tool that can track the evolution of effective carrier lifetimes of samples that are processed into cells. The tool has also been cross-calibrated with μ -PCD and eddy current based carrier lifetime measurement methods.



(Left) Schematic of modulated photoluminescence setup. (Right) Actual setup at SERIS' Characterisation lab.



Differential effective carrier lifetime measured by modulated PL for a range of bias light intensities.

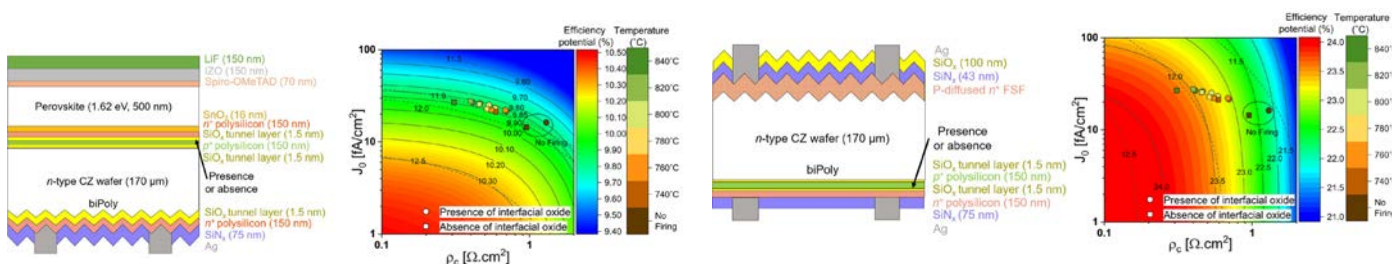
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PV DEVICE MODELLING AND SIMULATION

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
 - Metrology simulation
 - Energy yield simulation
 - Optical simulations
 - Loss analysis
 - Web based solar cell simulation platform
- n-PERT, contact passivated, perovskite, perovskite/Si tandems
I-V, EQE/IQE, carrier lifetime, EL/PL imaging, corona-voltage
PV modules and systems
Transfer matrix, ray tracing, path tracing
Solar cells (silicon, perovskite), PV modules and systems
XSolar-Hetero



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 in-house 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 MATLAB and COMSOL Multiphysics.

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, injection and corona-charge dependent surface photovoltage measurements, as well as injection and bias dependent luminescence images (EL and PL). This enables a self-consistent parameter extraction for PV devices using a raft of characterisation methods.

Energy yield simulation

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

Loss analysis

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

Web based simulation platform

A web based simulation platform (XSolar-Hetero) 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.

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PV MODULE DEVELOPMENT LABORATORY

Located at CleanTech Park, SERIS' 300-m² PV Module Development Laboratory houses a fully equipped PV module pilot line for industry-scale PV module R&D and related services.



 (Left) Automatic solar cell stringer. (Right) TLS cell cutter at the SERIS PV Module Development Laboratory located at CleanTech Park

TLS cell cutter (3D-Micromac, microPRO TMS)

The advanced solar cell cutter with thermal laser separation (TLS) technology is able to perform solar cell cutting with minimal laser-induced damage. The TLS cell cutter is able to cut silicon solar cells for half-cut and shingled PV module configurations, with minimal cell power loss.

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 silicon solar cells with 3, 4, 5 or 6 busbars. Both full-size cells and half-cut cells can be processed.

String repairing station (P.Energy, RP12M)

This station is used for manually repairing strings of solar cells if, for example, one cell in a string gets broken.

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

This advanced laminator has individual chambers to perform different lamination steps, enabling more precise temperature control and ensuring good lamination quality of glass/glass modules. Since October 2021 this laminator is housed in a collaborator's lab in Singapore, where it is used for collaborative module R&D with the industry partner and also for SERIS' internal module research.



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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. The Laboratory is accredited since 2012 to ISO/IEC 17025. 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

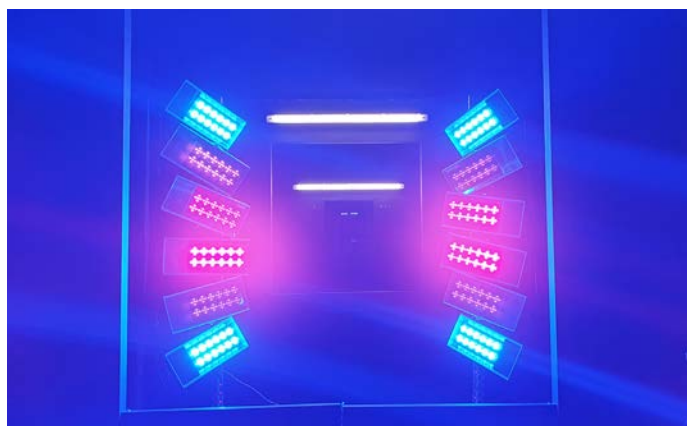
The Laboratory has high-level instrumentation that makes it one of the best-equipped test laboratories in the world for PV module testing, and the top module testing laboratory in South-East Asia.

Solar simulator classification

The “ABC” rating

Solar simulators can be classified in our lab according to the newest edition of IEC 60904-9, including spectral match classification in the extended range from 300 to 1200 nm, thanks to our world-class multi-channel fast-response spectrometer.

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 can be performed in our lab on two of the best solar simulators in the market:

- the 10-ms pulse Pasa 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 $\pm 1.5\%$ for the measured maximum power.



“Golden module” testing at SERIS

Spectral responsivity and spectral mismatch correction for the highest accuracy

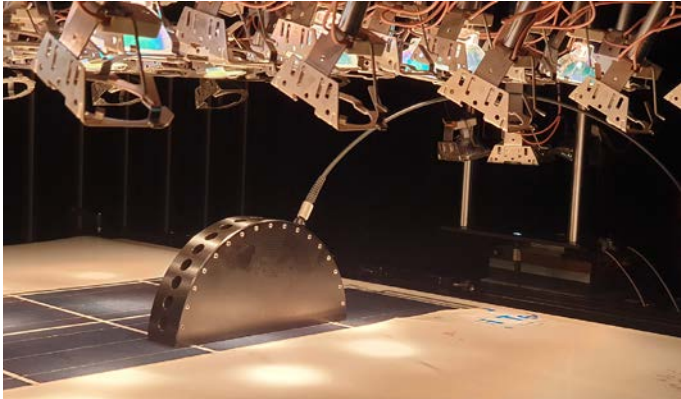
The Laboratory is fully equipped to assess the optical characteristics of the module under test for both spectral responsivity measurements and spectral mismatch correction, providing best-in-class precision in the electrical measurements. The spectral irradiance of the solar simulators is routinely checked with fast-response spectrometers, capable to measure in the 200 - 1700 nm spectral range.



Spectral responsivity measurement system

Incident Angle Modifier (IAM)

The level of irradiance that a solar 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 solar 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 equipment 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.



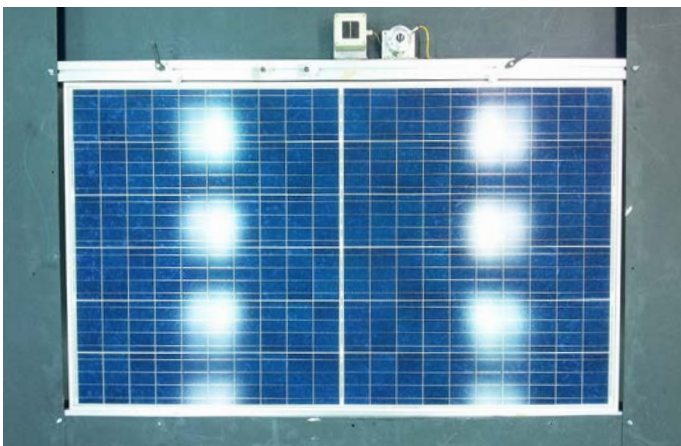
 Measurement of IAM at module level

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.

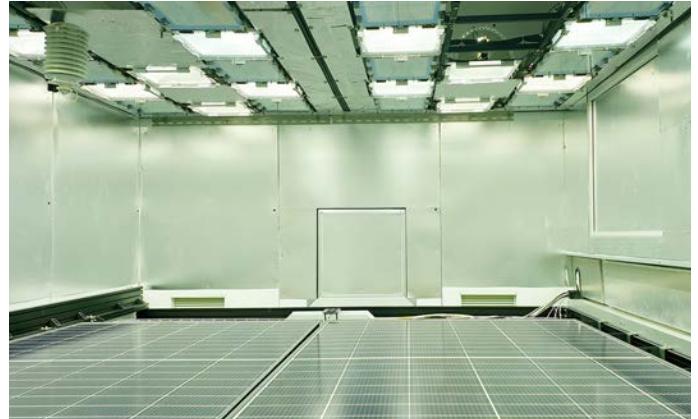


 Module stabilisation

UV Exposure

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

The module under test is irradiated with at least 15 kWh/m² to as high as multiple runs of 60 kWh/m² 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

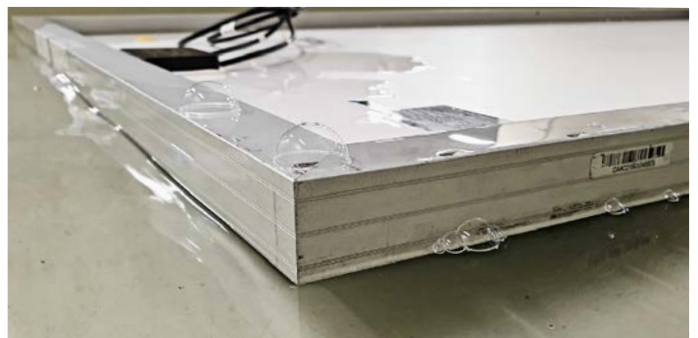
Insulation Tests

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 module.

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

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

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

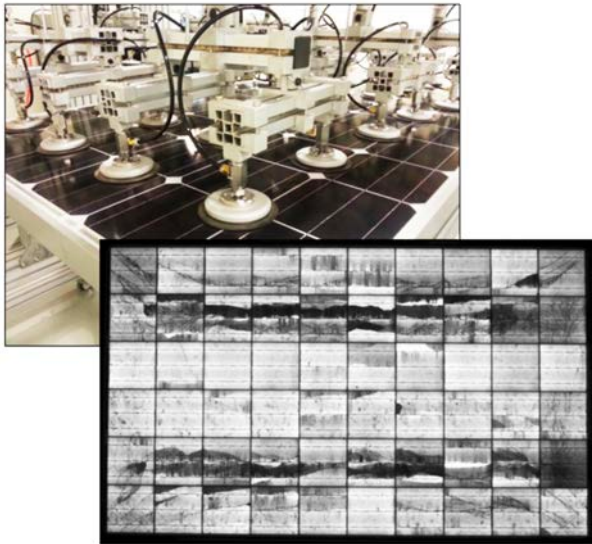


 Wet leakage test

Mechanical stress tests

Our equipment covers the following industry standard tests:

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

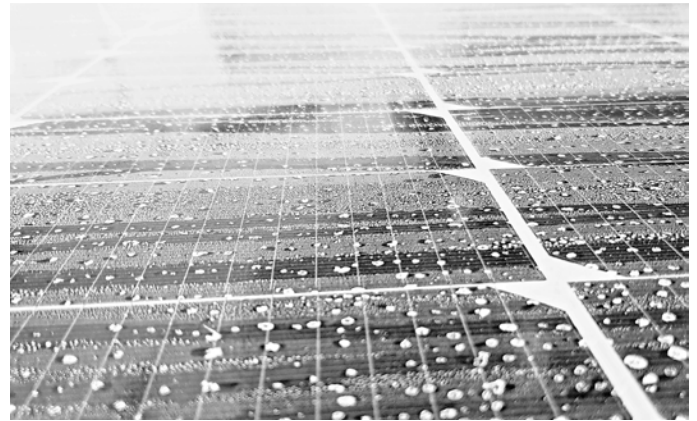


 Damages after dynamic MLT

Extended reliability for tropical regions

The location in the tropics makes SERIS' testing laboratory an ideal location to conduct 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

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 equipped to perform the prenormative Light and Elevated Temperature Induced Degradation (LeTID) test, a novel degradation mechanism that is supposed to slowly deteriorate PV module performance in hot climates.



