Reliability of modules in floating photovoltaics: stresses, severities and tests

Mauro Pravettoni, SERIS, National University of Singapore
SPREE Talk, UNSW, Sydney, 1 November 2023

Fred.Olsen Renewables

DNV

NATIONAL RESEARCH FOUNDATION
PRIME MINISTER'S OFFICE
SINGAPORE

ENERGY MARKET AUTHORITY
Smart Energy, Sustainable Future

EDB SINGAPORE

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

SERIS

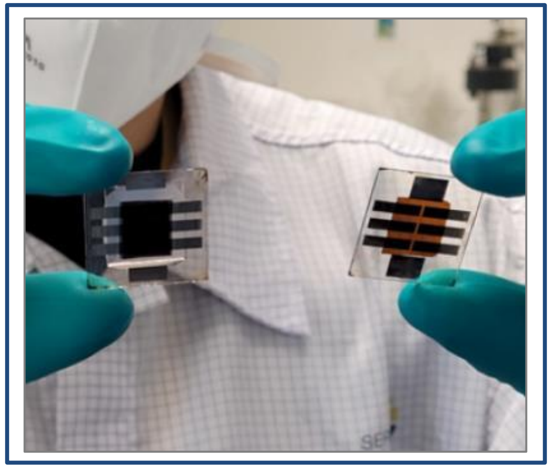
Solar Energy Research Institute of Singapore

- National Lab founded at NUS in 2008; supported by NUS, NRF, EMA & EDB
- Focuses on applied solar energy research (solar cells, PV modules, PV systems)
- ~120 staff & PhD students; state-of-the-art labs, ISO certified (9001, 17025)
- Close collaborations with companies & government agencies

SERIS' main R&D facilities at NUS E3A building

SERIS' off-campus facility – PV module testing and BIPV research at CleanTech One

Main R&D areas of SERIS



Solar cells:

- Perovskite/silicon tandem solar cells
- Next-generation industrial solar cells
- Characterisation & simulation

PV modules:

- **Module testing (indoor & outdoor)**
- Module development
- Building integrated PV (BIPV)
- Characterisation of optical properties
- **Module reliability**
- Recycling
- PV for vehicles (VIPV)

Solar PV systems:

- **System technologies, incl. Floating solar**
- Innovative deployment concepts
- Urban Solar, incl. agrivoltaics
- PV grid integration
- Solar potential & energy meteorology (solar forecasting)
- Quality assurance of PV systems
- Solarisation of Singapore

SERIS' Flagship projects

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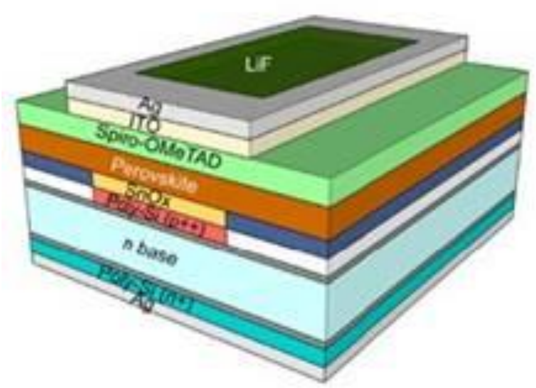
Thin-film on silicon tandem solar cells

- ❑ Goal: > 30% efficient silicon based tandem solar cells
- ❑ Top cell: Perovskite
- ❑ Bottom cell: Silicon



Building-Integrated PV (BIPV)

BIPV Innovations:

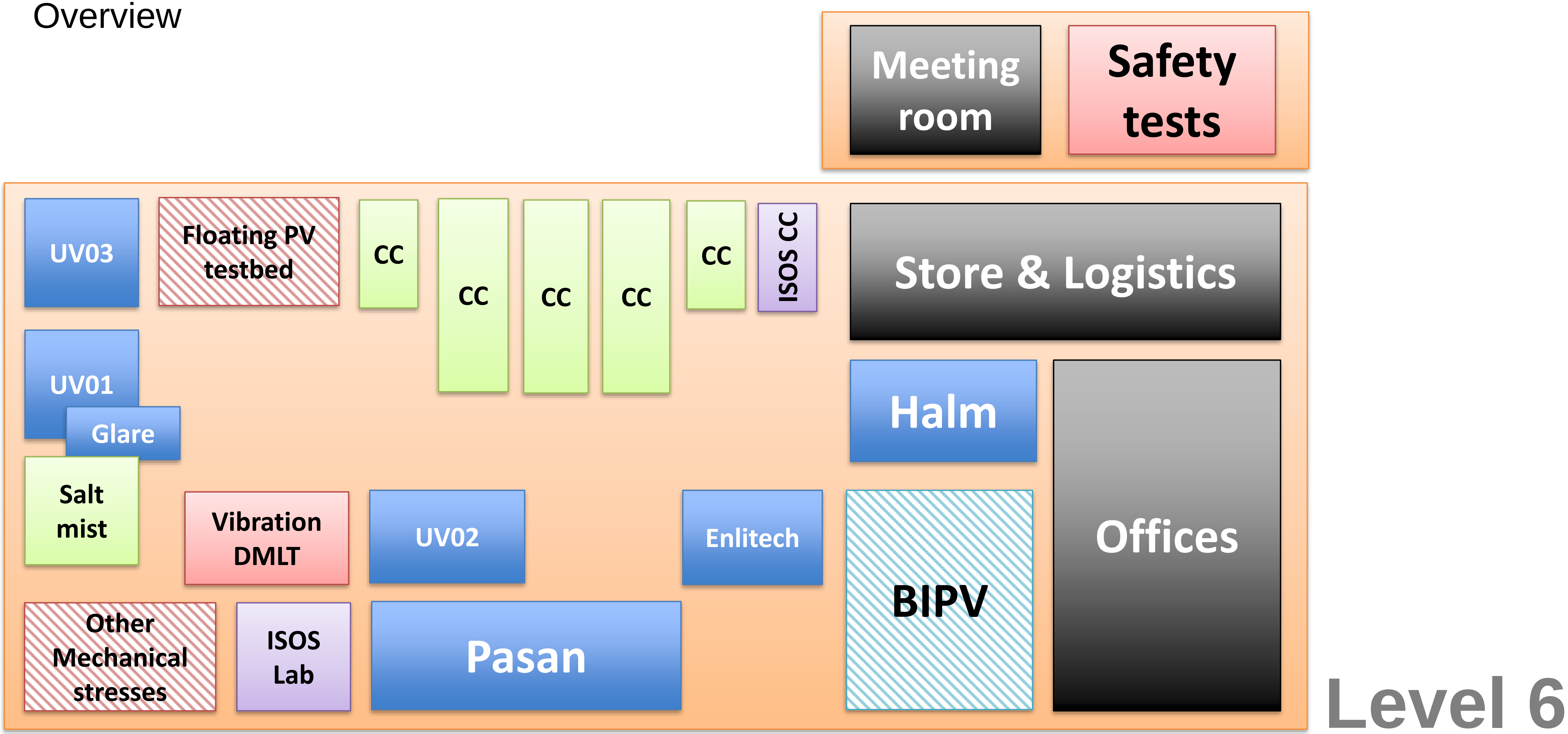
- ❑ Develop a reliable, cost-effective and high-efficiency BIPV module.
- ❑ Develop new and innovative BIPV modules that meet aesthetic requirements for buildings with minimum power loss and uniform shading to avoid hotspot reliability issues.
- ❑ Develop modular PV integrated building components to ease installation and promote BIPV deployment.
- ❑ BIPV integration into actual buildings

Floating Solar Systems

- ❑ SERIS is recognised as a global leader in R&D on "Floating Solar", operating one the world's largest testbed at Tengeh reservoir.
- ❑ Expanding the research towards near-shore and off-shore Floating Solar, also in combination with other uses such as fish farming, hydrogen generation and desalination.

Module qualification lab @ SERIS

Overview



Module qualification lab @ SERIS

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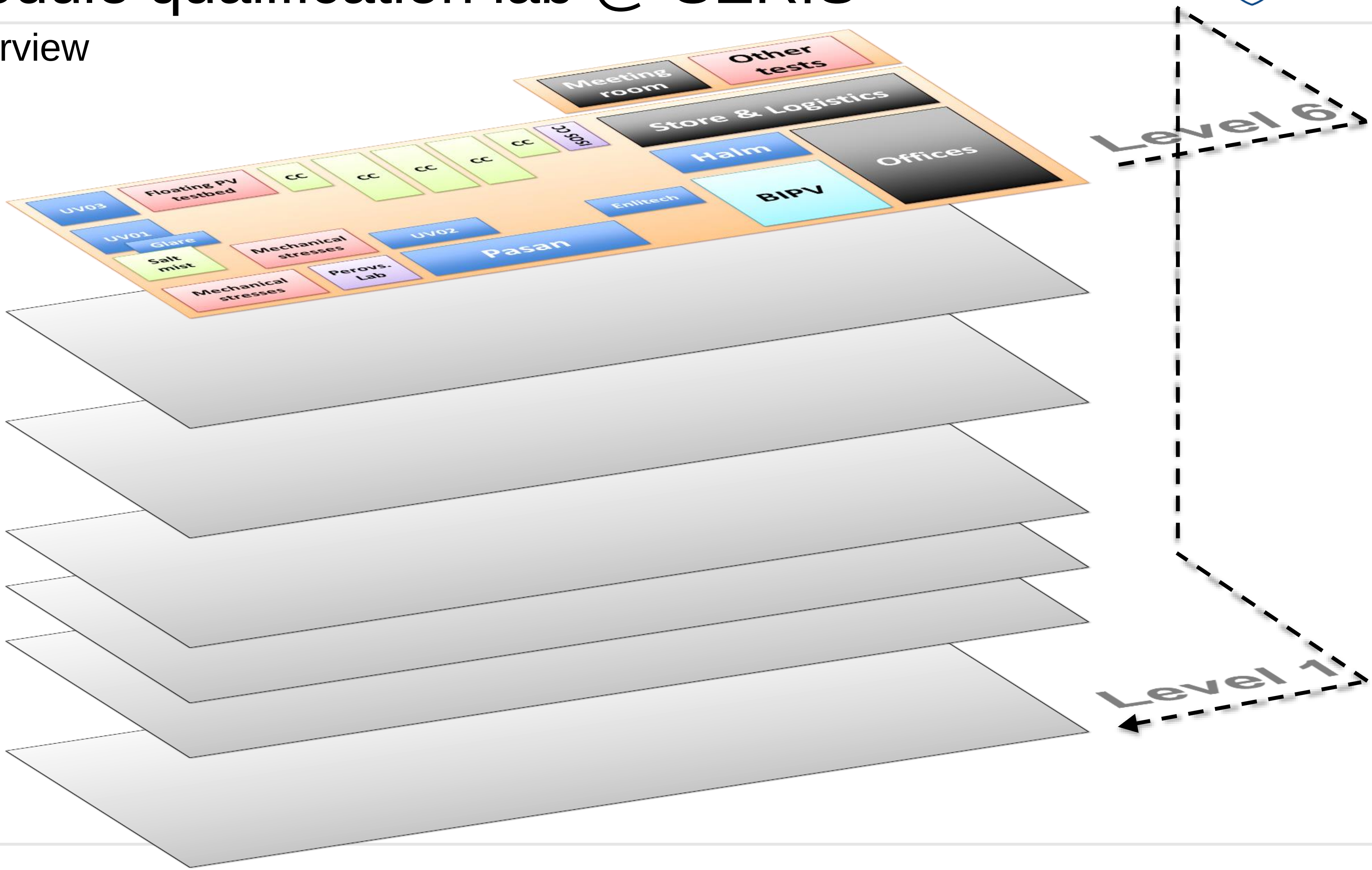

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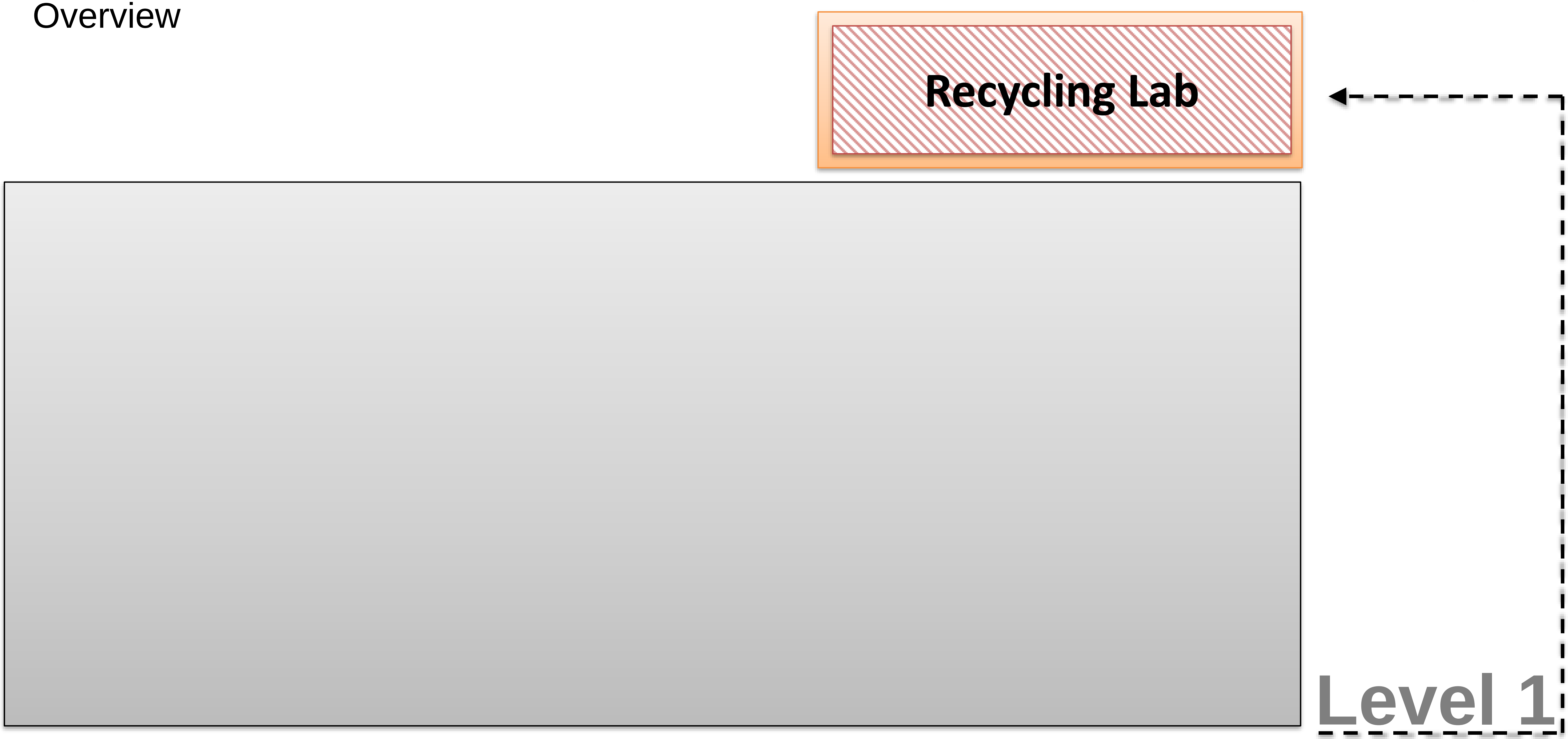

