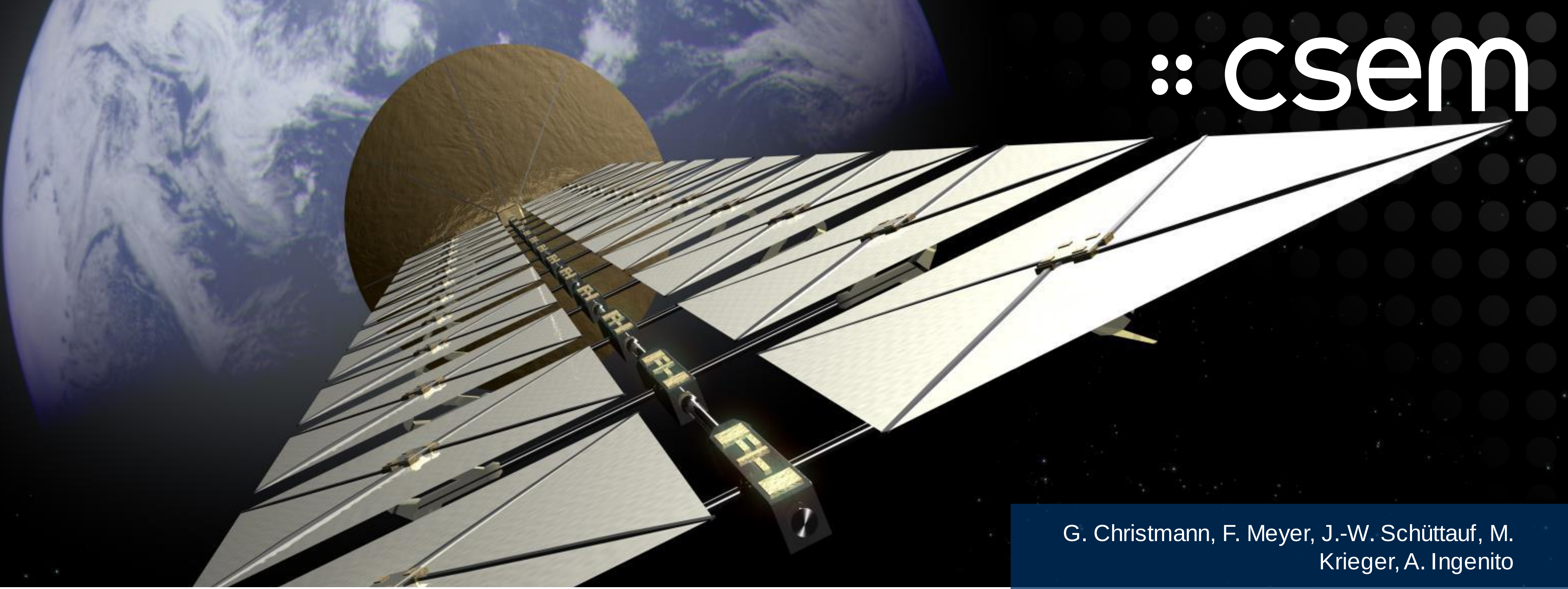


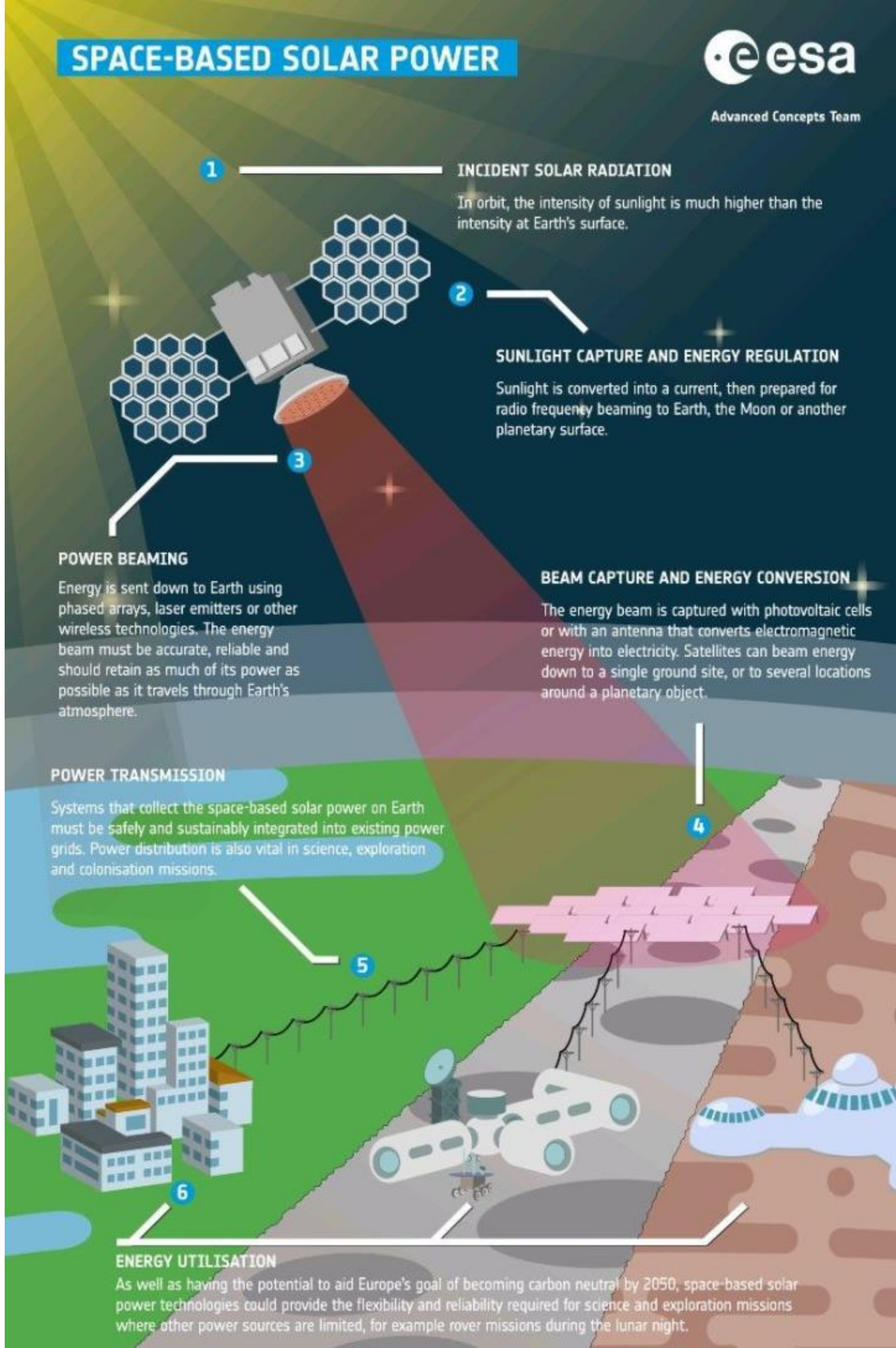
G. Christmann, F. Meyer, J.-W. Schüttauf, M. Krieger, A. Ingenito

14.07.2023

POWERSAIL FINAL PRESENTATION

MOTIVATION: SPACE SOLAR POWER

- Exploiting the abundant stable solar energy in geostationary orbit 24/7 and 30% higher intensity with no atmospheric absorption
- Microwave energy transmission in very large area low power density beam in optical transparency window of atmosphere
- Stable baseload electricity with a clean renewable carbon free alternative
- Limited need for smart grid and storage infrastructure