 Climate chambers for reliability testing

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OUTDOOR PV MODULE AND SYSTEM TESTING FACILITIES IN DIFFERENT CLIMATES

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

SERIS applies its self-developed data acquisition system at the TruePower™ sites. To date, through many years of working with clients and carrying out R&D projects, SERIS has achieved outstanding data acquisition rates of more than 99%, 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)
- Pyrhelimeter
- Spectro-radiometer
- UV radiometer
- Ambient temperature
- Other meteorological sensors (wind speed & direction, humidity, rainfall)



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



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



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



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



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PV SYSTEM MONITORING LABORATORY

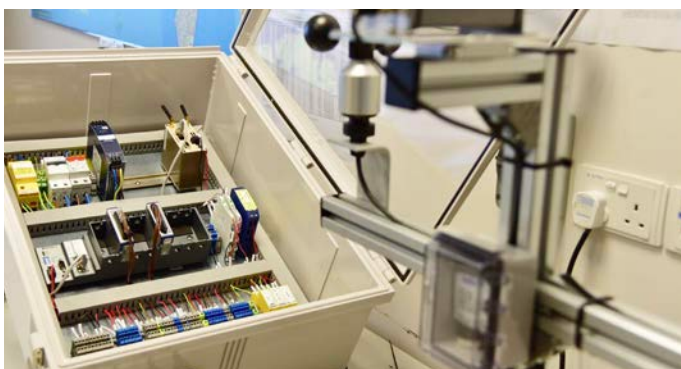
The PV System Monitoring Laboratory at SERIS conducts real-time analytical monitoring of photovoltaic systems as well as meteorological parameters. SERIS' proprietary award-winning monitoring system is based on rugged industrial-grade National Instruments hardware and LabVIEW software for remote data 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. Singapore's Energy Market Authority (EMA)
- 1-second resolution of various DC and AC parameters of PV systems, power quality parameters, and meteorological parameters, such as irradiances measured with different sensor devices and inclinations, module and ambient temperatures, relative humidity, wind speed, wind direction, air pressure, etc.
- ± 150 ms time synchronisation with SERIS' time server
- Greater than 99% data acquisition reliability
- 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



 A motion monitoring sensor for floating PV systems

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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.

Long-term LED performance monitoring

The lab also houses a purpose-built testing system for monitoring the long-term light output and efficiency of light emitting diodes (LEDs).



 (Top) 3D printer. (Bottom) Multiple Lab equipment for electrical works.



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CALORIMETER LABORATORY

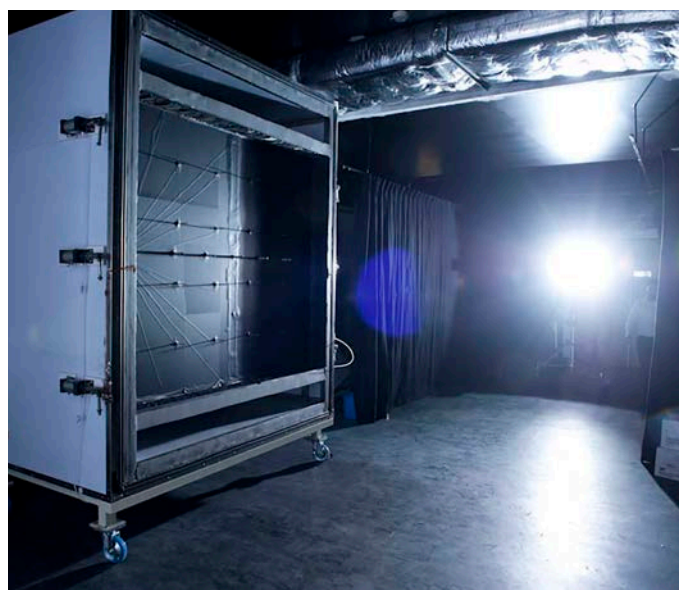
SERIS' Calorimeter laboratory enables high-precision measurements of the thermal performance of building façade assemblies and fenestration systems, including building-integrated PV (BIPV).

Calorimeters are used to accurately measure the solar heat gain coefficient (SHGC or g-value) of complex façade or fenestration systems (including shading devices) and the overall thermal transmittance (U-value). Both values are direct indicators of the energy efficiency of building façades. A low g-value is preferred in the tropics in order to minimise solar radiation heat gain particularly through fenestration systems. High solar heat gains increase the temperature in the building and thus the air conditioning cost. In the tropics, moderately insulated building elements (U-value) are already sufficient to reduce the transmission of absorbed solar heat and ambient heat through the building envelope to acceptable levels.

Calorimetric hot box

SERIS' calorimetric hot box is a combined solar heat gain coefficient (SHGC or g-value) and U-value measurement system with the following features:

- Measurement of large, thick, inhomogeneous and non-flat envelope assemblies up to 1.5 m x 1.5 m in size (for example fenestration systems with protruding shading systems, light-redistributing devices or assemblies including BIPV systems)
- For measurements of the solar heat gain coefficient, the sample is exposed to simulated sunlight from a high-powered lamp. The intensity, spectrum, divergence and spatial uniformity of the irradiance at the sample's surface comply with international standards. Various radiation angles on the sample can be realised, enabling the measurement of the SHGC as a function of the angle of incidence. The thermal properties of the illuminated sample are measured by the calorimetric hot box shown in the photographs.
- For U-value measurements, a climate chamber is put in front of the sample, maintaining the temperatures and surface heat transfer coefficients as required by various measurement standards (for example cool, warm or hot outdoor conditions).



Calorimetric hot box (left part of left photo) with solar simulator (lamp in right photo) for the measurement of the solar heat gain coefficient (SHGC). For U-value measurements, the solar simulator is switched off and a climate chamber (middle part of left photo) is put in front of the sample.

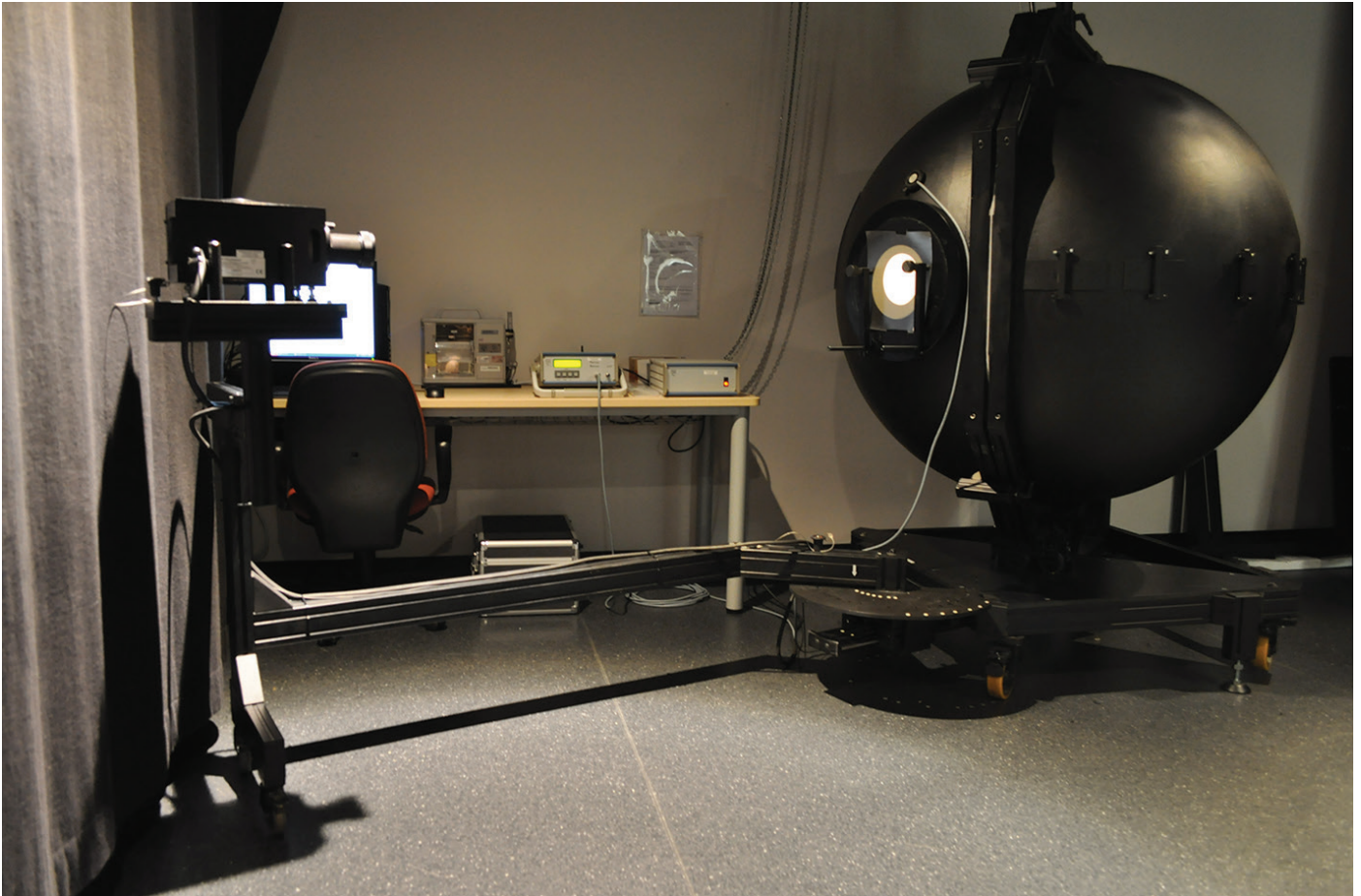
SERIS' calorimeter is superior to the more commonly used calorimetric hot-plate systems, which are limited to flat samples (as they need to be sandwiched between two plates). It is also superior to the optical determination and calculation of the SHGC with spectrophotometers, which is limited to small, flat and homogeneous samples (and which furthermore requires detailed information on the thermal properties of all components/layers of the sample). SERIS' calorimetric hot box can measure samples ranging from 0.3 m x 0.3 m up to 1.5 m x 1.5 m. The calorimetric hot box at SERIS is designed in compliance with the international standards ASTM C1363 (*Test method for thermal performance of building materials and envelope assemblies by means of a hot box apparatus*) and ASTM C1199 (*Measuring the steady-state thermal transmittance of fenestration systems using Hot Box methods*).

Large integrating sphere

The large integrating sphere (diameter 1.25 m) system at SERIS was built in compliance to DIN 5036-3 (*Radiometric and photometric properties of materials: Methods of measurement for photometric and spectral radiometric characteristics*). The system can accurately measure the optical transmittance and reflectance of materials in the visible wavelength range.

For commercially available spectrophotometers, the diameter of the integrating sphere is typically in the range of 6 to 15 cm. SERIS'

integrating sphere is much larger and thus the system has many advantages over standard spectrophotometers. First, it is able to measure large, inhomogeneous and non-specular samples (for example frosted or patterned glass panes, or fabric shading materials). Second, it is able to measure the transmittance and reflectance of samples as a function of the angle of incidence of the visible light. The SERIS system is also able to determine the diffuse and specular components of the optical transmittance and reflectance.



Large integrating sphere system for the measurement of the visible light transmittance and reflectance of a wide range of materials and sample sizes



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SERIS Services



PROCESSING SERVICES FOR SILICON SOLAR CELLS

SERIS operates state-of-the-art industrial high-throughput silicon solar cell processing equipment from leading manufacturers to support the PV research community. Selected examples of processing services for research-type silicon solar wafers and cells offered by SERIS are listed below.

Processing of large-area silicon solar wafers and cells

- M2 and M4 wafer size (up to 161.7 mm × 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
- Diffusion of phosphorus (POCl_3) or boron (BBr_3) into c-Si wafers and poly-Si layers
- PECVD of dielectric layers (SiN_x , AlO_x , SiO_x , etc)
- APCVD of phosphorus or boron-doped SiO_x layers
- LPCVD of intrinsic or doped (boron, phosphorus) poly-Si layers
- ALD of Al_2O_3 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), 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-sided or bifacial 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: (Left) PECVD and APCVD tools in zone 1B; (Right) Wet chemistry tools in zone 1A.