Module qualification lab @ SERIS

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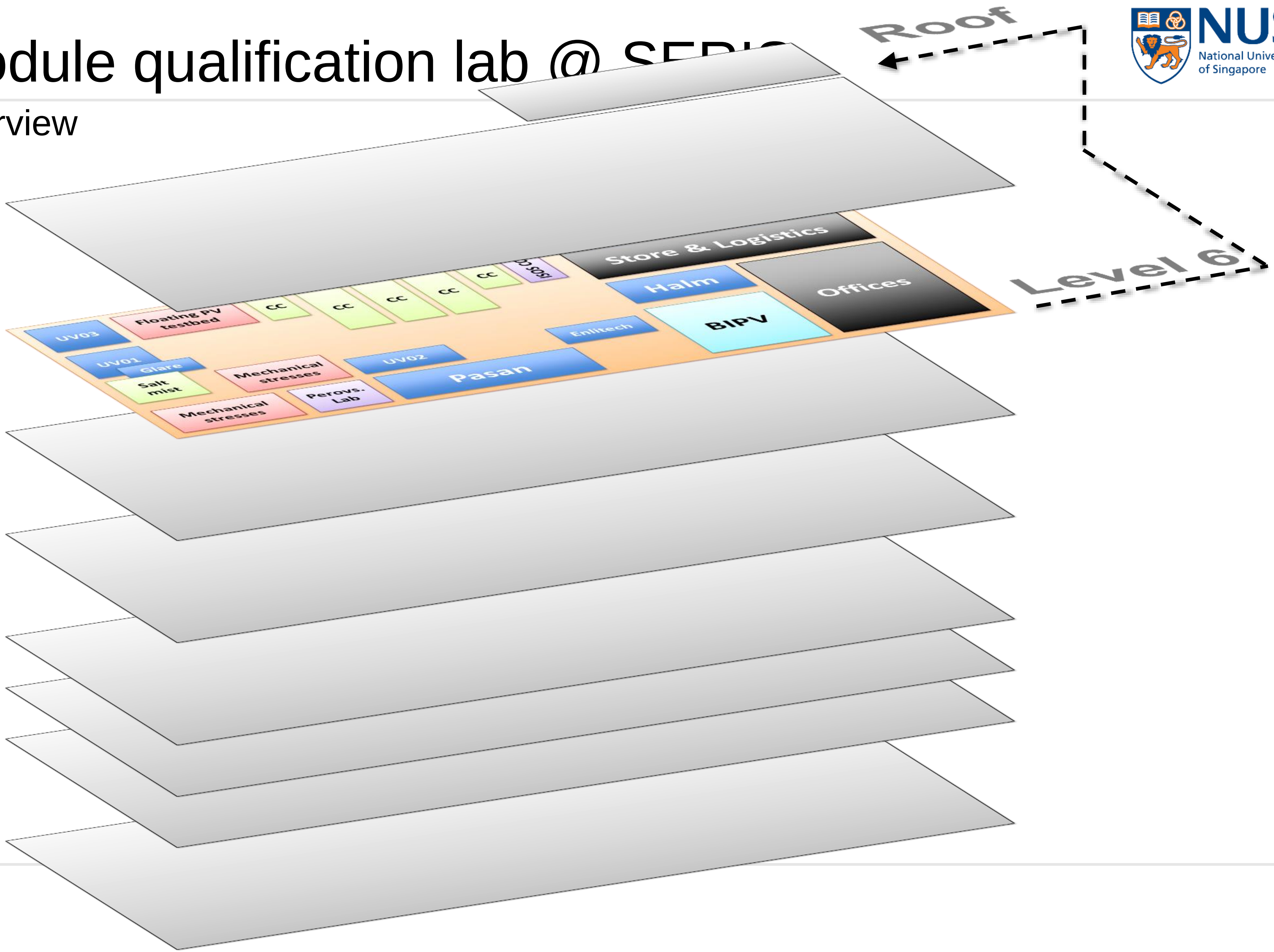
Recycling Lab

Module qualification lab @ SERIS

Overview



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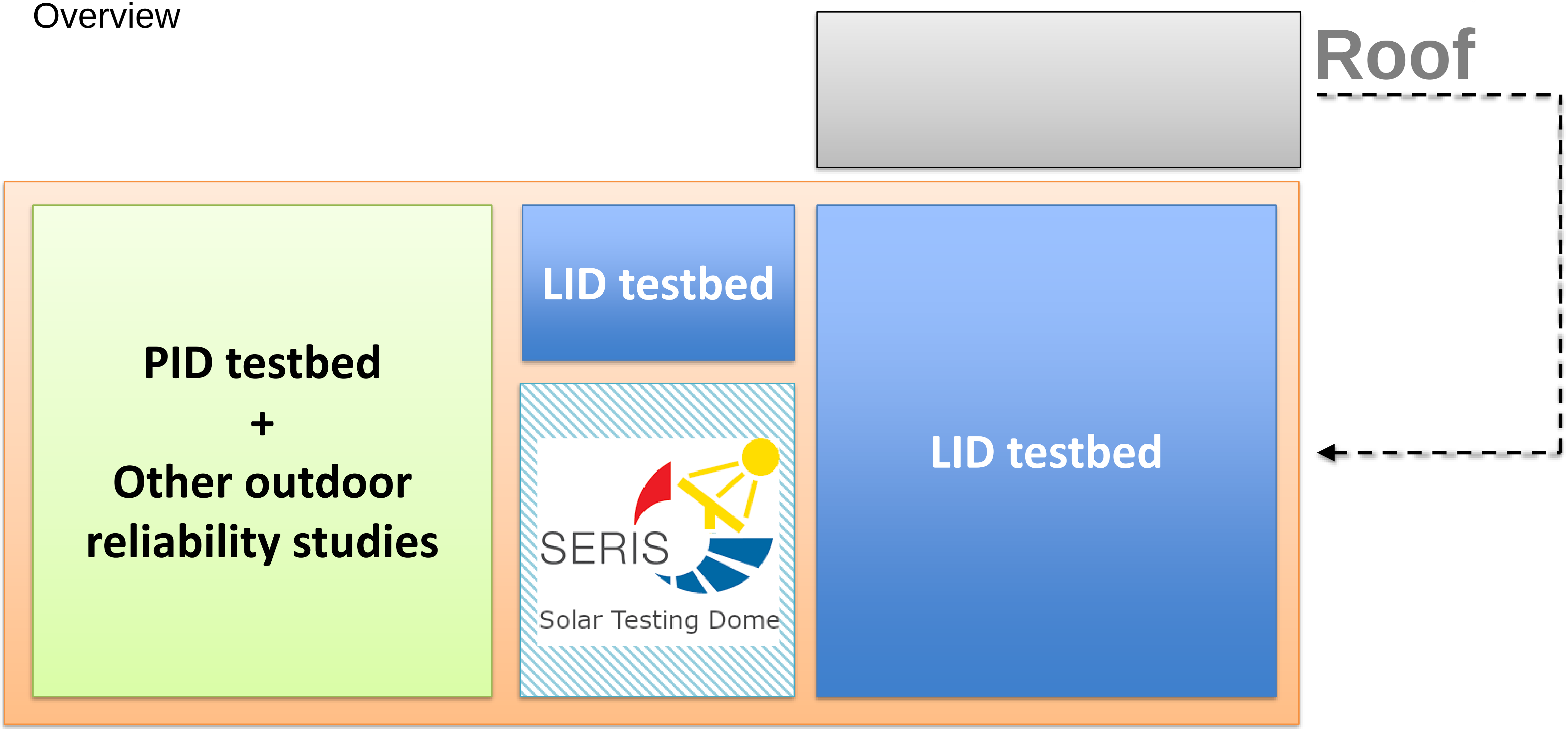