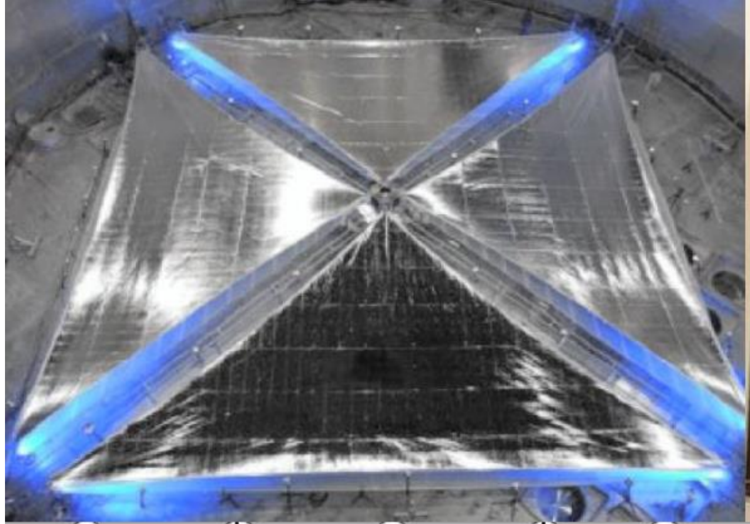


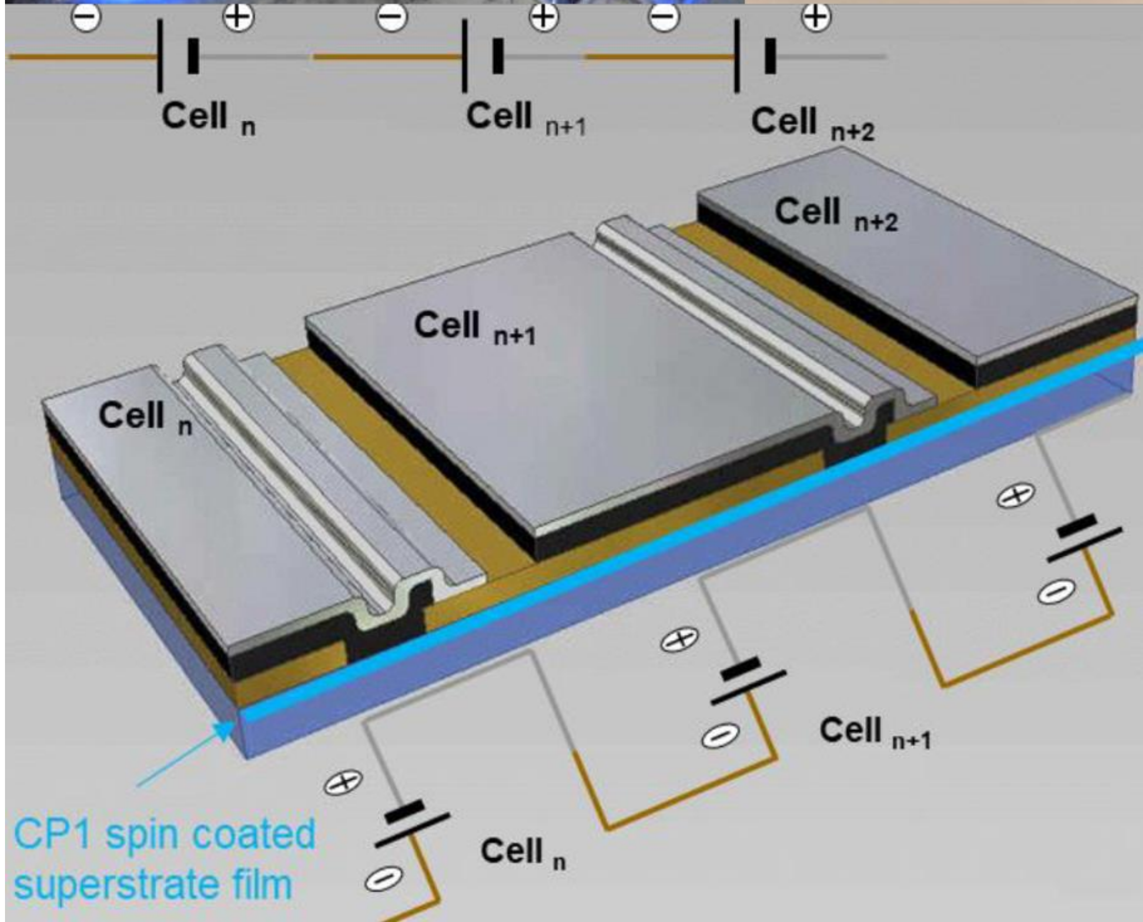
POWERSAIL SOLUTION

- Flexible, a-Si thin-film PV solar arrays from CSEM PV Center
- Space proven CP1 Polyimides from Nexolve
- Superior power density, radiation tolerant
- Superior stowing density
- Modular design scalable to very large high-power arrays
- Significant manufacturing cost savings

➔ Final objective of a project: demonstrator of a 10×10 cm^2 on CP1 for high power density

➔ Proof of concept of the technology





WORKPLAN STRUCTURE

POWERSAIL		start	end	length	2022												2023					
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	**Consolidated specifications**	*1*	*3*	*3*			D1															
T1.1	Material	*1*	*3*	*3*																		
T1.2	Electrical	*1*	*3*	*3*																		
T1.3	Test vehicle	*1*	*3*	*3*																		
T1.4	Tooling	*1*	*3*	*3*																		
2	**Assembly on carrier substrates and process flow testing**	*1*	*6*	*6*					D2, D3													
T2.1	Tooling design	*1*	*6*	*6*																		
T2.2	Taping to carrier	*1*	*6*	*6*																		
T2.3	Validation of assembly in process flow	*1*	*6*	*6*																		
3	**Deposition and Patterning**	*7*	*18*	*12*									D4			D5			D6			
T3.1	Patterning steps on thin films	*7*	*18*	*12*																		
T3.2	Perform sensitivity analysis and provide manufacturing accuracy requirements	*7*	*18*	*12*																		
T3.3	Define breadboard components test plan for validation against requirements	*7*	*18*	*12*																		
4	**Characterization**	*4*	*18*	*15*																		D7, HW
T4.1	Imaging, electrical and dimensional characterization	*4*	*18*	*15*																		
5	**Project Management**	*1*	*18*	*18*													FP, TDP, ESR, SR, TAS, WB, FPR, CCD					
T5.1	Management	*1*	*18*	*18*																		