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

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

The PVD sputtering platform at SERIS is designed for medium-to high-throughput applications such as solar cells, architectural glass, and flat-panel displays. The machine can handle any flat substrate with a size of up to 300 mm × 400 mm, with a maximum thickness of 5 mm. Typical substrates would be glass and silicon wafers. This state-of-the-art machine has dedicated chambers for the sputtering of metallic, dielectric and transparent conductive oxide (TCO) layers. The processing chambers are equipped with planar magnetron sources for DC sputtering of metals, oxides and oxynitrides in the reactive

mode, and with a cylindrical dual-magnetron source and planar sources for pulsed DC (DC+) and RF sputtering of dielectrics and TCOs, with substrate heating up to 400°C. This allows to deposit thin layers of metals, TCOs and dielectrics onto various substrates. It is also possible to deposit graded layers, or multi-layer stacks of up to six different materials, without breaking the vacuum conditions. As the platform is comparable with large-scale production machines, the processes developed on this machine can easily be scaled up to industrial production lines. At SERIS we use this tool for depositing metal layers, TCOs and multi-layers for Si and thin-film solar cells, as well as heterojunction silicon wafer solar cells. The features of our sputtering machine are listed in Table 1.

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



 In-line multi-chamber magnetron sputtering machine at SERIS

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

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

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CHARACTERISATION AND TESTING OF PV MATERIALS AND SOLAR CELLS

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

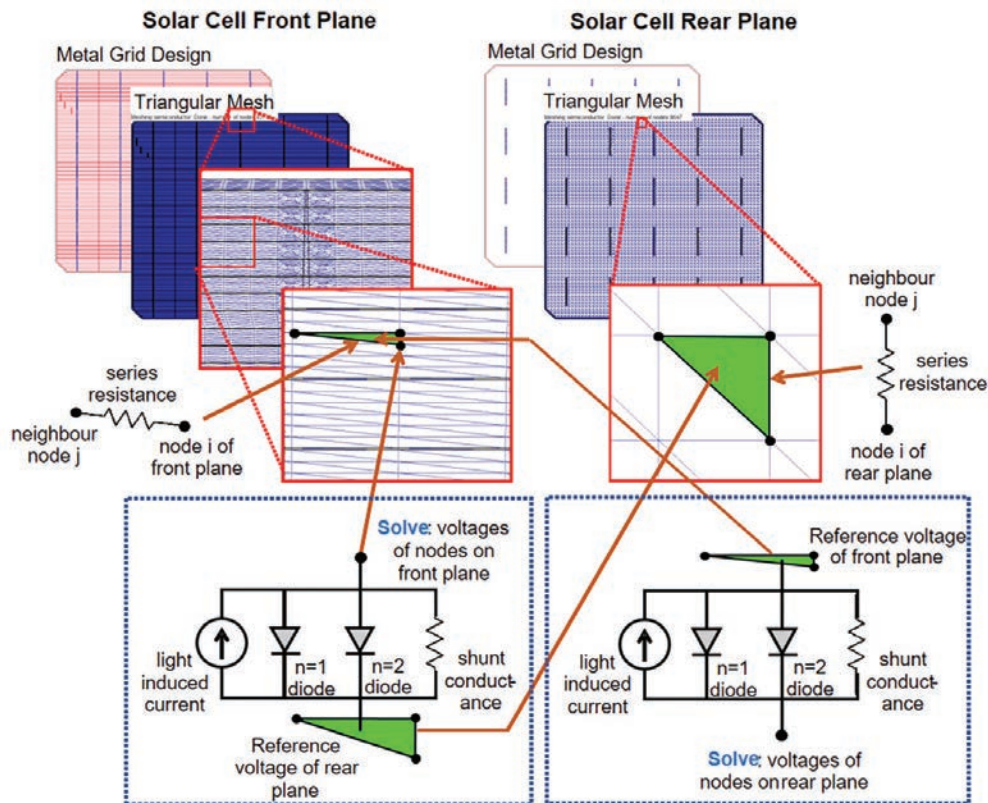
- Solar Cell Doctor: Detailed health check for solar cells
- High-precision steady-state light I-V and full-area spectral response measurements
- High-precision active-area spectral response and diffusion length mapping
- Photoluminescence and electroluminescence imaging
- Absolute luminescence quantum 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
- Dielectric coatings: Charge and interface defect density mapping
- 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
- Better than parts-per-trillion impurity detection of transition metals by inductively coupled plasma mass spectrometry (ICPMS)
- 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
- Comprehensive evaluation of metallisation pastes in terms of printability, line and contact resistance, and metal recombination
- Accelerated inspection, characterisation and analysis (for solar cell manufacturing and research applications) by artificial intelligence techniques

Expert finite element simulations

Actual silicon solar cells are large-area multi-dimensional devices with lateral variations in internal voltage, and consist of various layers across the thickness of the wafer. SERIS' PV Devices Characterisation Group is well equipped to analyse the nuances in various measurement data by matching them to detailed two-dimensional models. One of these is *Griddler 2.5*, a finite-element-method (FEM) simulator that constructs a metallised solar cell model from a two-dimensional plan-view perspective. This is capable of delineating various recombination mechanisms from photoluminescence images, for instance the influence of metal-induced recombination in a solar cell. Contact us to learn more about our expertise in the development and use of these simulators to solve real-world solar cell problems.

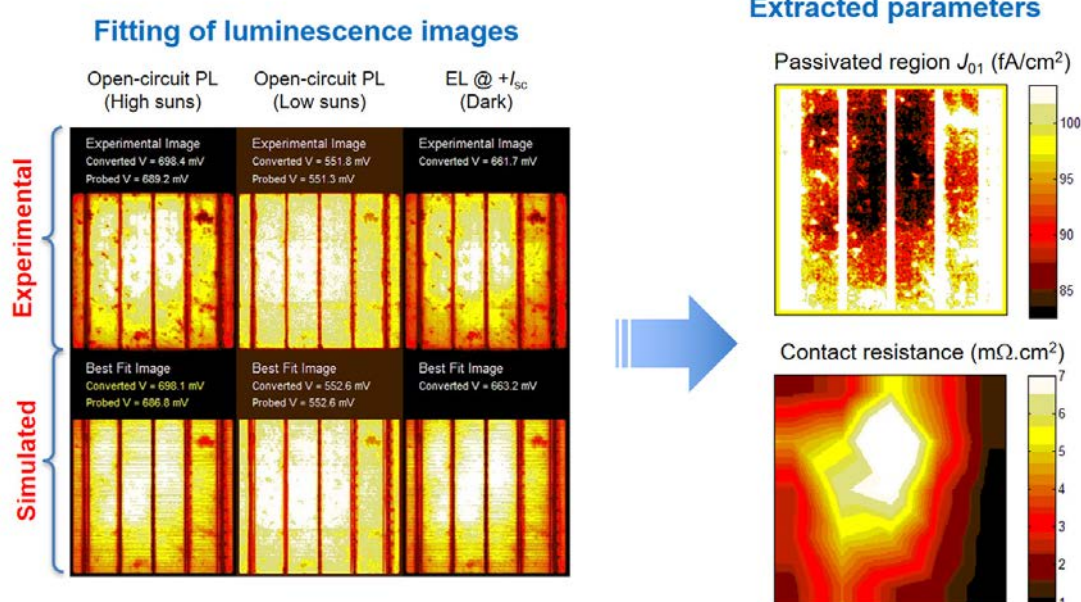


Two-dimensional front and rear plane representation of a solar cell in Griddler 2.5, showing the design of the metal grids, the finite element mesh in increasing detail, and the two-diode model associated with each section of the mesh. The large-area network representation by the software presents the capability to effectively model material and device spatial variations arising from the solar cell as well as incident illumination.

Solar Cell Doctor: Detailed health check for silicon solar cells

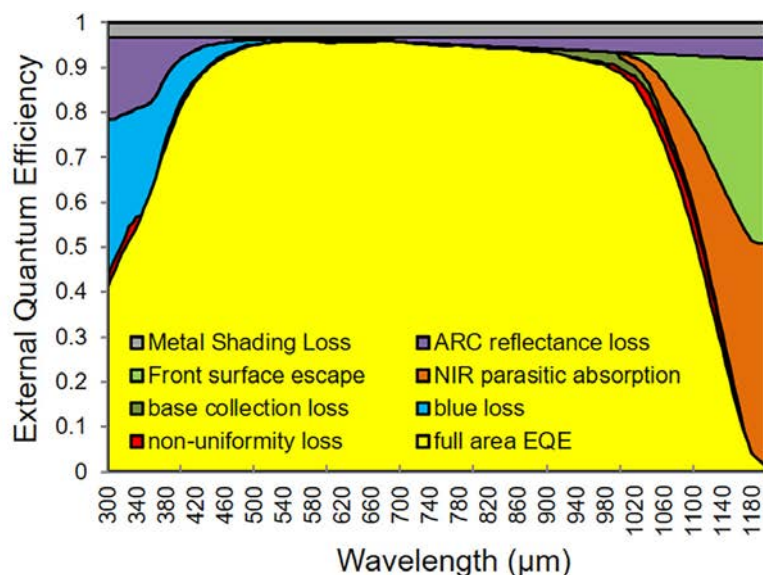
By combining solar cell characterisation methods with easy-to-make test structures and partially processed silicon solar cells from the production line, the *Solar Cell Doctor* loss analysis routine uses sophisticated computational methods to break down various cell loss mechanisms to generate process-related 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.

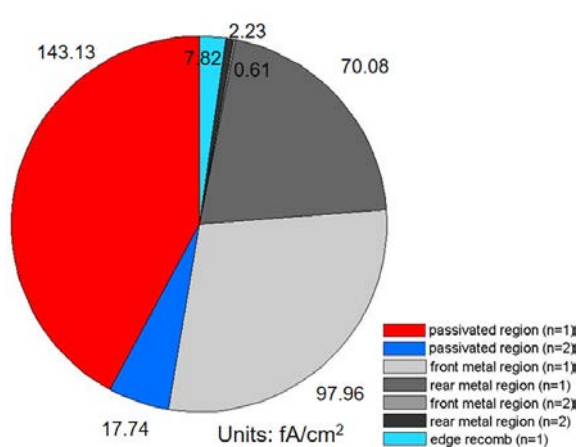
Current Loss Mechanisms



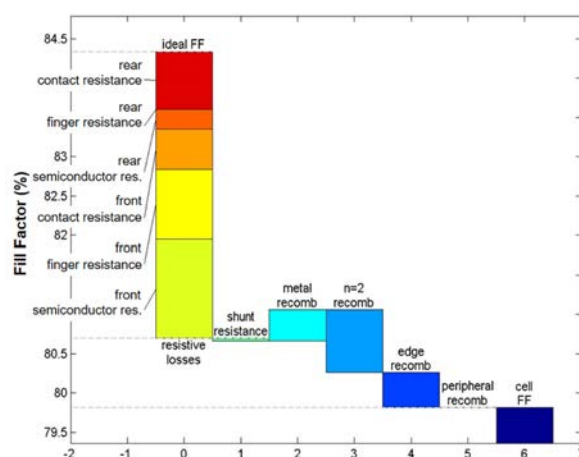
J_{sc} Breakdown (mA/cm ²)	
Cell Current	40.062
Base collection loss	0.314
NIR parasitic absorb	1.550
Front surface escape	1.287
ARC reflectance	0.977
Blue loss	0.464
Metal shading	1.567
Non-uniformity loss	0.207
WAR (300-1000nm) %	1.762
Base eff. diffusion length (μm)	3478

Elucidation of the short-circuit 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.