Module qualification lab @ SERIS

Outdoor testbed & SERIS Testing Dome

“Conventional” vs. “integrated” PV

Conventional PV

Novel “integrated” PV

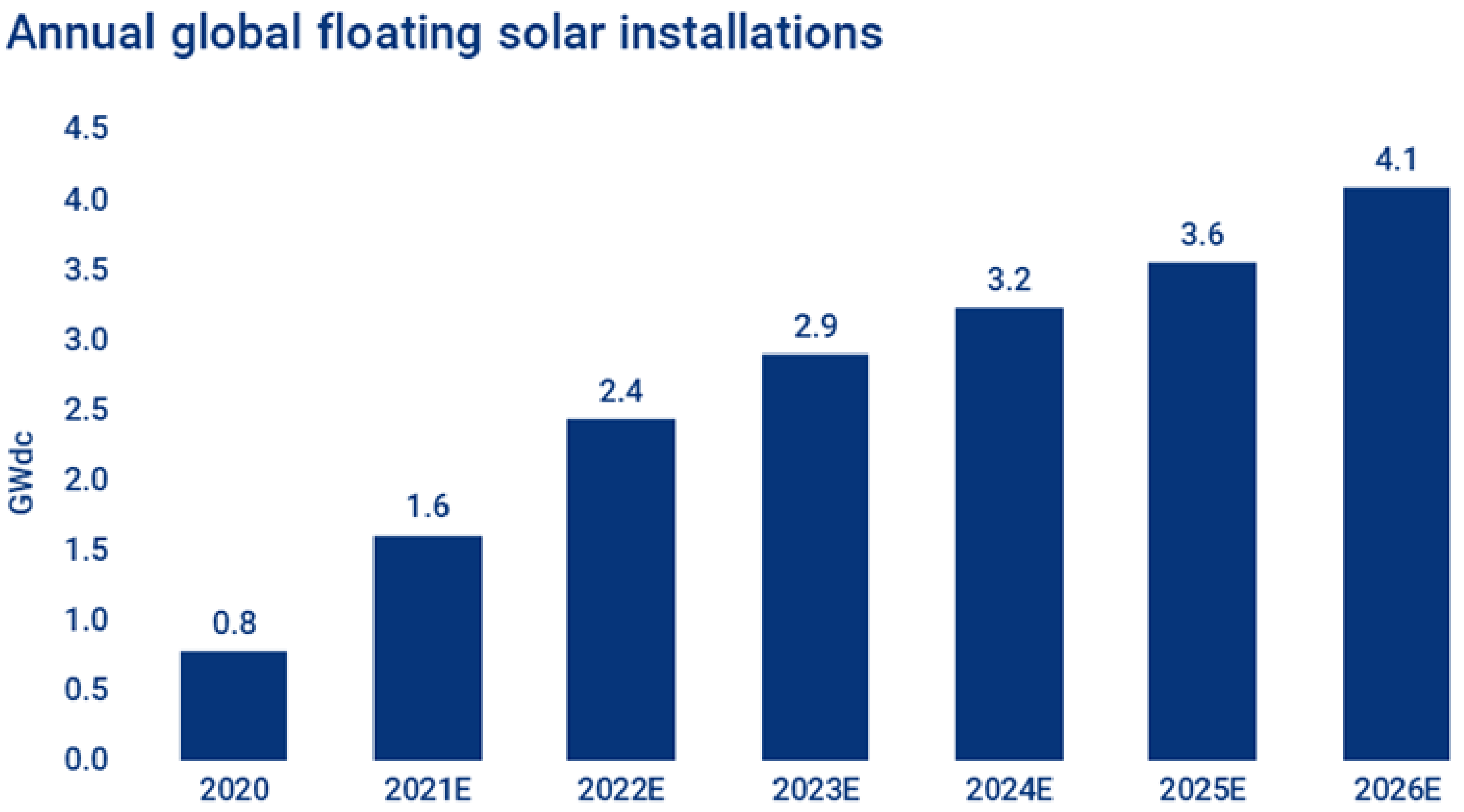
“Conventional” vs. “integrated” PV

Conventional PV

Novel “integrated” PV

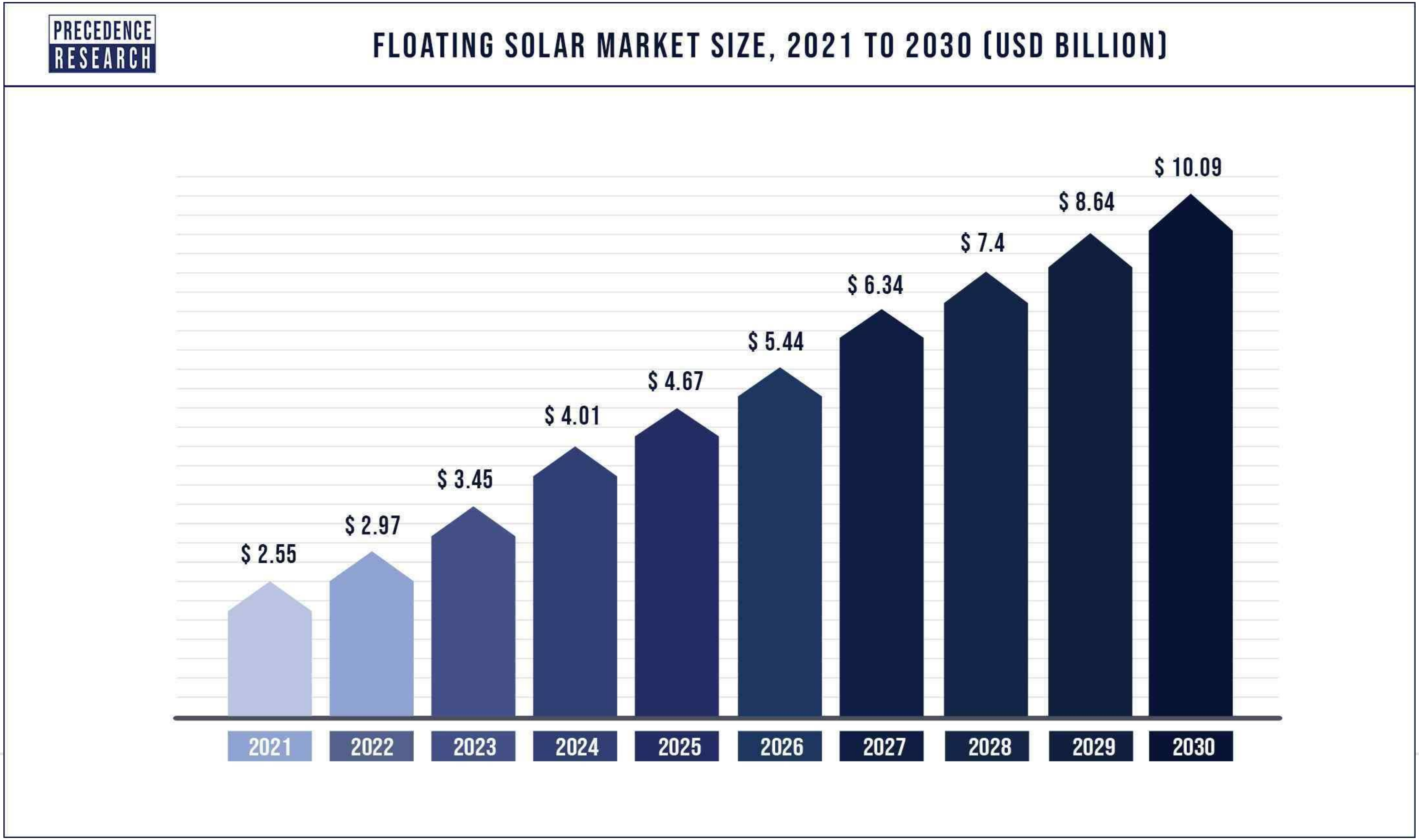
Floating PV: market perspective

National University of Singapore
SERIS Solar Energy Research Institute of Singapore

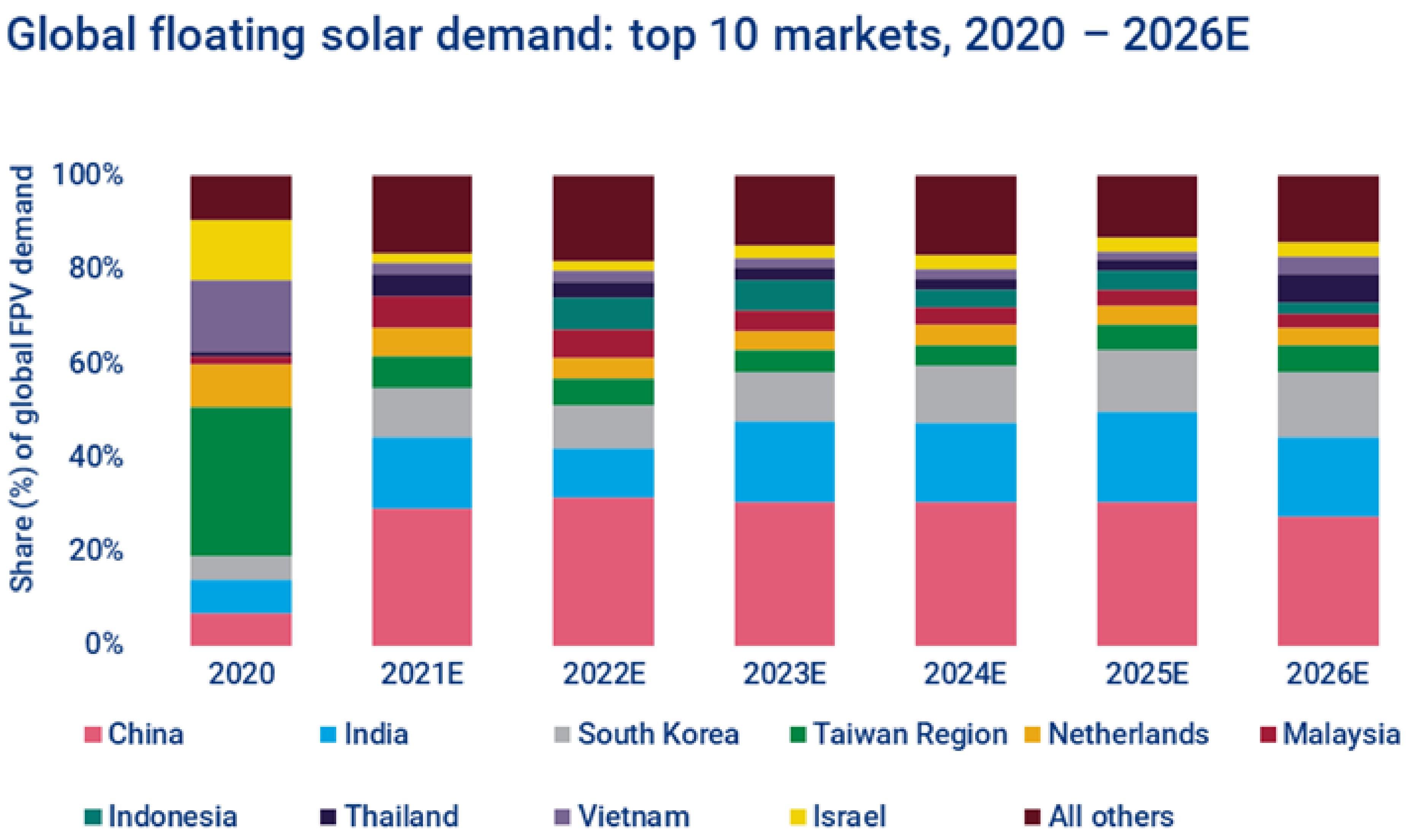


Source: Wood Mackenzie Global Solar Markets Service

Floating PV: market perspective



Floating PV: so far, mostly an Asian game



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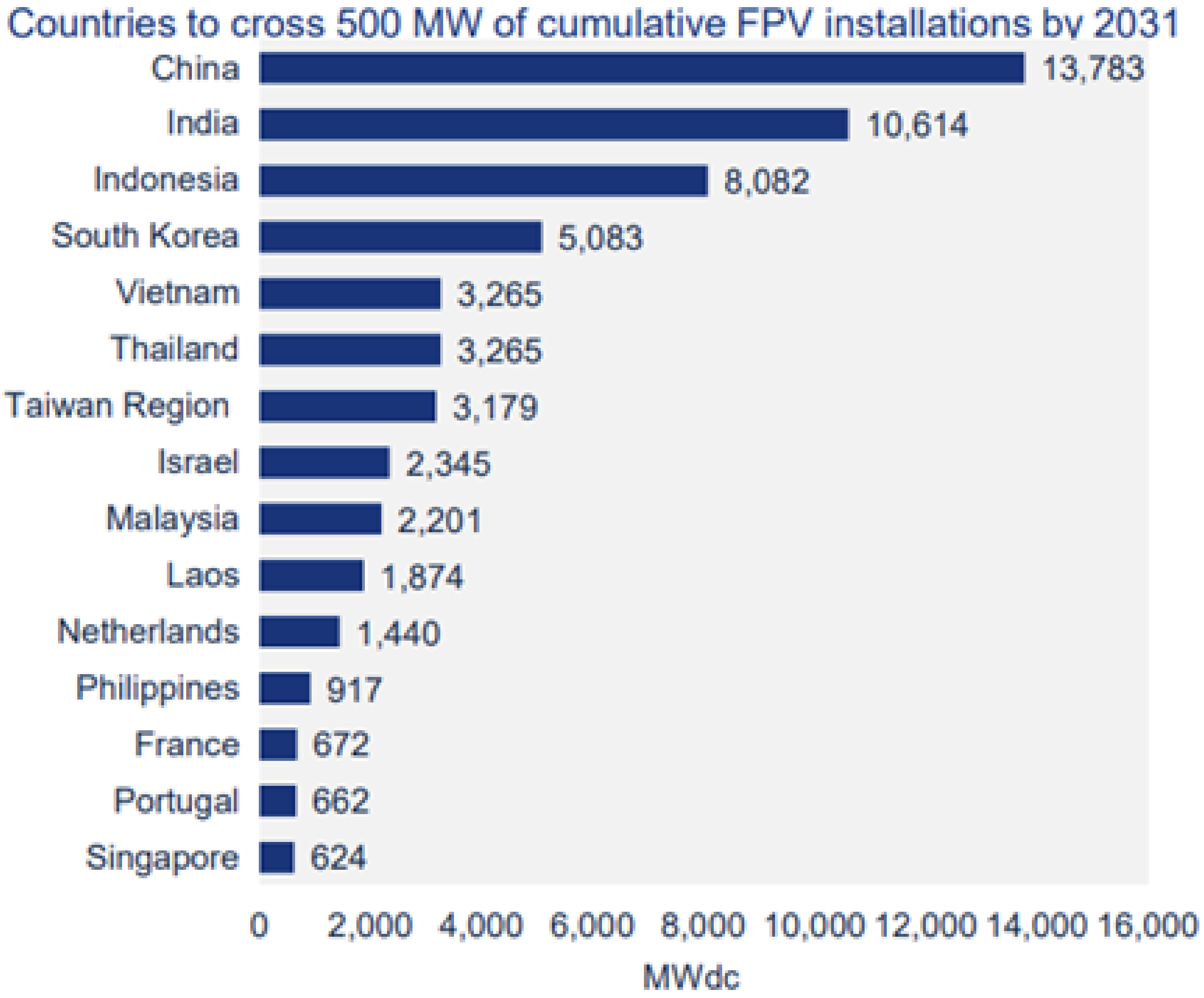
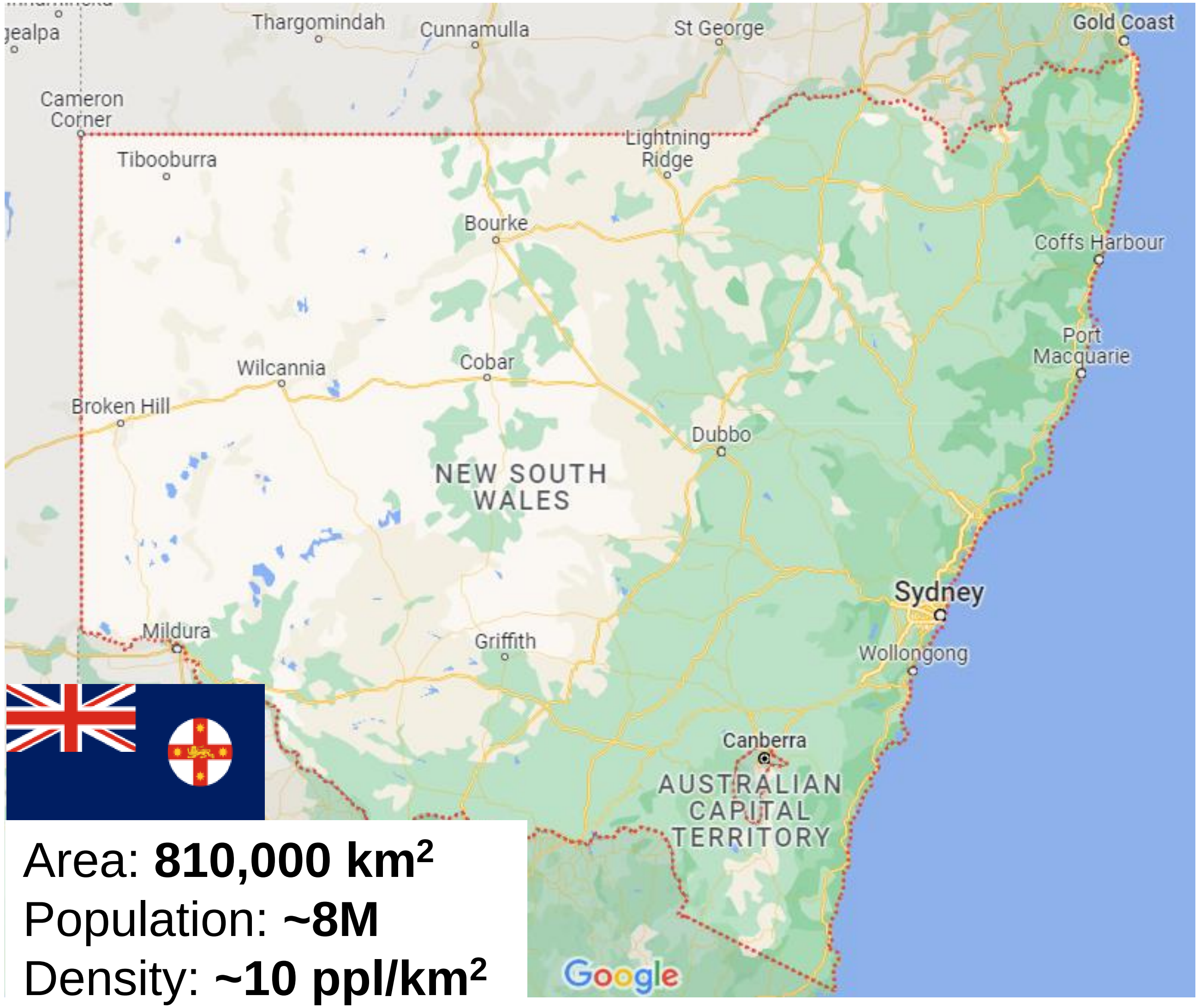


China and India will be well on their way to crossing 10 GW in the next 10 years. Netherlands and France lead the market in Europe and Israel leads the Middle-east region.