KOM M1 M2 FP

Milestones
Reviews

WP1: CONSOLIDATED SPECIFICATIONS
T1.1: MATERIALS

DECISIONS

- Polymer choice: CP1, compatible with geostationary and low earth orbit
- Assembly on glass: Spin coating of the polymer on 127 mm x 127 mm glass substrates that are compatible with the whole fabrication process at CSEM
- Glass substrates to be sent to Nexolve and spin coated there and shipped back to CSEM
- Evaluation of potential alternatives in case of procurement issues

IMPLEMENTATION

- Implementation mostly as specified
- Procurement and spin coated sample quality issues ➔ Spin coating at CSEM

WP1: CONSOLIDATED SPECIFICATIONS
T1.2: ELECTRICAL

DECISIONS

- Dead area
  - Outcome: laser spot size is <30µm, dead area due to laser patterning can be made small
  - Dead area due to cell design will be assessed in WP3 and WP4 (after mini-module fabrication)
- Number of segments per mini-module
  - Optimal trade-off between cell area (resistive losses and yield limitations) and interconnection losses to be defined based on the cell performance
- Performance evaluation
  - JV, EQE, lock-in thermography, R for cells (WP4)
  - Profilo, microscope, 4 probe, UV-Vis for individual layers (WP4)

IMPLEMENTATION

- Specifications mostly followed; long tool downtime prevented us from using lock-in thermography

WP1: CONSOLIDATED SPECIFICATIONS
T1.3: TEST VEHICLES

DECISIONS

- Task 1.3: Test Vehicle:
  - Cells and minimodules on glass and polymer coupons
    - ‘Fast loop cells’ (~1 cm^2) to assess cell performance and process development
    - Mini-module with 2 cells in series as proof of concept
    - Intermediate size minimodule
  - Final demonstrator 10x10 cm^2 with several cells connected in series

IMPLEMENTATION

- Specification followed, technical issues with 2 cell test device caused us to drop it

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WP1: CONSOLIDATED SPECIFICATIONS
T1.4: TOOLING

DECISIONS

- Cleaning, laser scribing, and electrode fabrication processes need to be adapted for processing of CP1 on glass substrates of 127x127 mm^2
  - Plastic racks for cleaning
  - Sample holders for sputtering, PECVD and laser

IMPLEMENTATION

- No real decisions, activities were conducted in WP2

Conclusions on WP1:

- Outcome: M1/D1, Consolidated specifications
- Decisions were mostly followed, time to set them was instrumental to the success of the project.