Equivalent J_{01} at V_{oc}

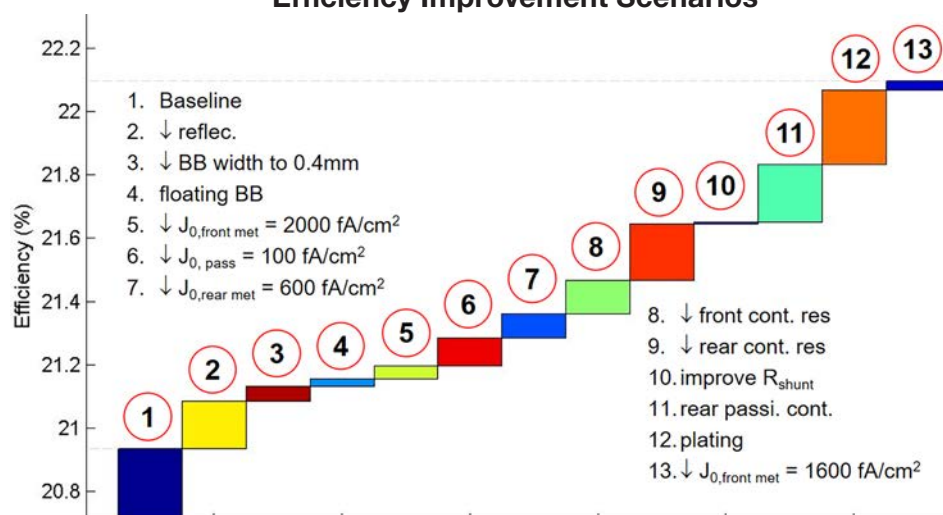


Fill Factor (FF) Drop Waterfall Diagram



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.

Efficiency Improvement Scenarios

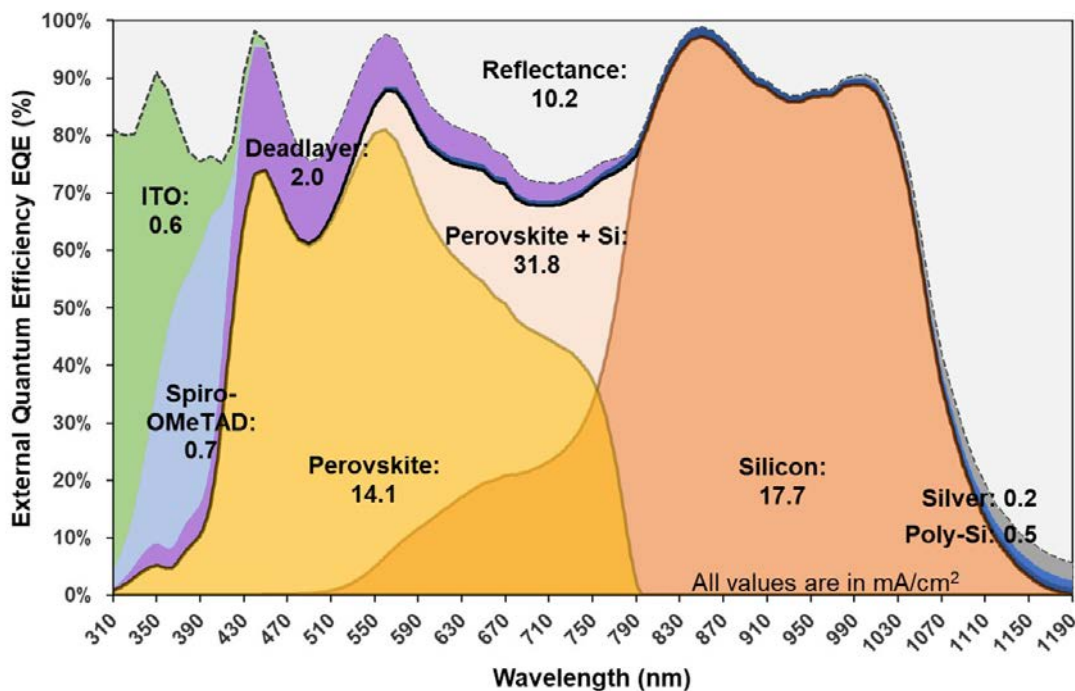


Griddler prediction of incremental silicon solar cell efficiency improvements due to specific process or cell design changes

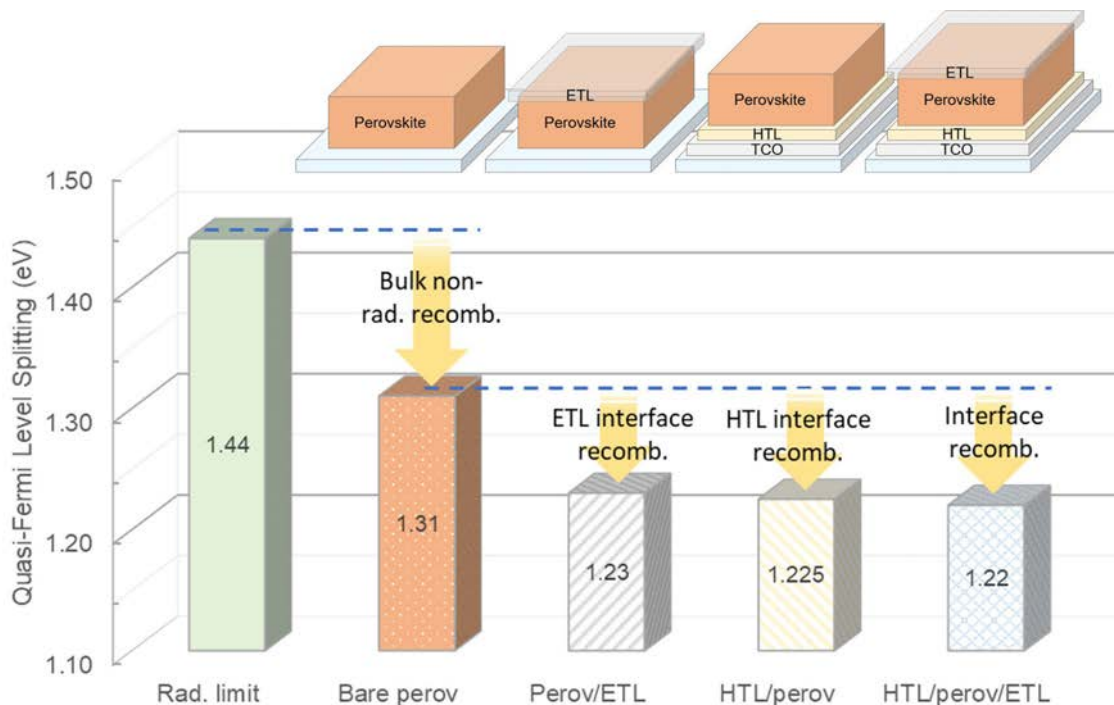
Analysis of next-generation solar cells

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-circuit 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.)

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DEVELOPMENT OF PV MODULES

SERIS operates a PV Module Development Laboratory where PV modules ranging from small single-cell modules for testing purposes up to full-size 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
- Design, customisation and development of PV-integrated building materials for building-integrated PV (BIPV) applications
- Solar cell cutting using thermal-laser separation (TLS)
- BIPV design, solar potential analysis, yield estimation and consultancy

Selected research activities currently conducted in the PV Module Development 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)
- Development of PV modules tailor-made for the tropical and hot climate
- Recycling of PV modules
- Comprehensive cell-to-module (CTM) power loss analysis

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

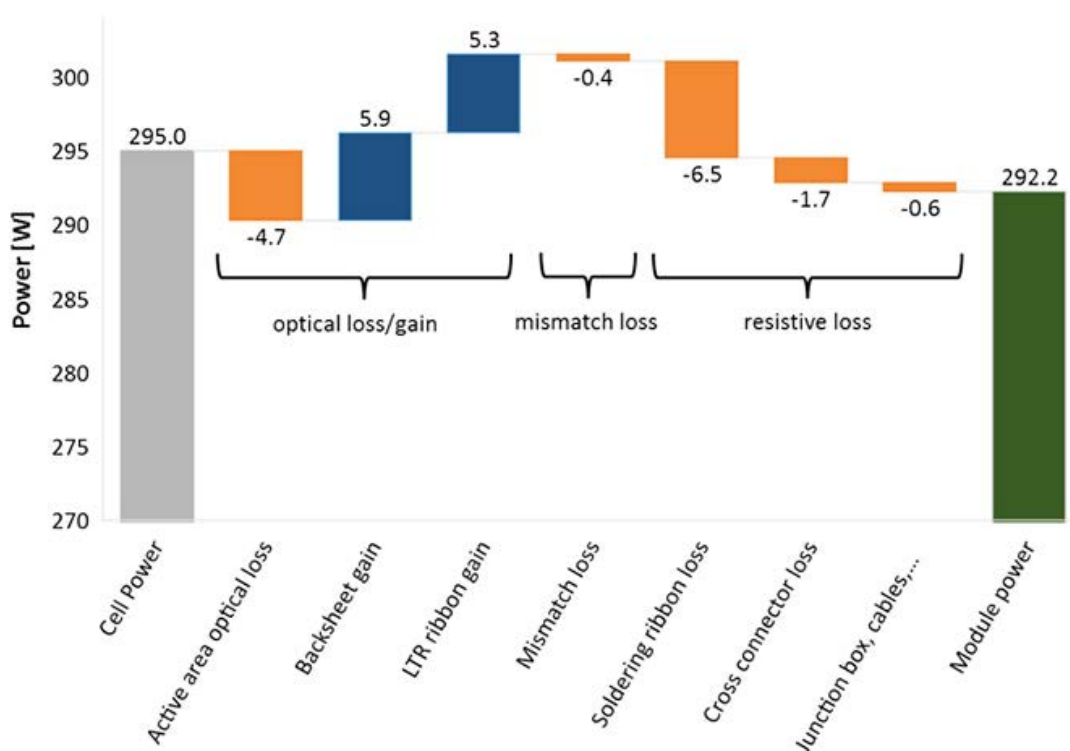
Quantify the light harvesting from inactive areas of a PV module (e.g. cell-gap area, ribbon) using EQE line-scans.

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

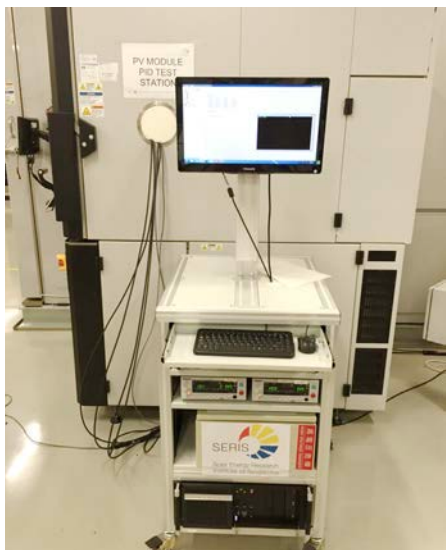
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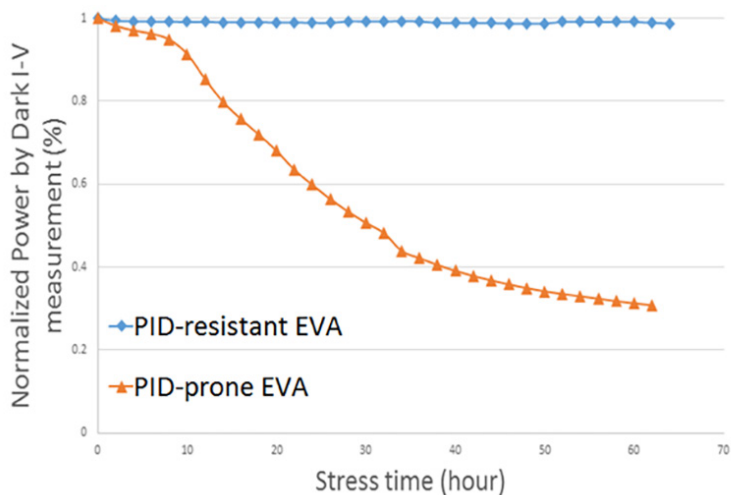


PID TESTING OF PV MODULES

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. For example, PID of PV modules can be continuously monitored *in-situ* using a SERIS developed dark I-V measurement chamber.