Source: Wood Mackenzie

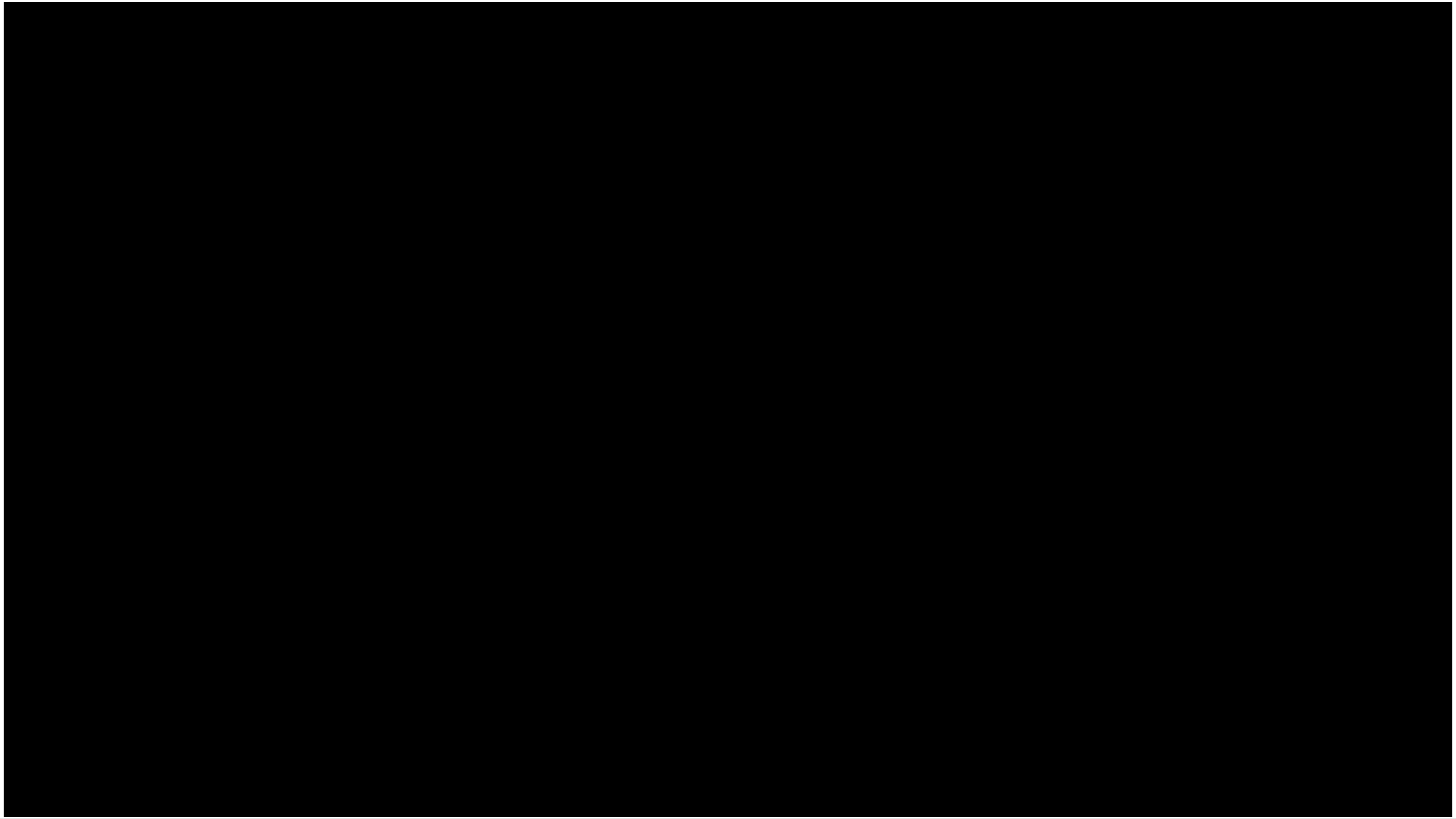
A small island, plenty of sun, and lot of people



Area: **810,000 km²**
Population: **~8M**
Density: **~10 ppl/km²**

Area: **734 km²**
Population: **~5.6M**
Density: **~7,600 pp/km²**

Reliability matters…



…even more for neighboring islands

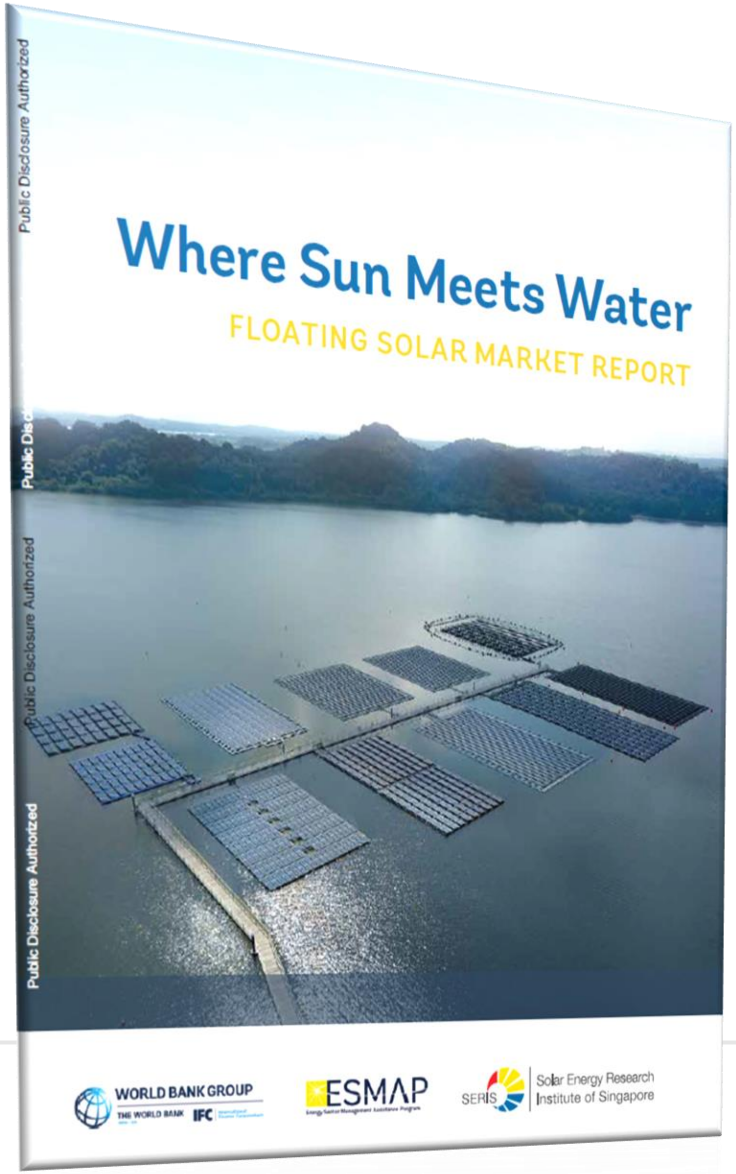
Floating PV system mysteriously washes up on Hong Kong beach

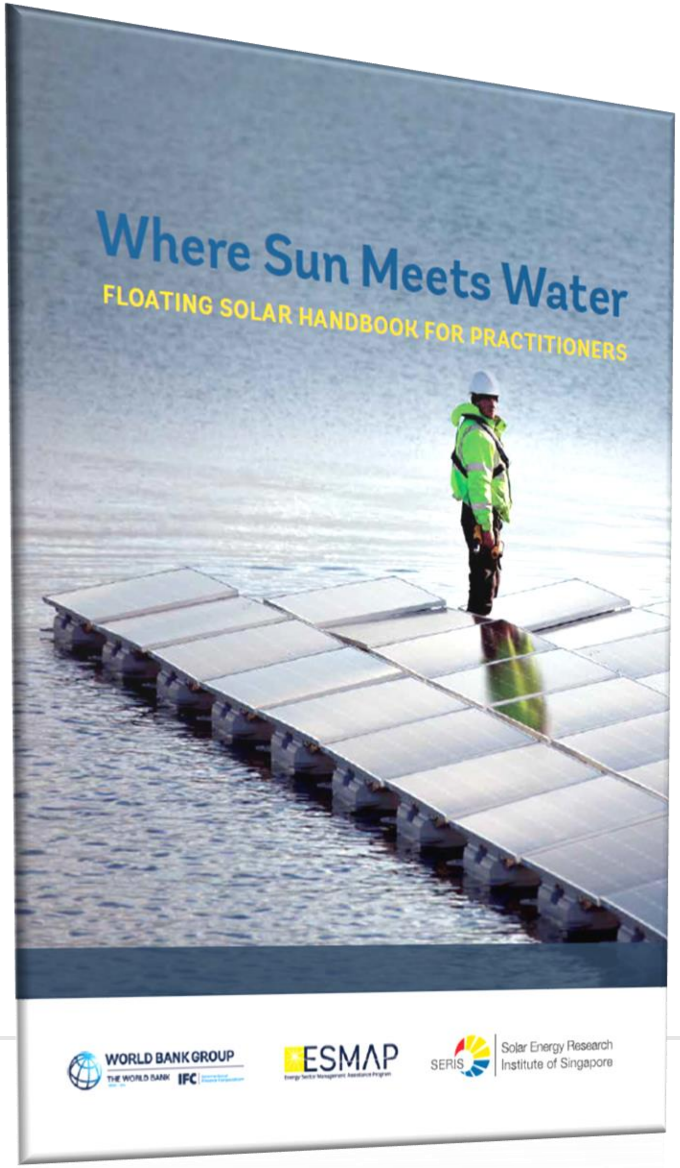
A local environmental organization has published pictures of the stranded array which appeared last week on two beaches. Hong Kong's Agriculture, Fisheries and Conservation Department is currently investigating where the installation came from.

MARCH 29, 2023 EMILIANO BELLINI

SERIS white papers

In collaboration with the World Bank





Towards a qualification program for FPV

Research Framework Agreement with Fred Olsen Renewables

2021 *Phase 1*

Technology mapping, financial modelling

2022 *Phase 2*

PV module qualification (initiation and contact with module suppliers), mismatch loss assessment (hydrodynamic simulation), electrical layout development, FPV project cost database

2023 *Phase 3*

PV module qualification (in collaboration with DNV), mismatch loss assessment (analysis of field data), electrical system failure mode analysis, Norway pilot engineering and data analysis, communication and publications

Towards a qualification program for FPV

Risk matrix **(with the participation of DNV)**

			Probability class (during lifetime)		
			1	**2**	**3**
			Unlikely	Probable	Very likely
Severity class	**1**	M[illegible] minimum/no downtime, minor reduction in electrical output	1	2	3
	2	Partial damage and/or significant shortfall of production	2	4	6
	3		3	6	9

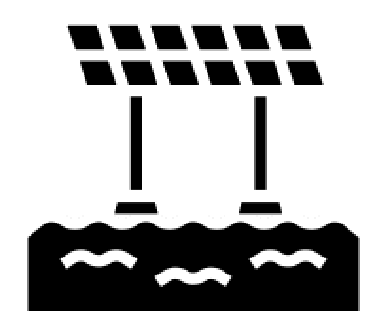
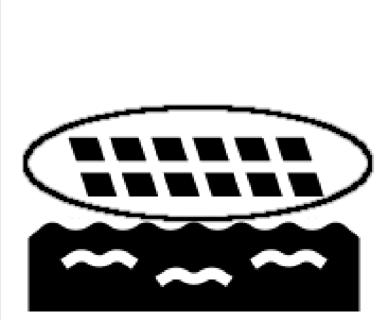
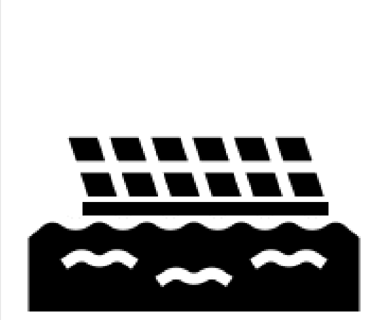
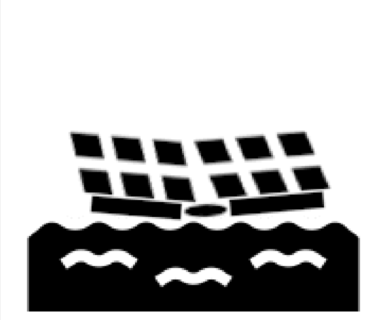
Soiling due to snow/ice → 1