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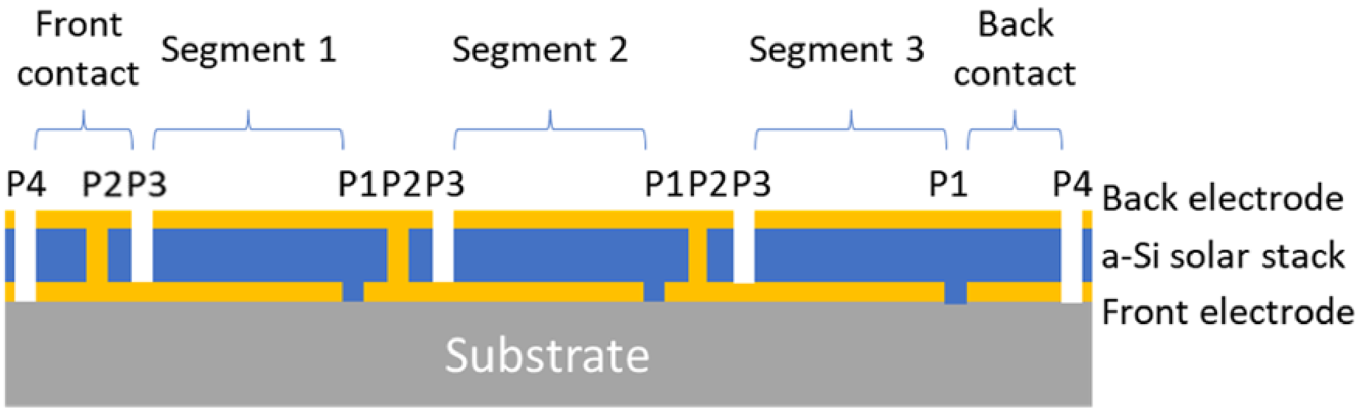
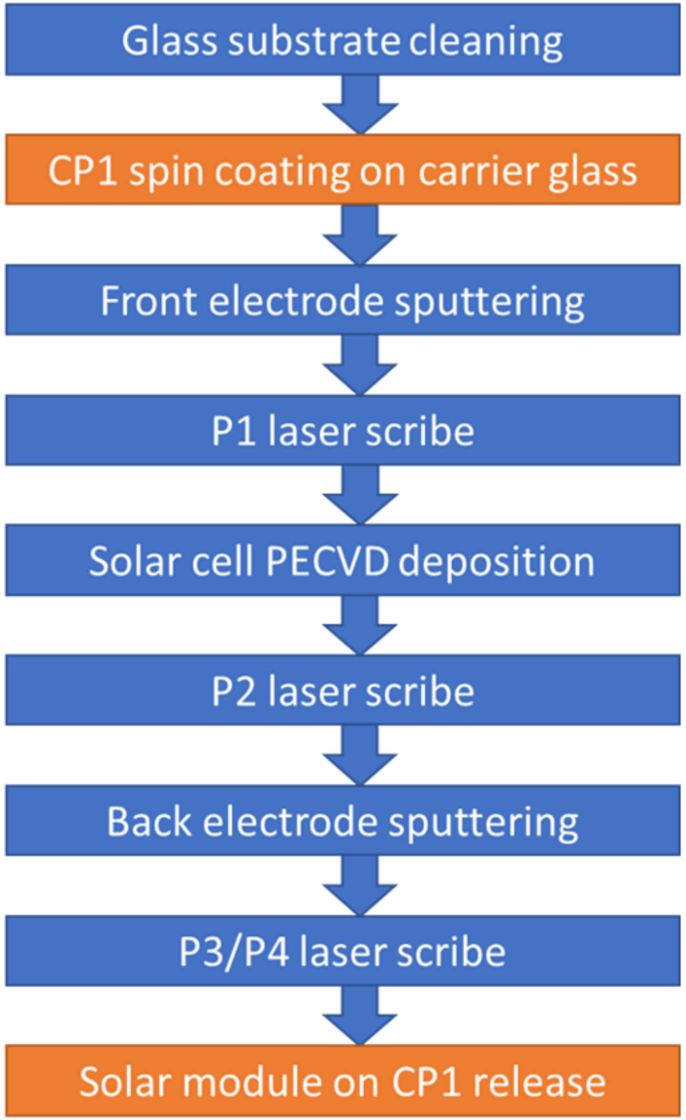
POWERSAIL MODULE PROCESS FLOW





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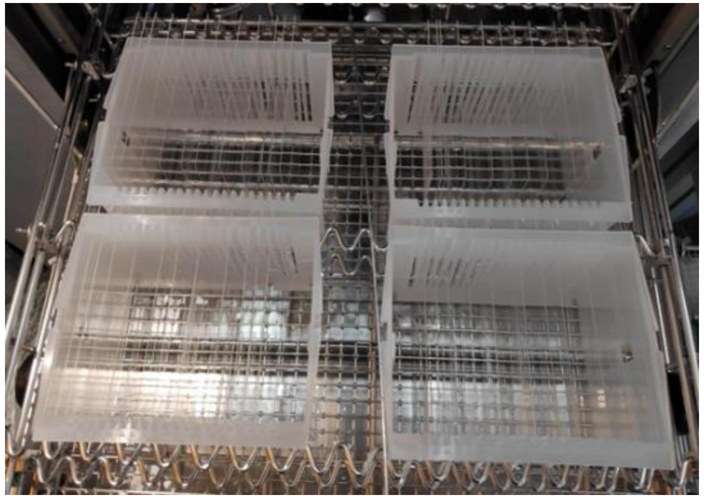
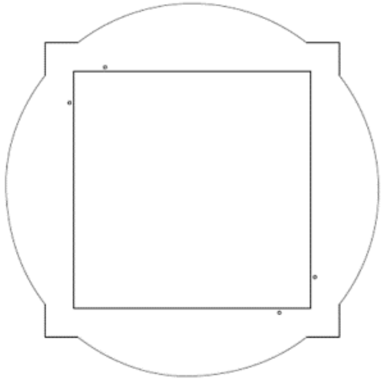
WP2: ASSEMBLY ON CARRIER SUBSTRATES AND PROCESS FLOW TESTING
T2.1: TOOLING DESIGN