 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%. Thus, the conventional PID testing as per IEC 61215 (with 1000 or 1500 V bias voltage, 60°C and 85% relative humidity for 96 hours) 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.



 SERIS' Outdoor Module PID Test Facility

Both indoor and outdoor PID testing of PV modules are offered by SERIS as a service to the solar industry.

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CHARACTERISATION AND RELIABILITY OF PV MODULES

SERIS' ISO/IEC 17025 accredited PV Module Laboratory started its testing operations in 2010. Located in CleanTech Park, it has regularly embarked on equipment upgrades and system updates to remain relevant to the changing needs of the solar industry. In addition to the standard testing, research activities such as on Light and Elevated Temperature Induced Degradation (LETID) and measurement of the Incident Angle Modifier (IAM) enable the Laboratory to address specific concerns of the customers. 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 both industrial and research partners.

Secondary reference standards, temperature coefficients, and irradiance dependence

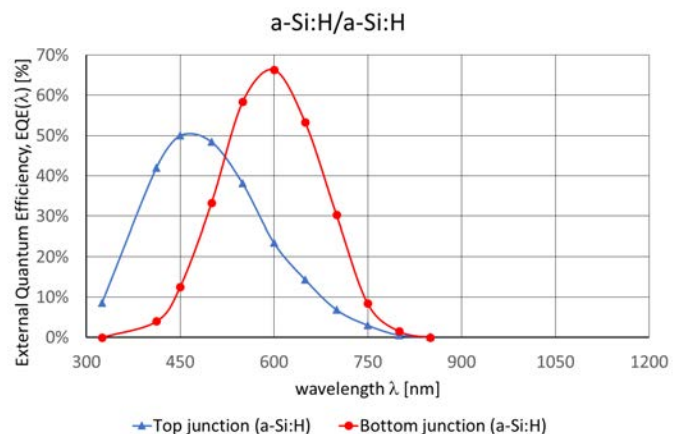
Equipped with two Class A+ large-area pulsed solar simulators, a 10-ms Pasan SunSim 3B and a 100-ms h.a.l.m. solar simulator, the Laboratory can characterise all types of commercially available modules at Standard Test Conditions (STC), including bifacial and heterojunction PV modules. This is particularly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

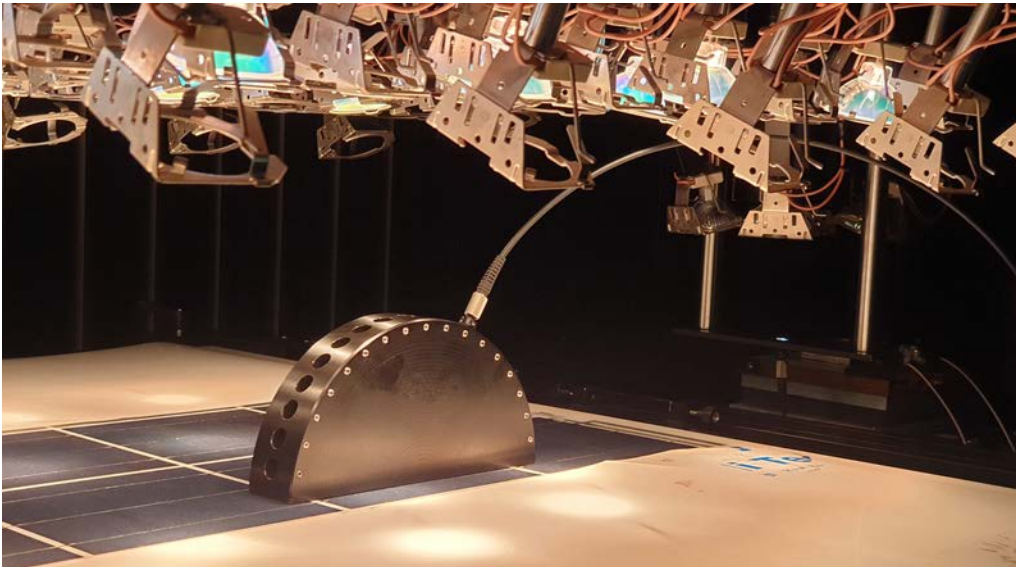
In view of the possible future revival of multi-junction terrestrial PV modules, and aligned with the new frontiers of research on perovskite-on-silicon tandem solar cells, SERIS' Laboratory is now equipped with an External Quantum Efficiency (EQE) measurement system for multi-junction modules, with 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, 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 experimental equipment to analyse the Incident Angle Modifier (IAM), both at mini-module level (in a tunnel solar simulator) and at full-size commercial module level, using a novel in-house developed measurement technology.



 Measurement equipment for IAM measurement at (left) full-size commercial module level and (right) at the 1-cell mini-module level.





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 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%, 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)
- Pyrliometer
- 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 in Marina Barrage, Singapore (tropical)



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



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



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



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PV SYSTEM 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 from initial yield estimations until the 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 verification	Project due diligence	Full project partnership
All "Optimised system design for high performance" services, plus: • Suitability of the key plant components • Detailed review of system design (mechanical, electrical up to medium voltage) and cross-check against current best industry practices <u>Optional:</u> • Review against given guidelines (statement of compliance)	All "third-party verification" services, plus detailed review of: • Track record of suppliers and 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 • Final acceptance • Operations and maintenance reviews • Analytical on-site monitoring with calibrated equipment <u>Optional:</u> • Sample testing of PV modules



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



Left: SERIS engineer performing on-site measurements during testing & commissioning.
Right: PV system installed on the roof of a HDB residential block in Singapore where SERIS performed various PV system quality assurance services.

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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. We provide highly reliable and scalable monitoring platform to accommodate multiple deployments in different regions across the world. Our monitoring capabilities have recently expanded beyond Singapore to 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. Singapore's Energy Market Authority (EMA)
- ± 150 ms time synchronisation with SERIS' time server

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



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



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



Contact person

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ON-SITE PV SYSTEM ASSESSMENTS

On-Site PV System Performance Testing and Commissioning

SERIS offers on-site PV system performance testing and commissioning services as a SAC-SINGLAS accredited laboratory. 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

Dr KAM Zhi Ming

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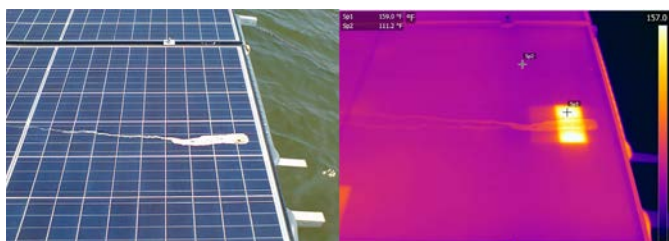


Thermographic Analysis of PV Systems

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 solar cells within a PV module (left image). Unusual thermal behaviour of module junction boxes can also be detected.

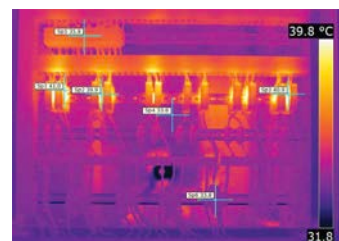
- DC and AC cable operating temperature measurements: Hotspots do not only occur in system parts that are exposed to sunlight, but may also be found within the wiring setup. Loose connectors and undersized cables can result in overheated parts (middle image). This lowers the PV system's power output.
- 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"). 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

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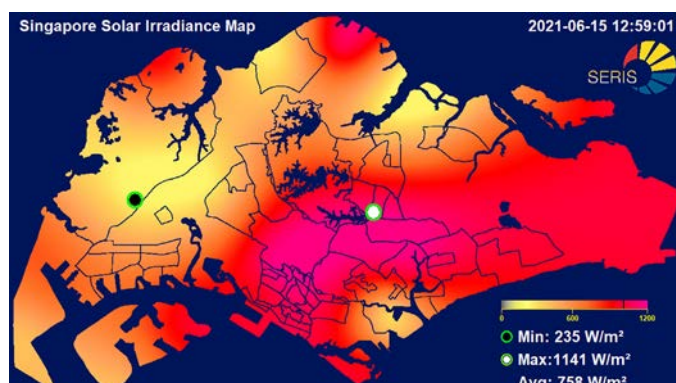
Real-Time Monitoring System of Irradiance

SERIS operates a network of 25 irradiance stations across Singapore on a ~5 km x 5 km grid, enabling a live solar irradiance map for Singapore based on irradiance measurements. The live irradiance map developed by SERIS can be seen at www.solar-repository.sg. A screen snapshot is shown here.

Parameters measured by SERIS at its fully equipped meteorological stations are:

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

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



 Snapshot of a typical irradiance distribution in Singapore

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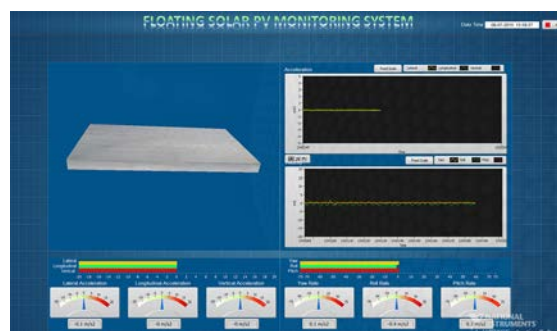
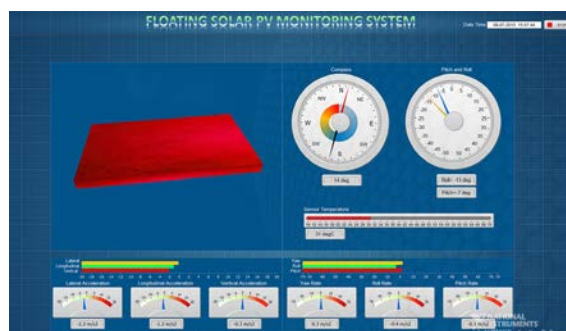
Six-Degree Freedom Motion Monitoring for Floating PV System Applications

One very fast-growing market segment in the solar industry is “Floating PV” on reservoirs, lakes, and other under-utilised water bodies. 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

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Glare Analysis of PV Installations

With increasing PV systems deployment, potential glare from the glass surface of modules has raised some concerns. Although PV modules are designed to reflect as little light 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 here.

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 – 32 locations
 - ii. Malaysia – 11 locations
 - iii. Cambodia – 1 location

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

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

 Table 1: Interactions with stakeholders in a typical glint and glare analysis (Example: Proposed installation near an airport).
* ATCT: Air Traffic Control Tower.

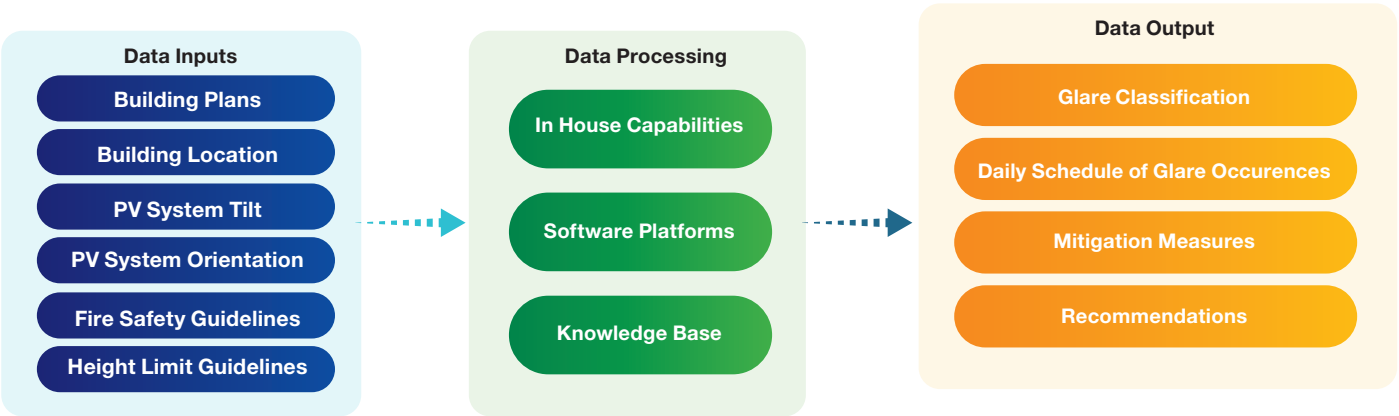


 Figure 1. Glare analysis framework at SERIS. Customised solutions can be designed to suit the needs of individual clients.