PID in maritime environment → 4

Event-based structural collapse → 3

Module breakage (torsion) → 9

Classification of floating systems

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

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Physically separated from water		Not physically separated from water	
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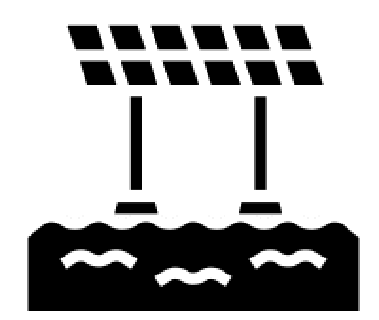
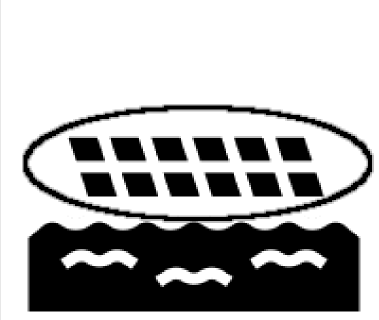
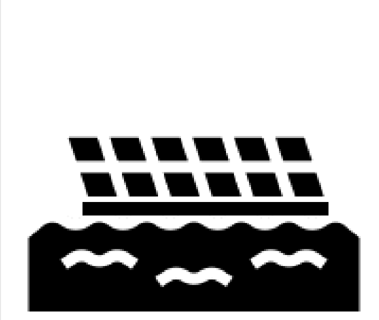
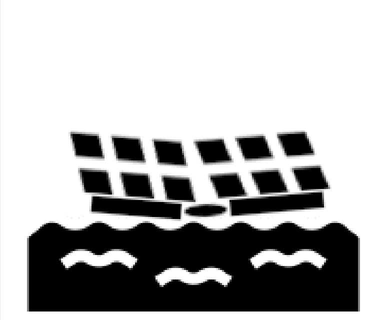
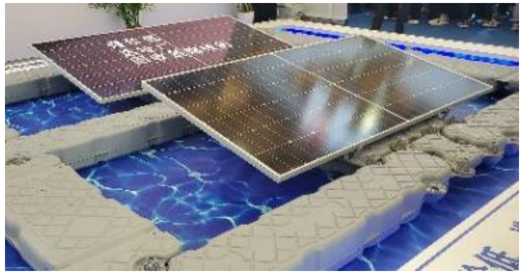
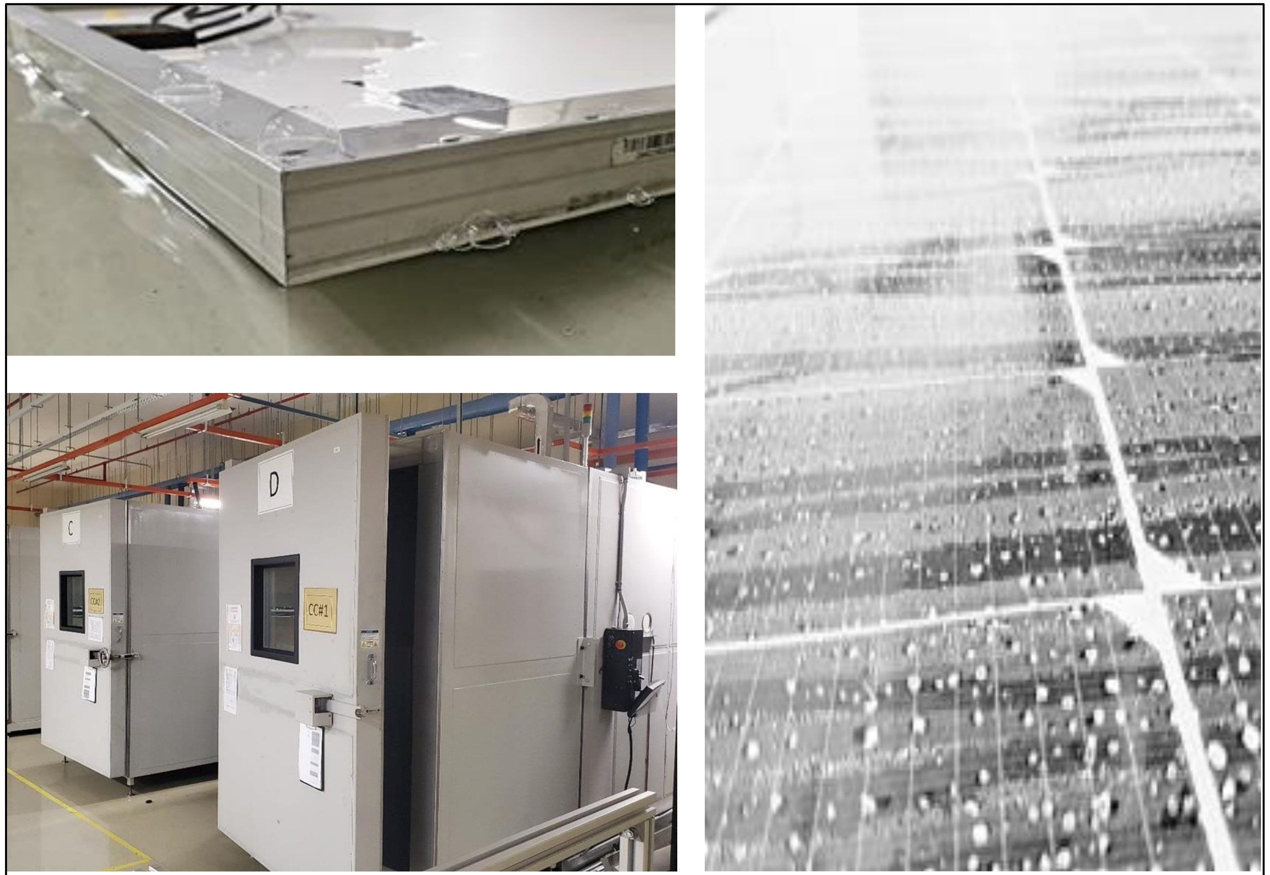
High complexity ←			*Low complexity*
Low risk →			*High risk*
			
			

Environmental conditions & stress tests

IEC 60721 series
(environmental conditions)



IEC 60068 series
(environmental testing)

IEC 61215:2021

Accredited Laboratory SAC-SINGLAS LA-2012-0526-E

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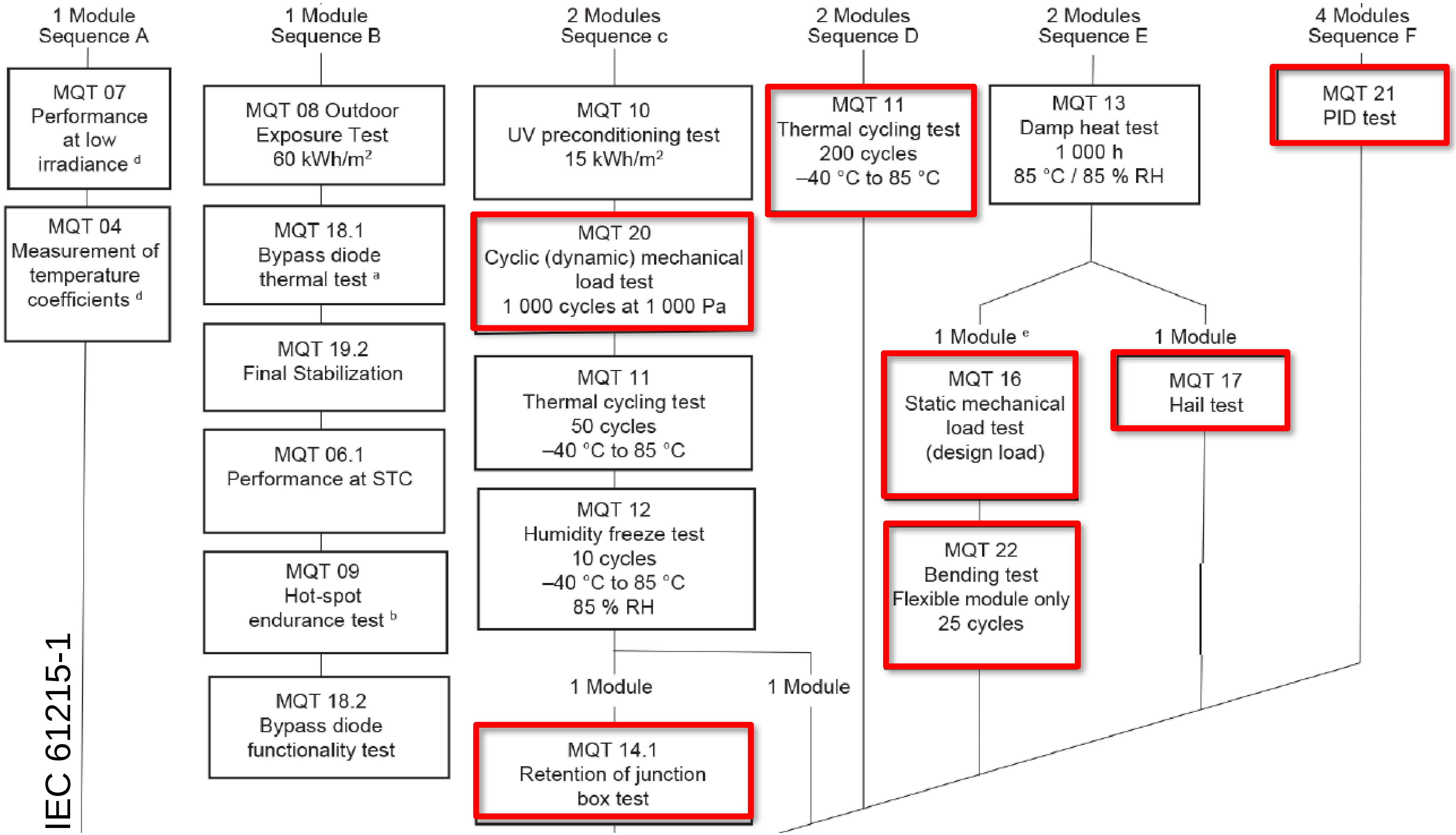
What are the tests that PV module suppliers carry out?



FPV: environmental conditions & stresses

Environmental conditions & class		Description	Severity	Possible effects & failures	New stress tests
Climatic: **6K6**	Cold & heat	**Thermal shock** caused by sudden impact of water	Air/water: +40/+5 °C Surface/water: +70/+5 °C	Electrical failure; mechanical failure; cracking; sealant failure; leaks	Thermal shock

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	Water (other than rain)	**Force** application to the center of the module with induced vibration and particle deposit	10 m/s	Insulation failures; electrical failure; cracking; leaks; surface deterioration; soiling; structural collapse	Water impact Water immersion

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	Water (other than rain)	**Force** application to the center of the module with induced vibration and particle deposit	10 m/s	Insulation failures; electrical failure; cracking; leaks; surface deterioration; soiling; structural collapse	Water impact ⚠ Water immersion ⚠
Biological: **6B2**	Flora & fauna	Presence of **mould, fungus**, etc. and of **rodents** and other animals potentially harmful to modules and components	Ammonia: 3.0 mg/m^3	Increased wear; mechanical failure; optical failure; surface deterioration; corrosion; soiling	Ammonia test List of fungus resistant materials ⚠

FPV: environmental conditions & stresses

Environmental conditions & class		Description	Severity	Possible effects & failures	New stress tests
Chem. Sub.: **6CX**	Chemically active substances	Extremely corrosive effect of salt (in the assumption of no other industrial pollutants); presence of ions (mainly Na^+ and Cl^-)	Salt in water: 30 kg/m^3 Ammonia: as above	Increased wear; mechanical failure; electrical failure; corrosion; potential induced degradation (PID)	Salt mist corrosion Ammonia test PID + salt mist

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Mec. Sub.: **6S3**	Mechanically active substances	Deposition of sand and dust transported by wind; deposition of salt by water	Sand: 10 g/m^3 Dust: 3.0 mg/(m^2 h) Salt: Not available	Increased wear; electrical failure; mechanical failure; overheating (hot spot); abrasion; PID	Sand abrasion Hot spot

FPV: environmental conditions & stresses

Environmental conditions & class		Description	Severity	Possible effects & failures	New stress tests
Mechanical: **6M1-2**	Stationary vibrations (sinusoidal)	Mechanical stress to the module caused by waves	Displacement: 1.5 mm Acceleration: 10 m/s^2 Frequency: 2-13 Hz	Mechanical failure; electrical failure; increased wear; structural collapse; cracking`	Vibration test

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	Vibrations (others)	Mechanical shock caused by the impact of waves	Type I (peak): 50 m/s^2 Type II (peak): 100 m/s^2		Water drop test

FPV: environmental conditions & stresses

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	Vibrations (others)	Mechanical shock caused by the impact of waves	Type I (peak): 50 m/s^2 Type II (peak): 100 m/s^2		Water drop test ⚠
	Angular motion	Rotation and twist of the module caused by the wave motion	Roll (X): 22.5 deg / 0.14 Hz Pitch (Y): 10 deg / 0.2 Hz Yaw (Z): 4 deg /0.05 Hz		Torsion test ⚠