Racks, holders, carriers for cleaning, lasering, and deposition equipment

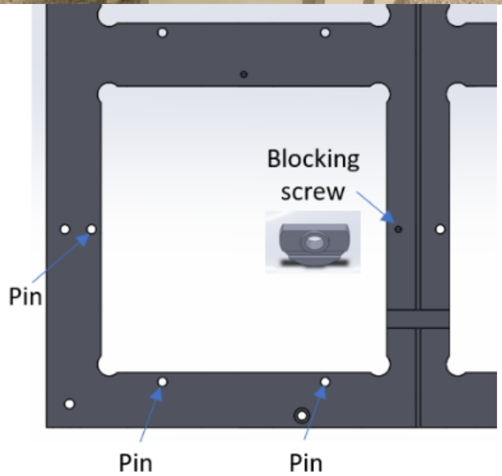
Racks in washing machine



Sputtering tool and carrier



lasering tool and holder



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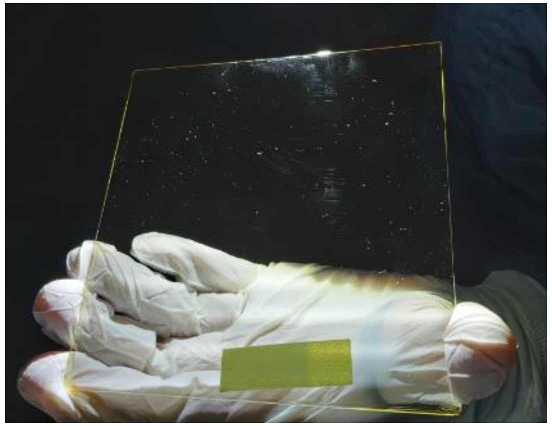
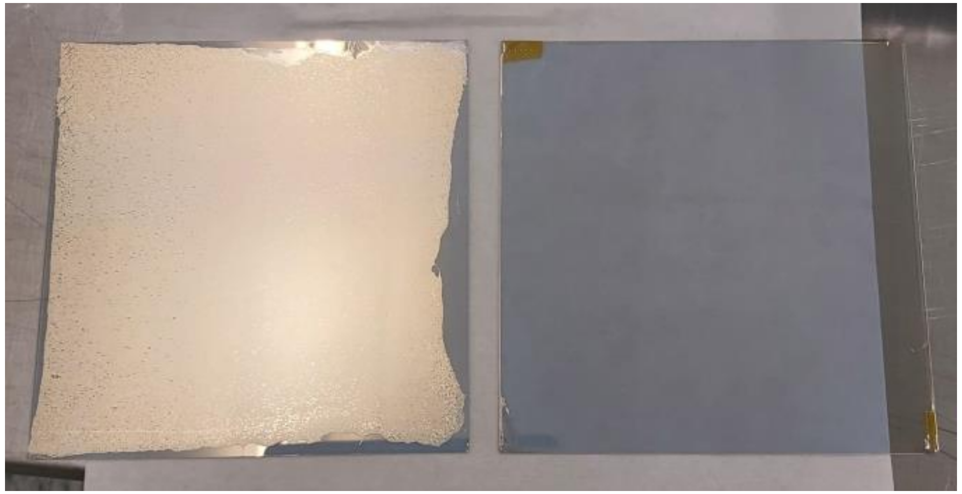
WP2: ASSEMBLY ON CARRIER SUBSTRATES AND PROCESS FLOW TESTING
T2.2: TAPING TO CARRIER



- Material selection (adhesion, release, vacuum compatibility)
  - Initially CP1 spin coated by Nexolve 5, 15 and 25 µm
  - Procurement and quality issues (not cleanroom processed): ➔ in house coating
  - Bar coating and spin coating tested
  - Initially some issues but OK after oven drying process optimization