TESTING OF BUILDING ELEMENTS

Testing of building façade elements, including building-integrated PV (BIPV)

Façades account for almost 50% of the thermal load in buildings in the tropics and are related to many occupant comfort issues, such as visual comfort and thermal comfort. SERIS operates a well-equipped laboratory for testing of thermal and optical properties of building façade materials and assemblies, conducted according to the ASTM C1199, C1363, C1371, NFRC 300-2010, NFRC 301-2010 and DIN-5036-3 standards.

The laboratory provides the following services:

- Measurement of the solar and luminous properties of architectural glasses [visible light transmittance, solar heat gain coefficient (SHGC or g-value), shading coefficient (SC), U-value]
- Measurement of the emittance and solar reflectance of roof surface materials (e.g., paints, coatings, membranes) and calculation of the solar reflectance index (SRI)
- Measurement of the thermal insulation properties (U-value, R-value, thermal resistance, thermal conductivity) and the shading coefficient of building envelope materials and assemblies (e.g., windows, walls, insulating glazing units)
- Measurement of the visible light reflectance of façade materials (e.g. cladding panels)
- Calculation of the shading coefficient, visible light transmittance and U-value of window or door systems

In the area of façade technologies, our services for industry partners and opportunities for collaborative research include:

- Determination of solar and luminous properties of glazing systems
- Determination of the SHGC (or G-value), SC and U-value of fenestration and façade systems, including BIPV systems
- Other services such as cool roof material testing and insulation material testing



-  Calorimetric hot box (left part of left photo) with solar simulator (right part of left photo) for the measurement of the solar heat gain coefficient (SHGC). For U-value measurements, the solar simulator is switched off and a climate chamber (middle part of right photo) is put in front of the sample.

On-site testing of the air-tightness of buildings

In energy audits, the so-called “blower door” tests are used to determine a building’s air-tightness. Reasons for establishing a proper building air-tightness include:

- Avoiding unwanted heat gains through gaps in the building’s envelope
- Reducing additional energy consumption for cooling
- Preventing moisture condensation problems

In this test, a blower door with one or two powerful fans temporarily replaces an actual door of the building under test. The fan pulls air out of, or blows air into, the building, thereby lowering or increasing the air pressure inside. Airflow through existing gaps in the building will be induced due to the pressure differences. In combination with the use of a smoke pencil, air leaks can easily be detected. These tests measure the air infiltration rate of a building. They can also be used to measure airflows between building zones, to test ductwork air-tightness, and to localise air leakage sites in a building envelope. The blower door test is conducted according to the ASTM E-779, ATTMA and BS EN 13829:2001 standards.



-  Blower door measurement of a building’s air-tightness



Contact person

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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
- Building-integrated / building-attached PV (BIPV/BAPV)
- Floating Solar
- Feasibility studies
- Technical due diligences
- Solar potential assessment
- Pre-qualification for government programmes (e.g. Solar Nova)
- Manpower training





CUSTOMERS FEEDBACK



Fred. Olsen Renewables

“Fred. Olsen Renewables (FOR) is a developer, owner, and operator of renewable energy assets since the mid-1990s. FOR is part of the Fred. Olsen related companies which are based in Norway and listed on the Oslo Stock Exchange (under Bonheur ASA). The origin of these companies dates back to 1848, and the Fred. Olsen related companies have more than 170 years of global experience from shipping, marine engineering, offshore construction, offshore energy production, and renewable power production. Floating Solar Photovoltaics (FPV) is a strategic growth area in FOR, and we are taking a first-mover position as project developer, owner and operator in selected countries in Asia and Europe. By being the key industrial partner of SERIS in the flagship project on near- and offshore FPV, we are tapping into the many years of experience at SERIS in floating solar and the broad research capabilities at the institute. This enables us to move faster and better manage the risks in the first projects we engage. As such, the collaboration with SERIS is of great value to us, and it stimulates us to solidify our presence in Singapore.”

Mr Rolf Benjamin JOHANSEN
Director – Floating Solar
Fred. Olsen Renewables AS

maxeon

“Maxeon Solar Technologies is a global leader in solar innovation. The company designs and manufactures pioneering Maxeon® and SunPower® brand solar panels, including the highest efficiency commercially available silicon PV modules.

With its Headquarters in Singapore, Maxeon collaborates with the Solar Energy Research Institute of Singapore – SERIS - on various cutting-edge research and development topics.

For example, a test bed at Marina Barrage will be repowered with Maxeon solar technology to study the impact of high-performance modules on the LCOE of PV solar systems in a tropical and urban environment.

Maxeon and SERIS also collaborate on the research and development of high-efficiency, customised glass-glass photovoltaic modules. Maxeon is looking forward to further intensify research, development, and testing with SERIS on novel technologies and solar application contributing to global sustainable development and Powering Positive Change.”

Dr Thomas MUELLER
Director, RD&D
Maxeon Solar Technologies, Ltd.



SUNSEAP

“Sunseap Group is a solar energy systems developer, owner and operator based in Singapore with solar energy projects contracted across various sectors in Asia.

Sunseap’s collaboration with SERIS on HDB SolarNova 1 and HDB SolarNova 4 proved to be instrumental in the success of these projects. As a collaborative partner, the SERIS team exhibited a high level of proficiency and professionalism, and it was a great working experience.

SERIS’ foray into advanced technology has provided invaluable insight, meeting the needs of the industry. We look forward to the next time that we might have the pleasure of working with the SERIS team again.”

Mr Laurence KWAN
Director, Energy
Sunseap Group



Facts and Figures



AWARDS AND ACHIEVEMENTS

02 Aug 2021: SERIS is among one of the 34 departments / institutes in NUS to receive a "Commitment Award" from the NUS Safety & Health Award (NUSSHA) 2020 scheme. The NUSSHA scheme rewards and recognises Departments, Research Institutes/Centres and Administrative Offices for their achievements in safety and health management and performance.

06-10 Sep 2021: SERIS' PhD student Yuchi LAN, supervised by Assoc Prof Aaron DANNER of the Department of Electrical and Computer Engineering, NUS and SERIS researcher Dr YAN Xia wins a Poster Award at the 38th European PV Solar Energy Conference & Exhibition (EUPVSEC 2021). The poster "Towards ultra thin silicon solar cells for high specific power applications" was co-authored by Yuchi LAN, Maryknol DELOS SANTOS, Donny LAI, YAN XIA and Aaron DANNER.

MEDIA COVERAGE

01 Jan 2021: "Trial to import electricity from Malaysia a 'useful first step' as Singapore prepares to connect with regional grid: Experts", Channel News Asia

12 Jan 2021: "System design key to enhancing cooling effect of water in floating PV", PV Magazine

19 Jan 2021: "Fred Olsen Renewables and Ocean Sun kick off floating solar power project", Splash247.com

07 Feb 2021: "节能提供高素质生活放眼成为"绿色火花", Zaoobao news

22 Feb 2021: "Climate for Change" documentary, Channel News Asia

15 Mar 2021: "Climate Change: A wicked problem: Ep 3: Our power problem" documentary, Channel News Asia

03 Apr 2021: "Solar vision: Why it's not all sunshine and roses for Singapore's solar energy plans", Business Times

16 Apr 2021: "Land-starved Singapore gets creative with solar in clean energy push", Global Banking & Finance Review and in Thomson Reuters Foundation News

25 Apr 2021: "Singapore looks to off-shore floating solar farms to meet its green energy targets", CGTN news

29 Apr 2021: "Singapore's Solar Energy Push: Land-strapped Singapore turns to sea-based floating solar farms", CGTN news

30 Apr 2021: "The Bright Future of Floating Solar", NRF-RIE News, Apr 2021 issue

10 May 2021: "装机容量 12 年增加千倍寻找岛国空间留住太阳能", Zaoobao news

07 Jun 2021: "Floating up to standard" in PV Magazine issue 06 – 2021 Jun 2021 global edition

13 Jun 2021: "Test-bedding technologies crucial to accelerating solar deployment: Experts", Straits Times

19 Jun 2021: "The long read: Floating solar up to standard", PV Magazine-India.com

24 Jun 2021: "Innovative solutions to tackle the energy crisis", NUS news

08 Jul 2021: "Singapore's 60 MW floating PV array up and running", PV Magazine Australia

12 Jul 2021: "Climate experts confident S'pore public sector can achieve ambitious carbon emission goals", Straits Times

13 Jul 2021: "Experts confident public sector can meet ambitious emission goals", Straits Times

29 Jul 2021: Channel 8 "Hello Singapore" featuring interview with Dr Thomas Reindl on SERIS on Meteorology

15 Aug 2021: "PUB planning 2 more large-scale floating solar farms at reservoirs", Straits Times

23 Aug 2021: CNA documentary series "Tomorrow City – Sun" contains a segment featuring SERIS' solar forecasting work and SERIS' spin-off QE lab's drones technology

05 Sep 2021: "Solar power offers S'pore...A ray of Hope", Sunday Times

12 Sep 2021: CNA Kids series "Mind Blown"

27 Sep 2021: "The future of solar panels: A serious question for Southeast Asia", Southeast Asia Globe.com

11 Oct 2021: "Green Warriors: Dr Thomas Reindl on the nascent rise and immense potential of solar energy", Prestige Singapore, Oct 2021 issue

15 Oct 2021: "BIPV and its role in advocating and deploying Urban Solar" in Rays of Light, Expert's Opinion, SSX Morning Ray issue 570 Pro, 14 Oct 2021, Singapore Solar Exchange Pte Ltd

18 Oct 2021: Green Warrior and "Mr Floating Solar": Thomas Reindl, Innovators Research, NUS News

08 Nov 2021: "Where to Put Solar Panels? How About on the Water?" The Wall Street Journal

02 Dec 2021: "Project briefing – Tengeh floating solar farm", PV Tech Power vol. 29, pp. 62-64

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)
- Organic Electronics, Elsevier, The Netherlands (Prof Peter HO, Associate Editor)
- Journal of Renewable & Sustainable Energy, AIP, USA (Dr James Matthew BRIGHT, Associate Editor)
- Energies - Special Issue: Characterisation and Reliability of Photovoltaic Module for Hot Environments (Dr Mauro PRAVETTONI, Guest Editor)