Pravettoni et al., *NREL Reliability Workshop*, 2023

Reliability research at SERIS for FPV

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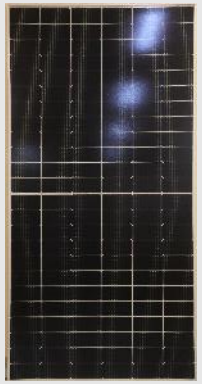
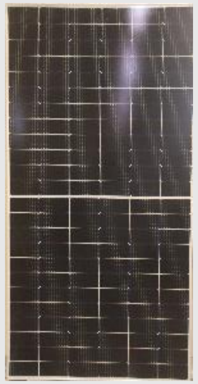
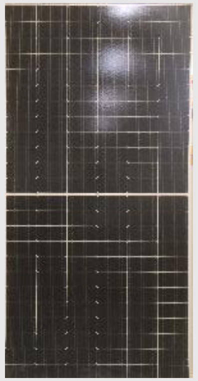
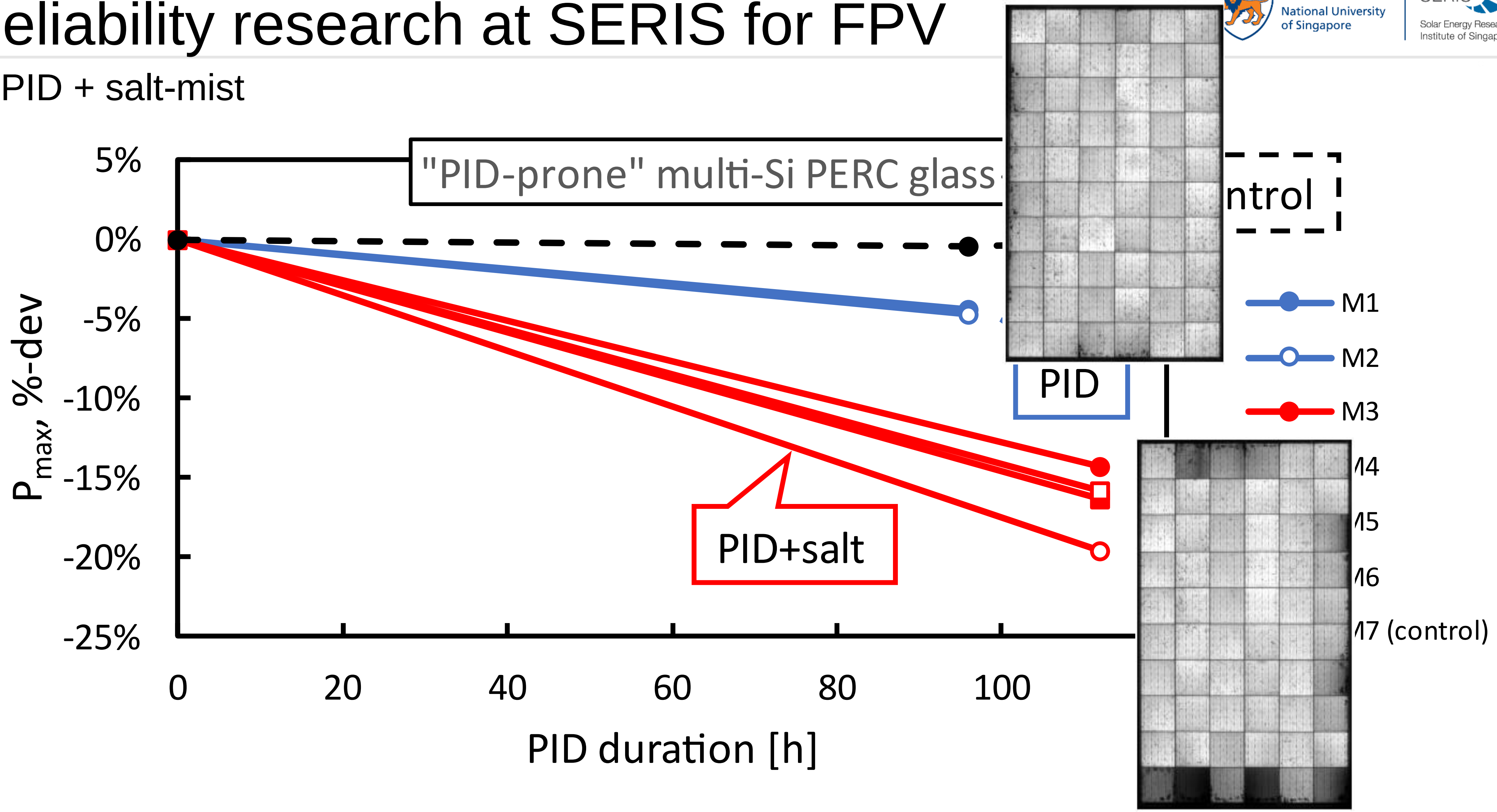
Test samples

PID + salt mist			Mechanical stress tests				
NA	Trinasolar Smart Energy Together	LONGi Solar	JA SOLAR	JA SOLAR	LONGi Solar	Trinasolar Smart Energy Together	YINGLI SOLAR
Poly-Si Glass-BS	Poly-Si Glass-glass	Mono PERC Glass-glass	Mono PERC Glass-BS	Mono-PERC Glass-glass	Mono-PERC Glass-BS	Mono-PERC Glass-glass	Mono-PERC Glass-glass
							
1.68 x 1.00	1.68 x 1.00	1.66 x 1.00	2.28 x 1.13	2.28 x 1.13	2.09 x 1.04	2.38 x 1.13	2.26 x 1.13
Unknown PID	“Anti-PID”	“PID resistant”					

Pravettoni, *50th IEEE PVSC*, 2023

Reliability research at SERIS for FPV

1. PID + salt-mist



Khoo et al., *NREL Reliability Workshop*, 2016

Reliability research at SERIS for FPV

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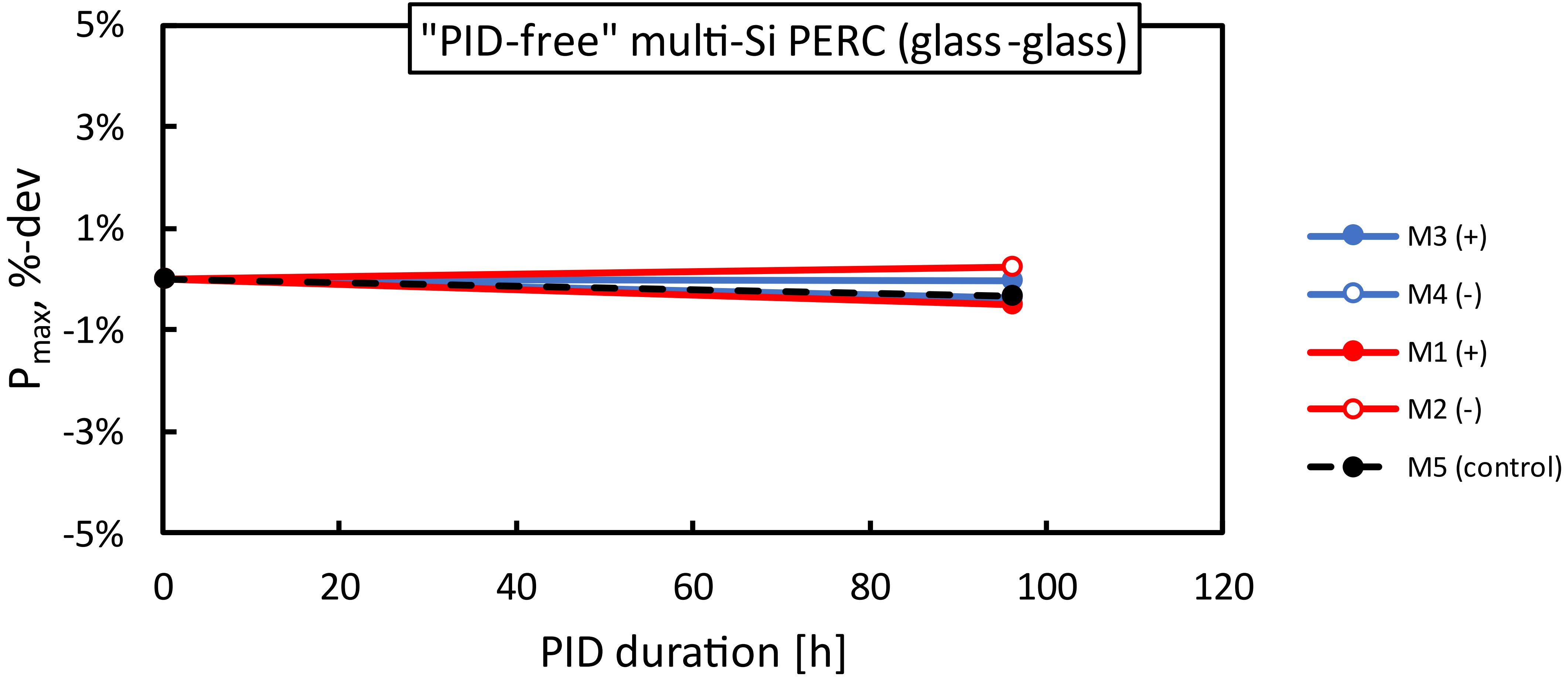

Reliability research at SERIS for FPV

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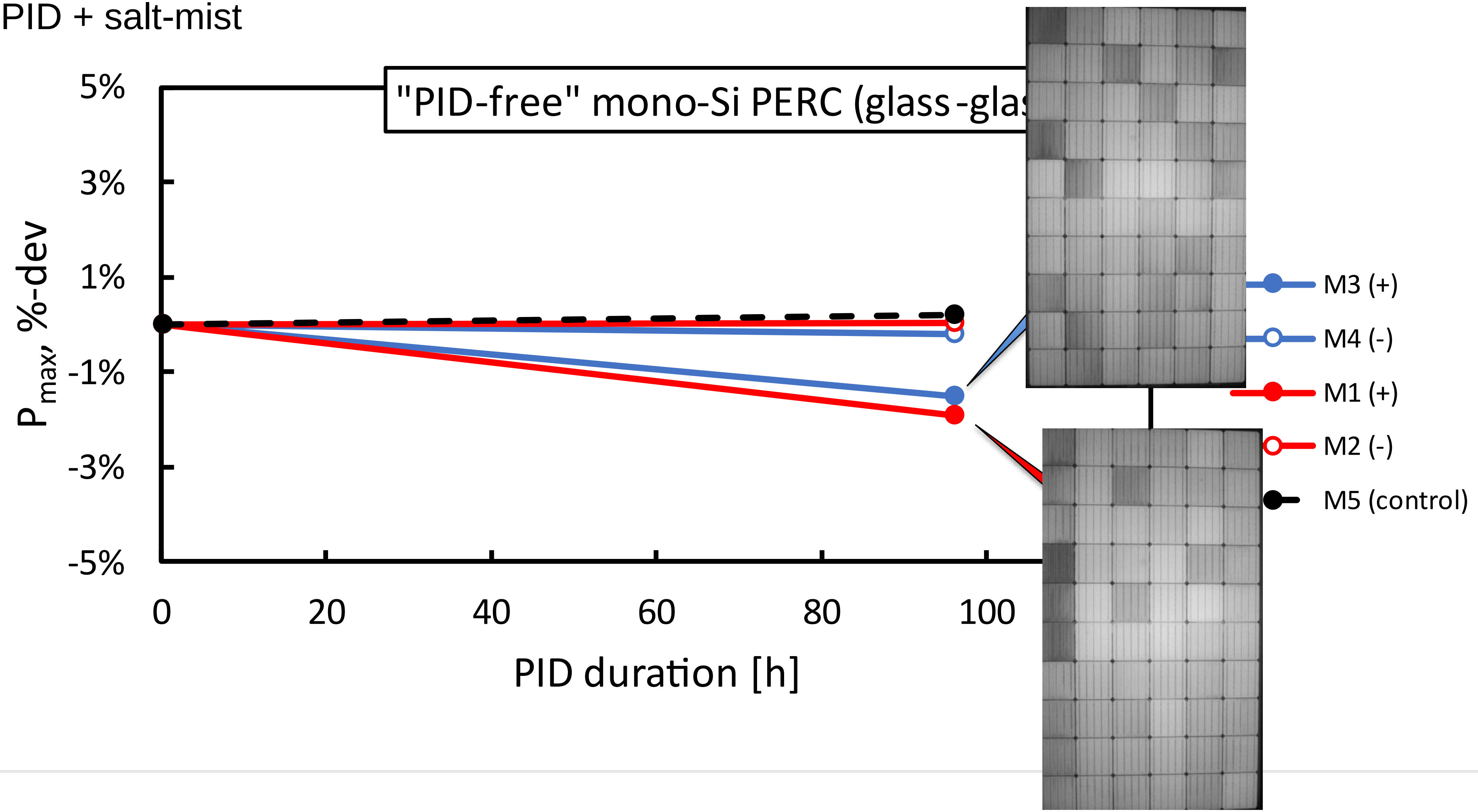
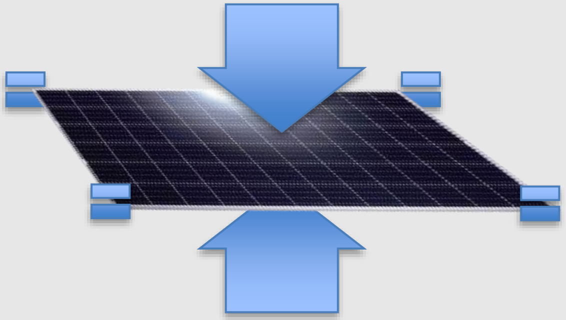
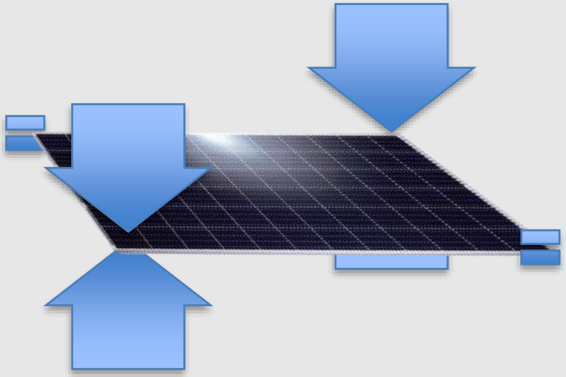
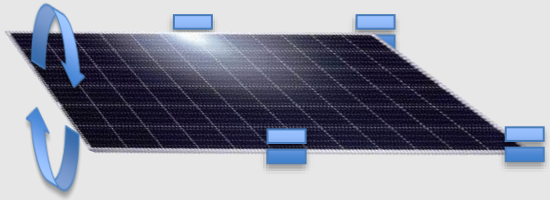