Rough after electrode deposition   Good process



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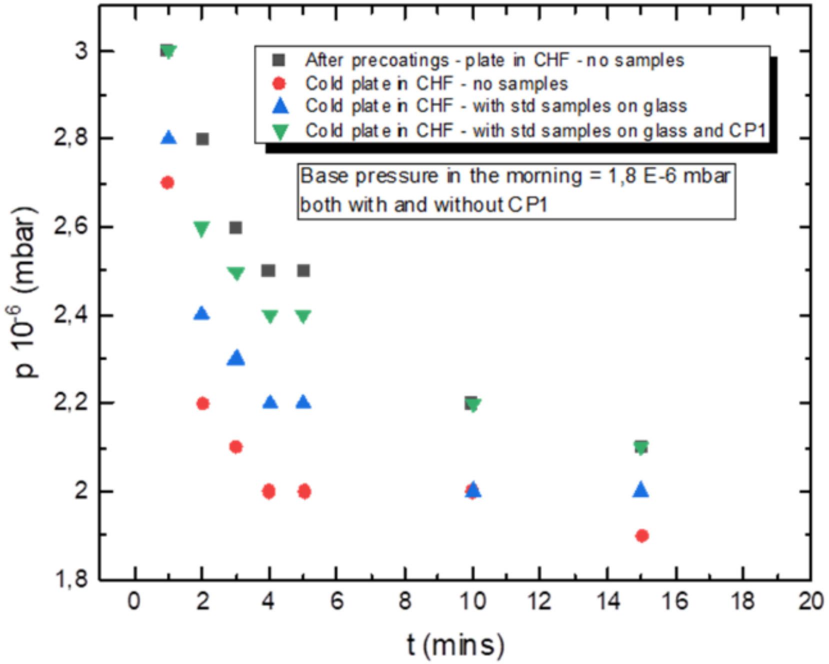
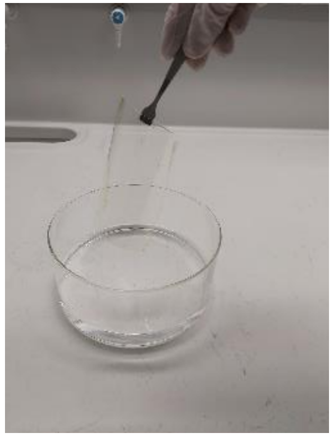
WP2: ASSEMBLY ON CARRIER SUBSTRATES AND PROCESS FLOW TESTING
T2.2: TAPING TO CARRIER

- Material selection (adhesion, release, vacuum compatibility)
  - CP1 spin coated on glass carrier is vacuum compatible (no excessive outgassing)
  - Release of CP1 from glass working prior PECVD
  - After PECVD of the solar cell release of CP1 is more challenging
  - Successful release of fully processed sample with extra care





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WP2: ASSEMBLY ON CARRIER SUBSTRATES AND PROCESS FLOW TESTING
T2.3: VALIDATION OF ASSEMBLY IN PROCESS FLOW

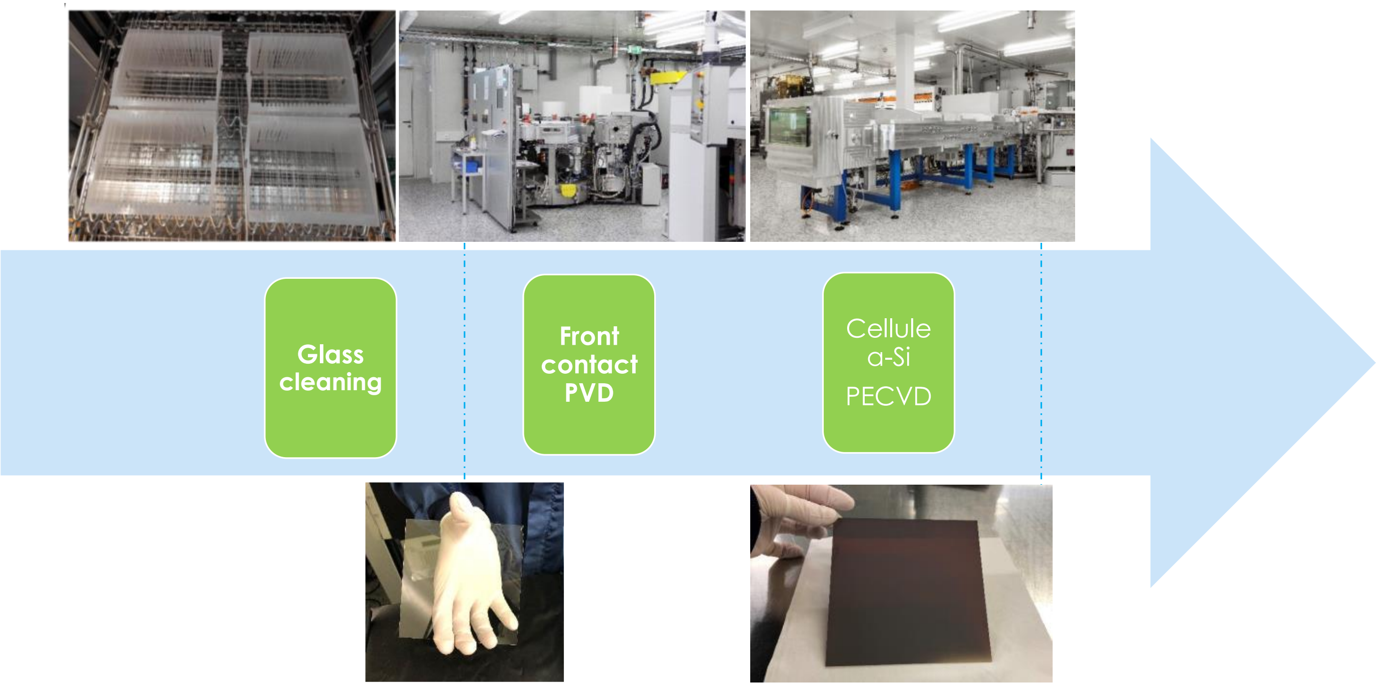
Run typical manufacturing flow on some carriers to validate the test vehicle