Committees

- 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)
- Expert Committee of the 1000Solutions project launched by the World Alliance for Efficient Solutions and Shanghai Green Energy Innovation Centre (Prof Armin ABERLE, member)
- International Advisory Committee of the Institut Photovoltaïque 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)
- International Advisory Committee of the AFORE2021 (Asia-Pacific Forum on Renewable Energy) (Prof Armin ABERLE, member)
- Technology expert for International Technology Roadmap for Photovoltaics (ITRPV) (Prof Armin ABERLE) <https://itrpv.vdma.org/viewer/-/v2article/render/29019617>
- International Scientific Committee of SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 15th Global Advanced PV Technology Conference (Prof Armin ABERLE, Chairman; Dr Thomas REINDL, Dr WANG Yan, Dr Abhishek KUMAR, Dr Mauro PRAVETTONI, members)
- Organising Committee of the SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 15th Global Advanced PV Technology Conference (Prof Armin ABERLE, Chairman)
- Reviewing Committee of the 11th International Conference on Crystalline Silicon Photovoltaics (SiliconPV 2021) (Dr LIN Fen, Dr KHOO Yong Sheng, member)
- Final Evaluation Committee of the Technology Enterprise Commercialisation Programme (TECS), Spring Singapore (Dr Thomas REINDL, member)
- Scientific Advisory Committee - State Key Lab of PV Technology (Trina Solar), Changzhou, P.R. China (Dr Thomas REINDL, member)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 14 (Dr Thomas REINDL, invited attendee)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 15 (Dr Thomas REINDL, Dr Veronika SHABUNKO, invited attendees)
- International Energy Implementing Agreement on Photovoltaic Power Systems, IEA-PVPS Task 16 (Dr Thomas REINDL, invited attendee)
- International Electrotechnical Commission (IEC) Technical Committee (TC) 82 ("Solar Photovoltaic Energy Systems"), (Dr Thomas REINDL, Dr WANG Yan until March 2021, and Dr Mauro PRAVETTONI, Singapore representatives; Dr Veronika SHABUNKO and Dr Jian Wei HO, as observers)
- National IEC Mirror Committee TC 1 WG10 ("Solar PV Product & Accessories"), Enterprise Singapore (Dr WANG Yan until March 2021, co-convenor; Dr Mauro PRAVETTONI since April 2021, co-convenor; Dr Jian Wei HO, member)
- National IEC Mirror Committee TC 3 WG6 ("Solar PV Systems"), Enterprise Singapore (Dr Thomas REINDL, co-convenor)
- Evaluation Committee of the 2022 Initiation into Research FONDECYT project competition, FONDECYT (Fondo Nacional de Desarrollo Científico y Tecnológico - the National Fund for Scientific and Technological Development of Chile)(Dr Mauro PRAVETTONI, evaluator)
- International PV Quality Assurance Task Force (PVQAT), Task Group 3 (Humidity, Temperature, and Voltage) (Dr WANG Yan, member)
- Clean Energy Committee of the Sustainable Energy Association of Singapore (Eddy BLOKKEN, Dr Veronika SHABUNKO)
- Energy Efficiency and Finance Committee of the Sustainable Energy Association of Singapore (Dr Veronika SHABUNKO, member)
- Working group for establishment of relevant national regulations and acceptable standards for innovative BIPV product in Singapore with governmental and regulatory bodies - SCDF, BCA, SGBC, NEA, HDB, NCCS, EDB, PMO (Dr Veronika SHABUNKO, Scientific Lead)
- International Building Performance Simulation Association (IBPSA) Singapore Chapter (Dr Veronika SHABUNKO, member)
- IEC Technical Committee TC82 /PT 63092 on establishment of the standards for BIPV module and system level (Dr Veronika SHABUNKO, invited attendee & observer since 2019)
- Institution of Engineers of Singapore (IES) (Dr Veronika SHABUNKO, member)
- "BAPV Review" working group organized by SCDF, Singapore (Dr Veronika SHABUNKO, member)
- Greenhouse Gas (GHG) Management Institute (Dr Veronika SHABUNKO, member)
- Chartered Banker Institute (CBI) Institute (Dr Veronika SHABUNKO, member)
- Global Association of Risk Professionals (GARP) (Dr Veronika SHABUNKO, member)
- Energy Efficiency, Clean Energy Committee, and Sustainable Infrastructure Committee of the Sustainable Energy Association of Singapore (SEAS) (Dr Veronika SHABUNKO, member)
- IEC Technical Committee TC82/PT 63092 on establishment of the standards for BIPV module and system level (invited attendee & observer since 2019)(Dr Veronika SHABUNKO, member)
- IEA PVPS Task 15 on "Enabling Framework for the Development of BIPV" (Observer and activity leader, since 2016)(Dr Veronika SHABUNKO, member)
- European Metrology Programme, EURAMET2021, Green Deal Virtual Review Conference, 24-25 Nov 2021 (Dr Mauro PRAVETTONI, invited referee)
- Task 13 Performance, Operation and Reliability of Photovoltaic Systems, of the Photovoltaic Power Systems Programme (PVPS) at the International Energy Agency (IEA) (Dr Wei LUO, member)

SERIS MEMBERSHIPS / PARTNERSHIPS

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

OUTREACH ACTIVITIES

09 Mar 2021	Talk by Dr Stephen TAY at Zhonghua Primary School (by Zoom)
12 Mar 2021	Talk by Dr Stephen TAY at Kuo Chuan Presbyterian Primary School (by Zoom)
20 Apr 2021	Talk by Eddy BLOKKEN at Raffles Girls School (Secondary) Earth Day
24 Apr 2021	Talk by Prof Armin ABERLE at the 09th EdukCircle International Convention on Engineering and Computer Technology, Philippines (by Zoom)
29 May 2021	Talk by Dr Thomas REINDL at the Symposium on Futures Sustainability 2021, organised by the NUS Bachelor of Environmental Studies (BES) Student Committee (by Zoom)
16 Jul 2021	Dr Thomas REINDL as one of the Resource Persons/ Experts at the NUS-NYC Singapore Green Plan 2030 Youth Conversation (by Zoom)
19 Jul 2021	Dr Carlos RODRÍGUEZ, interviewed by a group of students from Jurong Pioneer Junior College for their 2021 A Level Project Work
Jul 2021	Dr Mauro PRAVETTONI, provided e-consultations (via email and google meet) for 3 groups of students from Jurong Pioneer Junior College for their 2021 A Level Project Work
11 Aug 2021	Launch of Energy Story Exhibition at Singapore Science Centre (participant)
01 Nov 2021	Talk by Dr Donny LAI to a group of students at Singapore Management University on climate change issues and clean energy technologies (by Zoom)
15 Nov 2021	Participated in the production of a video on "Energy Efficiency in the Hospitality Industry". This video is part of the German government's commitments under the Paris Climate Accord (Dr Veronika SHABUNKO)
23 Nov 2021	E-learning Expedition for TOTAL staff, via a webinar session (SERIS speakers: Dr Carlos RODRÍGUEZ and Dr Veronika SHABUNKO; Moderator: Eddy BLOKKEN)
21 Dec 2021	Talk by Dr LEOW Shin Woei organised by the National Library Board, Singapore (by Zoom)

CONFERENCES / EXHIBITIONS / SEMINARS / WEBINARS / WORKSHOPS ORGANISED / CO-ORGANISED BY SERIS

18 Jan 2021	Webinar on Myanmar floating solar, co-organised with Infrastructure Asia "Technical design and key bankability considerations"
02-05 Jun 2021	SNEC 15th (2021) International Photovoltaic (PV) Power Generation and Smart Energy Exhibition & Conference, China
08 Sep 2021	Technical Webinar on "Solar Potential in Singapore: Accelerating Deployment for Decarbonisation of the Energy Sector" for industry, government agencies and engineers/professionals. Dr Veronika SHABUNKO, co-organiser and speaker for Solar Energy Research Institute of Singapore (SERIS)
26-29 Oct 2021	Asia Clean Energy Summit (ACES 2021), Singapore

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), AY20/21, Semester 2, National University of Singapore (NUS)

Prof Armin ABERLE, for Electrical and Computer Engineering Module EE4438 Solar Cells and Modules, AY20/21 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), AY21/22, Semester 1, National University of Singapore (NUS)

Dr Thomas REINDL. Lecture on "Floating Solar Technology (L11)", invitation by TU Delft. Annual Summer School programme for the PV System Summer School (PVSSS) 2021, 08 Jul 2021 (virtual)

Dr Veronika SHABUNKO. Guest Lecturer for 2-days course programme "Solar Architecture" for Green Mark Advanced Accredited Professionals and Facilities Management, approved by Building Construction Authority Academy (BCAA), Singapore, 30-31 Mar 2021.

Dr Veronika SHABUNKO. Guest Lecturer for Department of Architecture, School of Design and Environment, module AR2723 "Strategies of Sustainable Architecture", invited by A/Prof Yuan CHAO at the National University of Singapore, 16 Apr 2021

Dr Rolf STANGL, 4 guest lectures on "Thermodynamic limits, advanced solar cell characterisation and loss analysis", ECE 484/584 Photovoltaics, invitation by Prof Tito Busani from University of New Mexico, USA, 12/14 Apr 2021 (virtual)

PATENT APPLICATIONS IN 2021

Yong Sheng Khoo, Yan Wang, Min Hsian Saw, Kong Fai Tai. Building-integrated photovoltaic (BIPV) modules that emulate building materials. PCT/SG2021/050073 filed (11 Feb 2021)

Maung Thway, Serena Lin Fen, Rolf Stangl, Ho Jian Wei. Rapid energy yield estimation measurement methodology for solar cells and modules. PCT/SG2021/050140 filed (17 Mar 2021)

Jiancheng Donny Lai, Ying Huang. Time-efficient laser ablation geometry and pattern for manufacturing a solar cell with local back contacts. Nationalised PCT, India, 202117011332 (17 Mar 2021)

Pradeep Padhamnath, Shubham Duttgupta. Method for fabricating solar cells with carrier selective contacts. Non-provisional, Singapore, 10202103200Y (29 Mar 2021)

Mauro Pravettoni. Solar testing dome for electrical characterisation of solar photovoltaic modules. Non-provisional, Singapore, 10202103889R (15 Apr 2021)

Muhammad Arifeen Wahed, Thomas Reindl. A Floating apparatus, and a method of operating the floating apparatus. PCT/SG2021/050334 (10 Jun 2021)

Ho Jian Wei, Chan Keng Siew, Xin Zheng, Heng Min Xuan Clarence. Machine learning accelerated extraction of diffusion and surface passivation parameters from finished solar cells. Non-provisional, Singapore, 10202108206Q (27 Jul 2021)

Jeremie Werner, Nitin Nampalli, Shubham Duttgupta. Method of inline manufacturing semiconductor devices and semiconductor devices thereof. Non-provisional, Singapore, 10202109092W (19 Aug 2021)

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Saw Min Hsian, Srinath Nalluri, Tai Kong Fai, Pravettoni Mauro, Khoo Yong Sheng. Design principles for multi-coloured and patterned photovoltaic (PV) modules. Non-provisional Singapore, 10202111422S (14 Oct 2021)

Rolf Stangl, Thway Maung, Ling Zhipeng, Ng Xin Ren, Fen Lin. Double-side passivated contact solar cell, deploying a tunnel junction, suited as bottom cell for thin-film on silicon tandem integration, and process to realise such solar cell, China national filing in progress (Oct 2021)

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PUBLICATIONS

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Synthetic Solar Irradiance: Modeling Solar Data, edited by Jamie M. Bright [AIP Publishing (online), Melville, New York, 2021], available at: <https://doi.org/10.1063/9780735421820>

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.; “Chapter 2: Main Requirements for Solar Cells” for a book “Silicon Solar Cell Metallisation and Module Technology” which is in at the final editing stage with IET (in prep)

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, IET (in press)

Journal papers

Balaji, N., Lai, D., Shanmugam, V., Basu, P.K., Khanna, A., Duttagupta, S., Aberle, A.G. Pathways for efficiency improvements of industrial PERC silicon solar cells. *Solar Energy*, vol. 214, pp. 101-109 (2021), <https://doi.org/10.1016/j.solener.2020.11.025>

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Yan, X., Suhaimi, F., Xu, M., Yang, J., Zhang, X., Qi Wang, Q., Jin, H., Duttagupta, S. Process development and integration of double-side Poly-Si passivated solar cells with printed contacts via LPCVD and ex-situ tube diffusion. *Solar Energy Materials & Solar Cells* 230 (2021) 111249, <https://doi.org/10.1016/j.solmat.2021.111249>

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Zhao, X., Tan, H.Q., Birgersson, E., Xue, H. Elucidating the underlying physics in a two-terminal all-perovskite tandem solar cell: A guideline towards 30% power conversion efficiency. *Solar Energy* 231, pp. 716-731 (2022)(online 17 Dec 2021)

Conference papers

Bright, J.M., Sun, X. Statistical satellite-derived irradiance estimation: A case study in Singapore. 48th IEEE Photovoltaic Specialists Conference (PVSC 48), 20-25 Jun 2021

Foo, A.Y., Saw, M.H., Khoo, Y.S., Tay, S.E.R. Developing a methodology towards designing aesthetic BIPV modules. 48th IEEE Photovoltaic Specialists Conference (PVSC 48), 20-25 Jun 2021