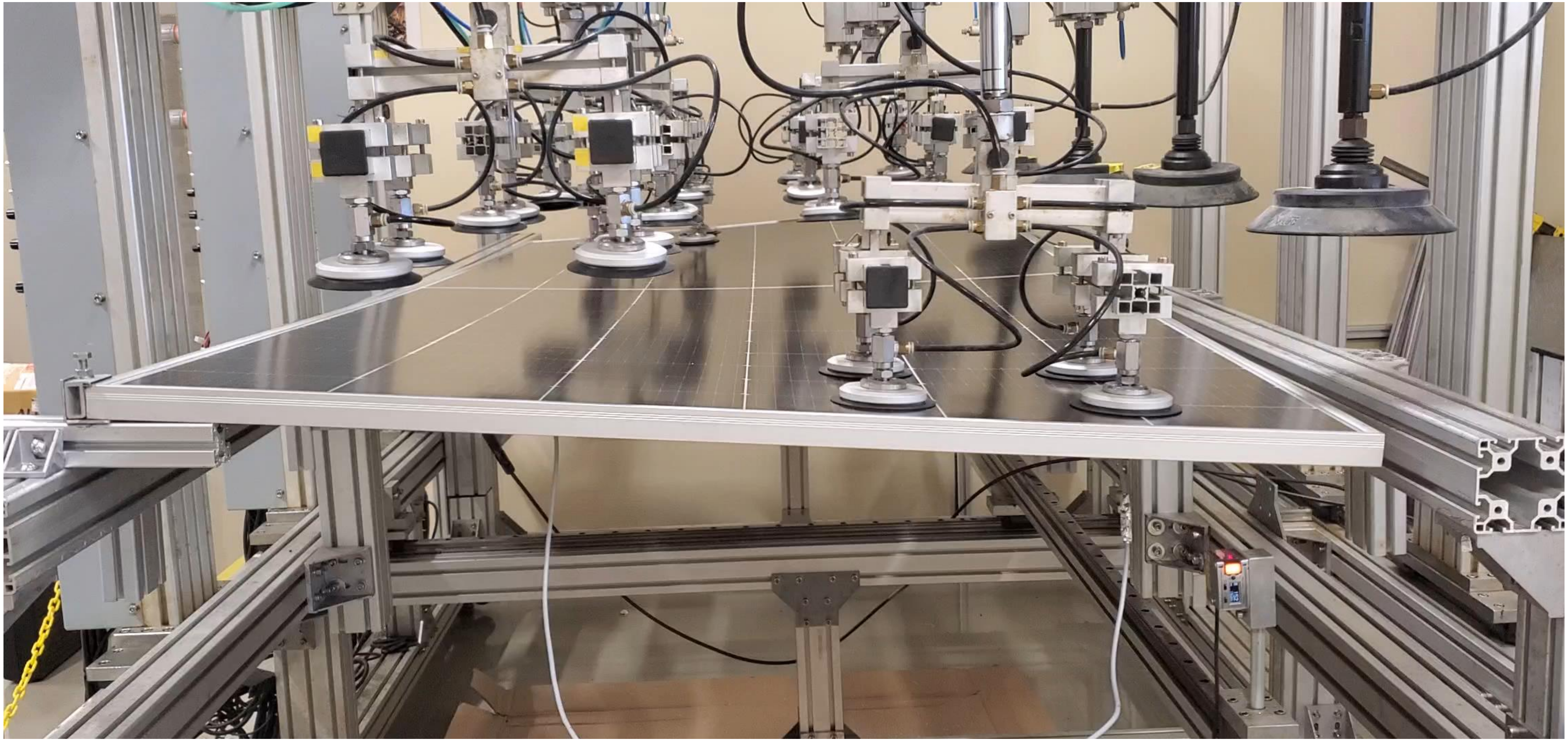
Reliability research at SERIS for FPV

2. Mechanical stress: test plan

Control	Dynamic Mechanical Load Test (DMLT)	Torsion Test	Vibration Test
			
	<u>Standard IEC 61215 (MQT 20):</u> • 1000 cycles (~4-5 hours) • ±1000 Pa • Load at the centre, clamped at the edges	<u>Non-standard test:</u> • 1000 cycles • ±400 Pa • Load at 2 opposite corners, clamped at the others	<u>Non-standard test:</u> • 8 hours • 3 Hz (angular motion) • Half-module clamped, half free to move
Pre + post STC	Pre + post tests: EL + STC	Pre + post tests: EL + STC	Pre + post tests: EL + STC

Reliability research at SERIS for FPV

2. Mechanical stress tests



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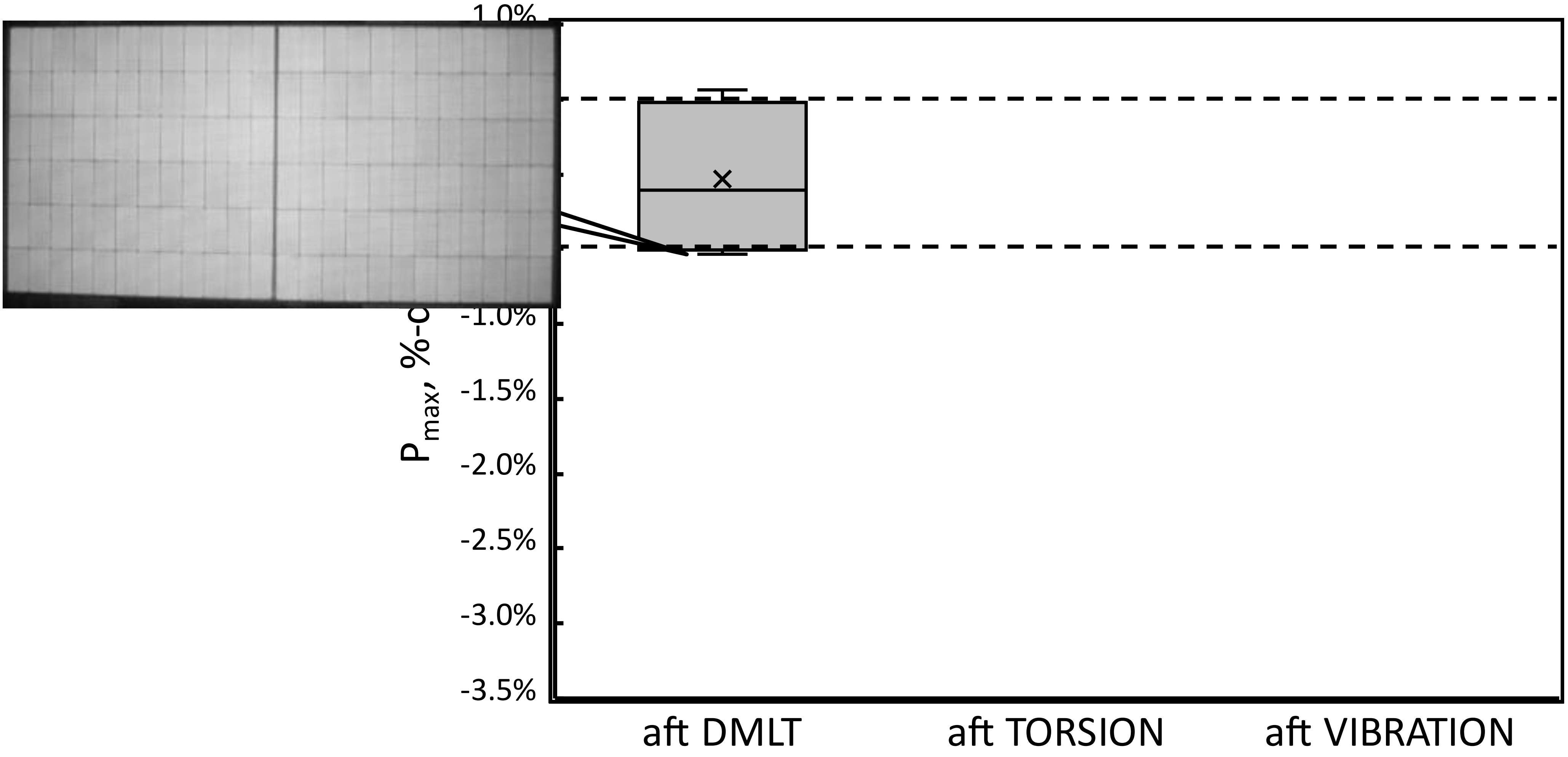

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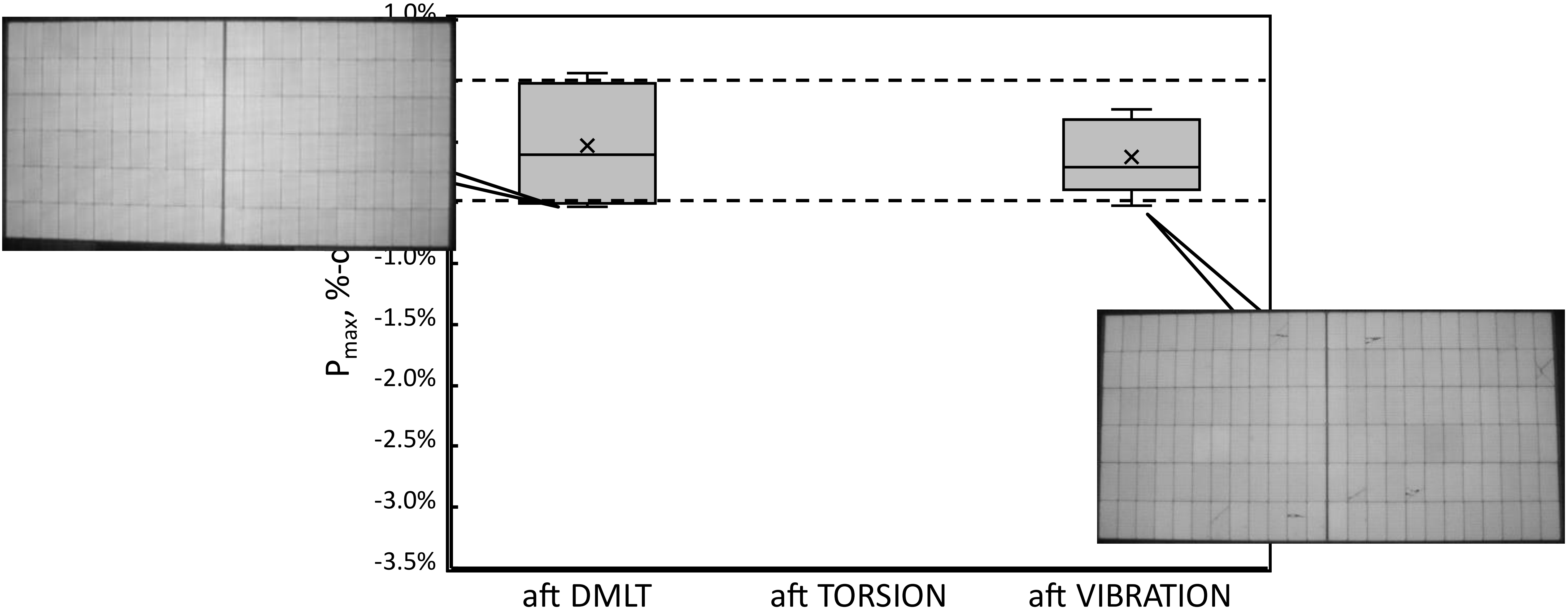

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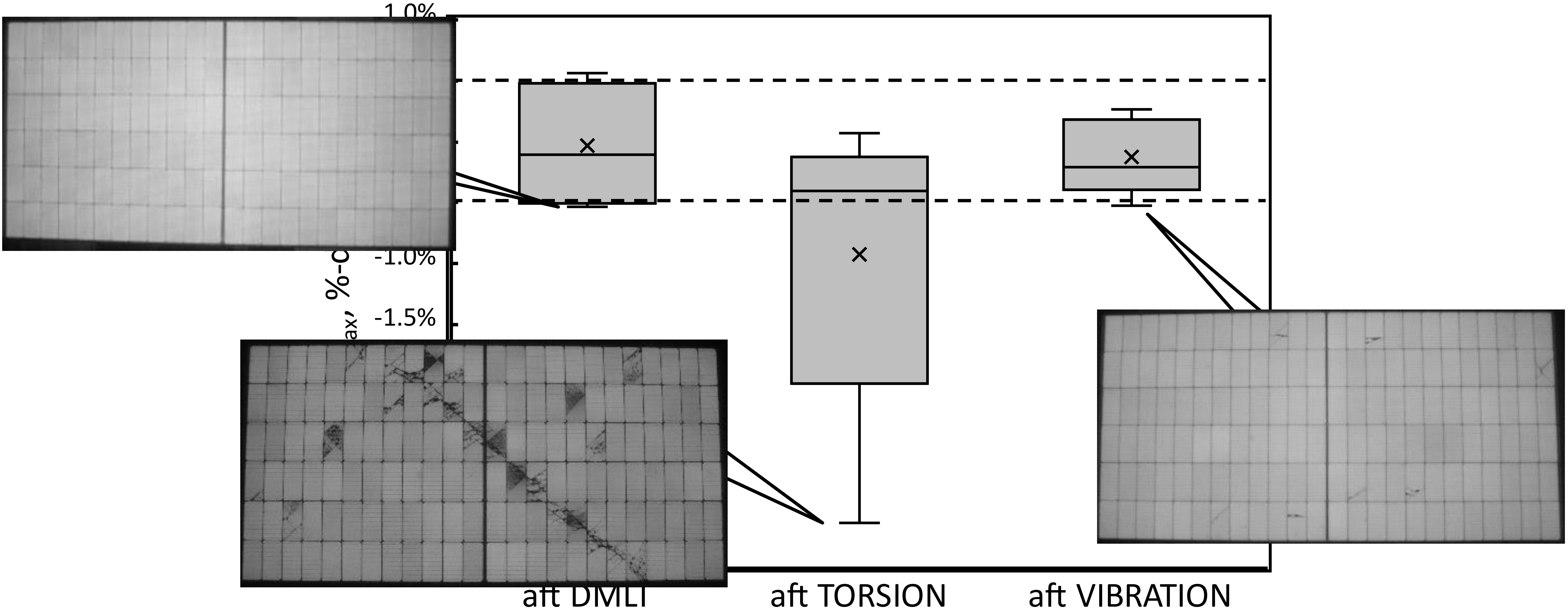