Lan, Y., Santos, M.D., Lai, D., Yan, X., Danner, A. Towards ultra-thin silicon solar cells for high specific power applications. Proc. of 38th European PV Solar Energy Conference & Exhibition (EUPVSEC 2021), 06-10 Sep 2021

TALKS AT CONFERENCES, WORKSHOPS AND SEMINARS

(Speaker's name underlined)

Paton, C. Global and regional market trends for FPV. Webinar on Myanmar floating solar, co-organised with Infrastructure Asia "Technical design and key bankability considerations", 18 Jan 2021 (invited)

Kumar, A. Key technical consideration for floating PV systems. Webinar on Myanmar floating solar, co-organised with Infrastructure Asia "Technical design and key bankability considerations", 18 Jan 2021 (invited)

Kumar, A., Luo, W., Reindl, T. Performance loss rates of floating PV systems in the tropics. NREL 2021 Photovoltaic Reliability Workshop (PVRW), 24 Feb 2021 (virtual) (invited)

Hou, Y. Textured Perovskites/Si Tandem Solar Cells: from lab to fab? nanoGe Spring Conference, 08-12 Mar 2021 (virtual) (invited speaker and Conference Chair)

Pravettoni, M. PV technologies issues with temperature coefficients and spectral mismatch. 9th PV-Outdoor-Spectral Measurement Mini Workshop, AIT Austrian Institute of Technology GmbH, Austria, 15-16 Mar 2021 (virtual) (invited)

Yan, X., Nandakumar, N., Duttagupta, S. Progress with SERIS monoPoly™ solar cell technology. 1st TOPCON Forum. Development of TOPCON cell technology and equipment innovation, 16 Apr 2021 (virtual) (invited)

Aberle, A. Status of solar electricity. 9th EdukCircle International Convention on Engineering and Computer Technology, Philippines, 24 Apr 2021 (virtual)(invited)

Reindl, T. Performance and reliability of floating PV systems. Workshop PV Days in Brazil. Live Broadcast YouTube Channel: Fotovoltaica UFSC, 28 Apr 2021 (virtual) (invited)

Vinayagam, L. Cable reliability considerations and electrical issues in Floating solar – experiences from 5 years' of operation of the FPV testbed in Singapore. PV magazine Webinar, 28 Apr 2021 (invited)

Paton, C. Global market trends of floating solar. International Green Energy Conference - PVMI 2021, South Korea, 28-29 Apr 2021 (virtual) (invited)

Reindl, T. Fire-side chat for the opening of SolarDuck's launch event for their off-shore Floating PV platform, 30 Apr 2021 (virtual) (invited)

Tan, H.Q., Zhao X., Birgersson, E., Lin, F., Xue, H. Optoelectronic modeling and sensitivity analysis of a four-terminal all-perovskite tandem solar cell – identifying pathways to improve efficiency. Virtual Global Renewable Energy Researchers Meet, 07-08 May 2021 (virtual) (invited)

Reindl, T. Status and trends in solar energy. 2021 Fred. Olsen Summit, 20 May 2021 (virtual) (invited)

Reindl, T. Techno-economic road-mapping and the reliable integration of renewable energies into power systems. IEEE ECCE Asia 2021, 24-26 May 2021 (virtual)(invited plenary)

Reindl, T. Outlook for solar PV in Singapore. NUS BES, Symposium on Future Sustainability, 29 May 2021 (virtual)(invited speaker / panellist)

Aberle, A. Chairman welcome speech at the SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 02 Jun 2021, China (virtual) (invited)

Pravettoni, M. Correlation between temperature coefficients and spectral responsivity: an overview. 15th Global Advanced PV Technology Conference, at the SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 03 Jun 2021, China (virtual) (invited)

Reindl, T. Global market trends and standards in floating solar. 15th Global Advanced PV Technology Conference, at the SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 03 Jun 2021, China (virtual) (invited)

Wang, D. The PV DOCTOR™ (a SERIS spin-off company): Comprehensive service offerings to detect, analyse and rectify under-performing PV systems. 15th Global Advanced PV Technology Conference, at the SNEC 15th (2021) International Photovoltaic Power Generation and Smart Energy Conference & Exhibition (SNEC2021), 04 Jun 2021, China (virtual) (invited)

Bright, J.M., Sun, X. Improving statistical satellite-derived irradiance estimates: A case study in Singapore. 48th IEEE Photovoltaic Specialists Conference (PVSC 48), 20-25 Jun 2021 (virtual)

Reindl, T. Floating Solar: The 3rd pillar of the PV industry. DEWA "CleanTech Connect" Expert Series. Webinar organised by the Dubai Electricity & Water Authority (DEWA) and the Dubai Solar Innovation Centre, Dubai, 24 Jun 2021 (invited)

Reindl, T. Floating Solar PV: Technology, cost trends and lessons learned from Singapore's pilot project. Renewable Energy Policy and Development Forum, jointly organised by the Ministry of Energy (ME) and Universiti Brunei Darussalam (UBD) through the Energy and Environmental Policy and Management Cluster of the Institute of Policy Studies (IPS), 29 Jun 2021 (virtual) (invited)

Shabunko, V. Towards low carbon technologies: urban solar applications. renewable energy policy and development forum, jointly organised by the Ministry of Energy (ME) and Universiti Brunei Darussalam (UBD) through the Energy and Environmental Policy and Management Cluster of the Institute of Policy Studies (IPS), 29 Jun 2021 (virtual) (invited)

Hou, Y. Textured perovskite/Si tandem solar cell. Materials Research Society of Singapore (MRS-S), Singapore, 06-09 Jul 2021 (virtual) (invited)

Reindl, T. Hybrids of floating solar with hydropower. SOLAR-HYDRO Conference, UK, 08 Jul 2021 (virtual) (invited)

Reindl, T. Floating Solar Technology (L11). PVSSS-21, The Netherlands, 09 July 2021 (virtual) (invited)

Shabunko, V. Solar PV potential in Singapore: Accelerating deployment for decarbonisation of the energy sector. Institution of Engineers Singapore (IES)-SERIS joint seminar, 24 Aug 2021 (virtual) (invited)

Pravettoni, M. Solar technologies roadmap: materials, applications and reliability for urban areas in the Tropical region. SMF-SPECS workshop, 27 Aug 2021 (invited speaker / panellist)

Shabunko, V. Solar PV potential in Singapore: Accelerating deployment for decarbonisation of the energy sector. IES- SERIS Joint Technical Seminar, 08 Sep 2021, Singapore (invited)

Xue, H., Stangl, R., Birgersson, E. Elucidating the recombination losses in perovskite-based solar cells: A scaling analysis. 3rd Virtual Congress on Materials Science and Engineering, 27 Sep – 01 Oct 2021, USA (virtual)

Padhamnath, P., Nandakumar, N., Yan, X., Nampalli, N., Rodriguez, J., Aberle, A., Duttagupta, S. Advances in screen-printed metallisation of SERIS' monoPoly™ technology. 7th TOPCon and PERC+ Forum, 28 Sep 2021, China (online)(invited keynote speech)

Aberle, A. Strategising PV in SEA – next chapter. Solar International Dialogue of South East Asia. Global Solar Council, 13 Oct 2021 (virtual)(invited panellist)

Reindl, T. Status and trends in floating solar. 2021 East Asia Summit - New Energy Forum, China, 20 Oct 2021 (virtual)(invited panellist)

Reindl, T. Floating Solar: Status, trends and how to grow the community. Solar World Congress 2021, 27 Oct 2021 (virtual) (invited keynote)

Reindl, T. Official Launch of the “International Floating Solar Society” (IFS²). Asia Clean Energy Summit Conference and Exhibition, 28 Oct 2021

Shabunko, V. Invited panellist for the talk jointly organised by CAPE and Energy TC on “Energy and Chemical Landscape”, 29 Oct 2021 (virtual) (invited).

Hou, Y. Perovskite-based tandem solar cells. 4th World Laureates Forum, China, 03 Nov 2021 (virtual)(invited)

Padhamnath, P., Nampalli, N., Werner, J., Aberle, A.G., Duttagupta, S. Modelling of contact resistivity of fire-through Ag-Al contacts to B-doped polysilicon layers. 10th Metallisation and Interconnection Workshop, Belgium, 16 Nov 2021 (virtual)

Vinayagam, L. Then and Now of the “Small Brother” of Sembcorp's 60 MW_p System. Sembcorp Suppliers Appreciation Day 2021, Singapore, 18 Nov 2021 (invited)

Padhamnath, P., Nandakumar, N., Aberle, A., Duttagupta, S. Metallisation of “monoPoly™” passivated contact silicon solar cells. 17th CSPV, China, 18-20 Nov 2021 (virtual)(invited)

Pravettoni, M. Smart sustainable energy systems in desert climates. International Conference on Sustainable Energy- Water-Environment Nexus in Desert Climate 2021 (ICSEWEN21), Doha, 22-25 Nov 2021, (virtual)(invited panellist)

Rodriguez, C. Floating PV: Local and global status. Virtual Learning Expedition for TOTAL Energies, 23 Nov 2021 (virtual) (invited speaker / panellist)

Shabunko, V. Towards low carbon technologies: urban solar applications. Virtual Learning Expedition for TOTAL Energies, 23 Nov 2021 (virtual) (invited)

Lin, F. Scientific perspectives towards industrially viable solutions for perovskite/Si tandem solar cells. The 3rd Global Perovskite & Tandem Cell Industrialisation Forum, China, 05-07 Dec 2021 (virtual) (invited)

Reindl, T. Policy and Implementation of RE Development in Singapore. Carbon Neutrality Task Force - Renewable Energy Development, Government of Hong Kong, 06 Dec 2021 (workshop)(virtual)(invited)

Reindl, T. Solar technology & BIPV. Innovation Xchange, CapitaLand, Singapore, 09 Dec 2021 (seminar)(invited)

Reindl, T. 100% Renewable Energy scenario. Where should all the solar panel go? 100% Renewable Energy session at the 31st International Photovoltaic Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)(invited plenary speaker & panellist)

Abdul Aziz, M.N., Saw, M.H., Tay, S., Pravettoni, M. A novel approach for the measurement of the incident angle modifier at the module level. 31st International PV Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

Pravettoni, M. Module reliability in tropical Asia: three case studies. 31st International PV Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

Nandakumar, N., Padhamnath, P., Duttagupta, S. Large-area monoPoly™ cells on 110 μm c-Si wafers with efficiency approaching 24%. 31st International Photovoltaic Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

Rajput, A.S., Wan, L., Pravettoni, M. Estimation of individual solar cell electrical performance parameters using statistical analysis of electroluminescence images for silicon photovoltaic modules. 31st International PV Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

Saw, M.H., Tai, K.F., Pravettoni, M. Analysis of spectral effects on the performance of various coloured BIPV modules at different locations. 31st International PV Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

Leow, S.W. Singapore's transition to clean energy. Public talk jointly organised by the National Library Board and Ridge View Residential College (NUS), Singapore, 21 Dec 2021 (virtual)(invited)

POSTERS AT CONFERENCES AND SEMINARS

(Presenter's name underlined)

Foo, A.Y., Saw, M.H., Khoo, Y.S., Tay, S.E.R. Developing a methodology towards designing aesthetical BIPV modules. 48th IEEE Photovoltaic Specialists Conference (PVSC 48), 20-25 Jun 2021 (virtual)

Reindl, T., Srinivasan, D., Salinas Cortijo, S.V., Kong, X., Chia, Z. Operational solar power forecasting for safe and reliable photovoltaic grid integration in Singapore. Energy Innovation 2021, 23 Jul 2021 (virtual)

Lan, Y., Santos, M.D., Donny Lai, D., Yan, X., Danner, A. Towards ultra-thin silicon solar cells for high specific power applications. 38th European PV Solar Energy Conference & Exhibition (EUPVSEC 2021), 06-10 Sep 2021 (virtual)

Nakka, L., Aberle, A., Lin, F. Effect of overnight oxidation on the performance of Co(III) doped spiro-OMeTAD based perovskite solar cells. 31st International Photovoltaic Science and Engineering Conference (PVSEC-31), Australia, 13-15 Dec 2021 (virtual)

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