Conclusions

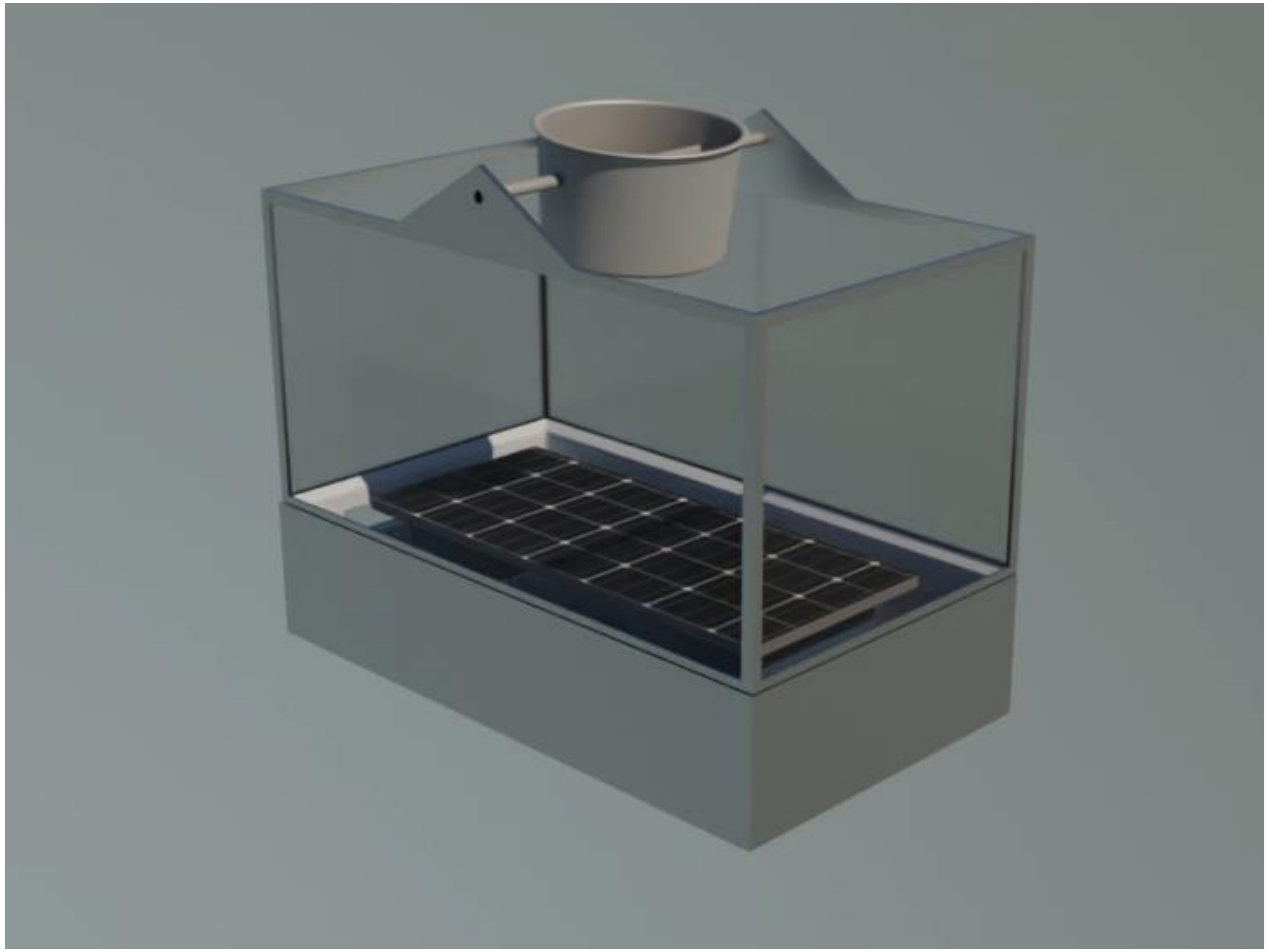
- FPV is receiving growing interest, with projected >4 GW new installations in 2026, and >10 b$ market size by 2030
- SERIS has pioneered research in FPV at the system level since almost 10 years now
- Concerns on PV module reliability are being addressed, particularly for offshore FPV
- ~100 new risks have been identified so far by the consortium, labelled in a scale 1-9 of criticality
- Among the most critical aspects – confirmed by “field” data – are PID and the mechanical stress due to torsion
- Results confirm that the saline maritime environment accelerates and increases the risk of PID
- Torsion test seems to be more severe than vibration test

Further works

- On mechanical stress tests:
  - Explore combined vibration in cold environment (5 deg C)
  - Explore the propagation of cracks under vibration test
  - Design of accelerated stress tests
  - Design water impact tests
  - Mechanical/thermal stresses to components
- On PID + salt mist:
  - Design a round-robin with commercial-size modules
- On module qualification:
  - Submit to IEC as NWIP
  - Draft a qualification flowchart

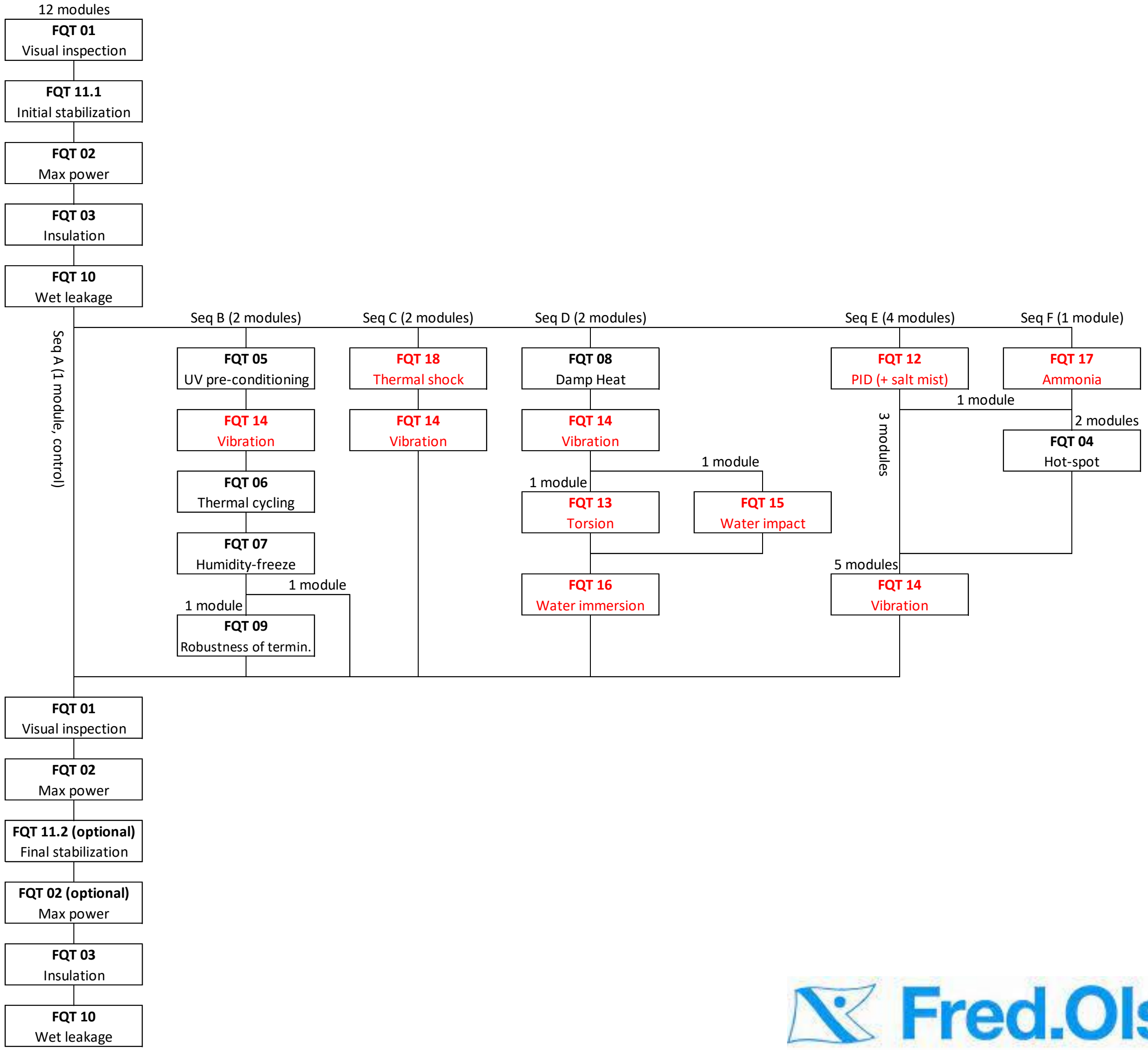
Further works

Conceptual design for water drop test



NWIP for an IEC TS in preparation

Additional qualification tests for floating PV (“FQT xx”)



NWIP for an IEC TS in preparation

Additional qualification tests for floating PV ("FQT xx")

12 modules

FQT 01
Visual inspection

FQT 11.1
Initial stabilization

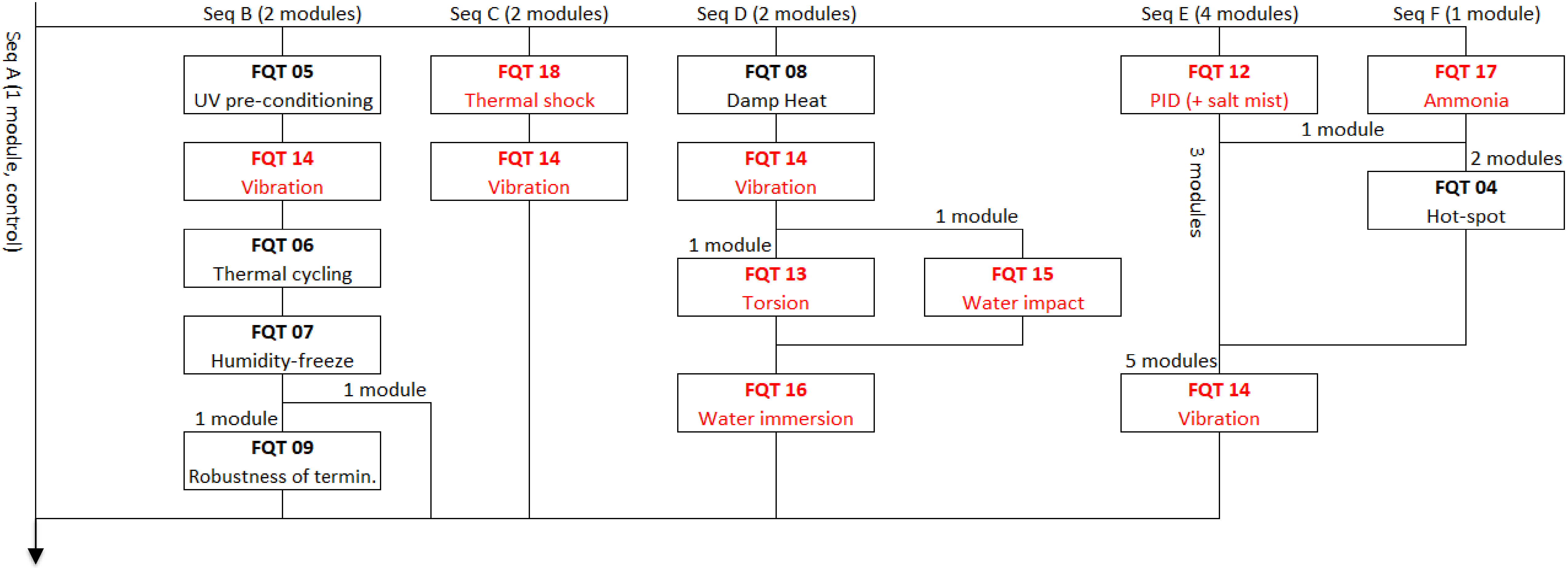
FQT 02
Max power

FQT 03
Insulation

FQT 10
Wet leakage

NWIP for an IEC TS in preparation

Additional qualification tests for floating PV ("FQT xx")



NWIP for an IEC TS in preparation

Additional qualification tests for floating PV ("FQT xx")

FQT 01
Visual inspection

FQT 02
Max power

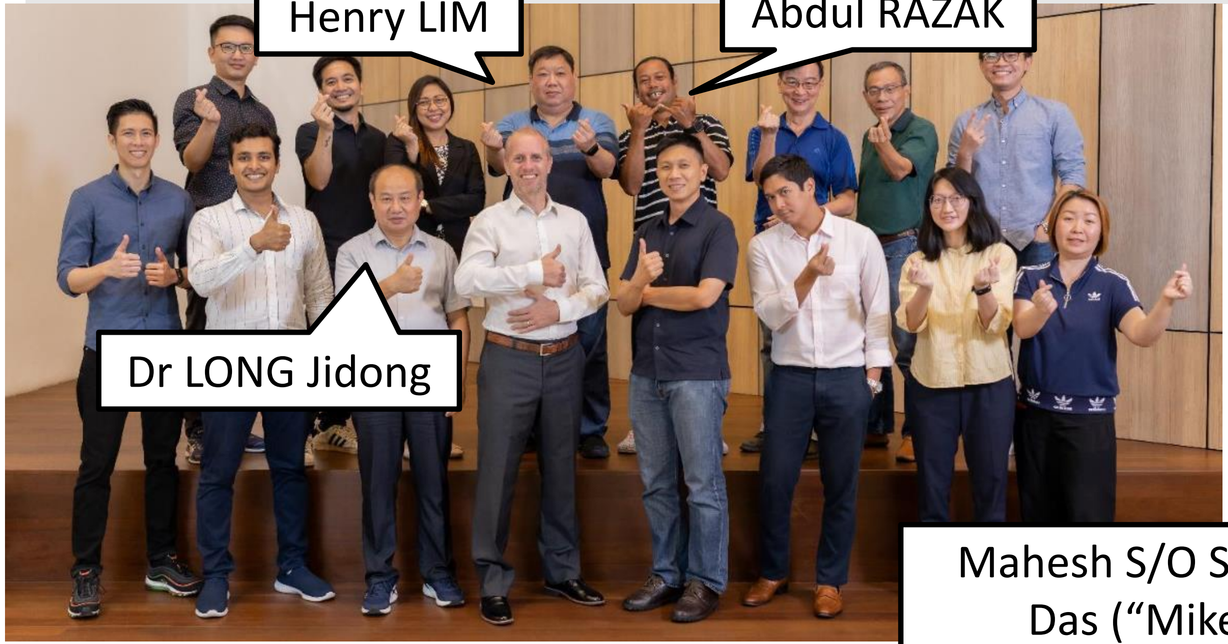
FQT 11.2 (optional)
Final stabilization

FQT 02 (optional)
Max power

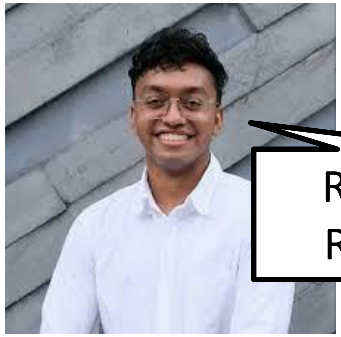
FQT 03
Insulation

FQT 10
Wet leakage

Acknowledgments



…with my precious students…



…and in strong partnership with:

Fred.Olsen Renewables

Even HJETLAND, Andreas BALZER, Rolf B. JOHANSEN

DNV Harald HAMMER, Robin HTUN

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Thank you for your attention!
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