➔ Process for TCO and PECVD was validated on a glass substrate with CP1

Conclusions on WP2:

- D2: Tooling design prepared
- D3: Material selection and validation of assembly in the process flow
- M2: Material selection and validation of assembly in the process flow

➔ Ready to start sample fabrication



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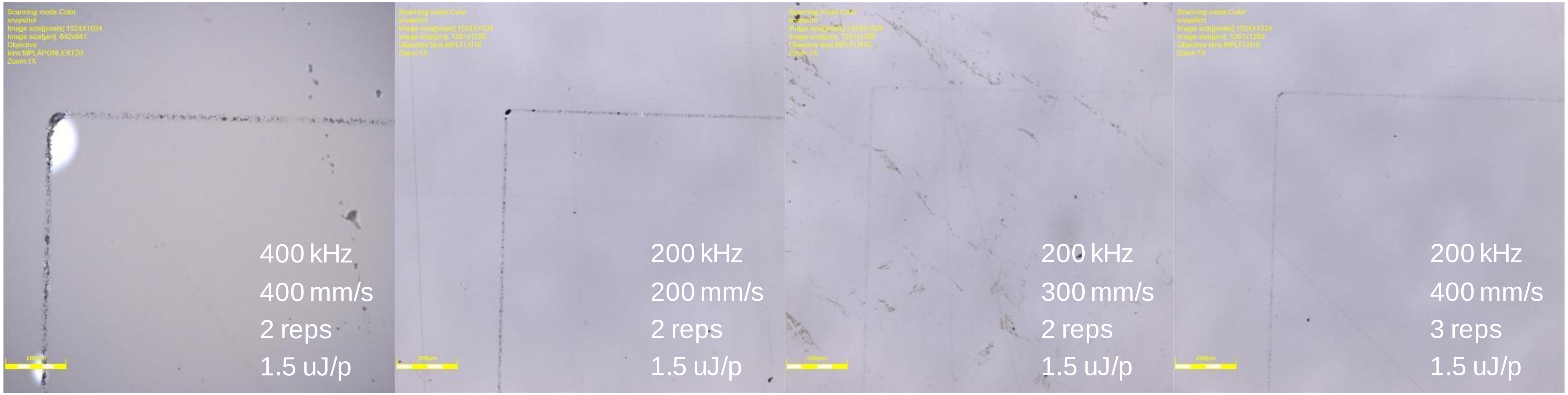
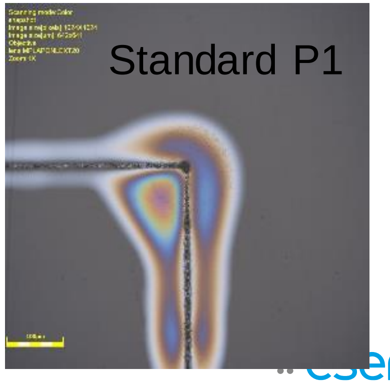
WP3: DEPOSITION AND PATTERNING
T3.1: PATTERNING STEPS ON THIN FILMS

- Challenge of the project: no damage to CP1 films, especially for P1 &P4

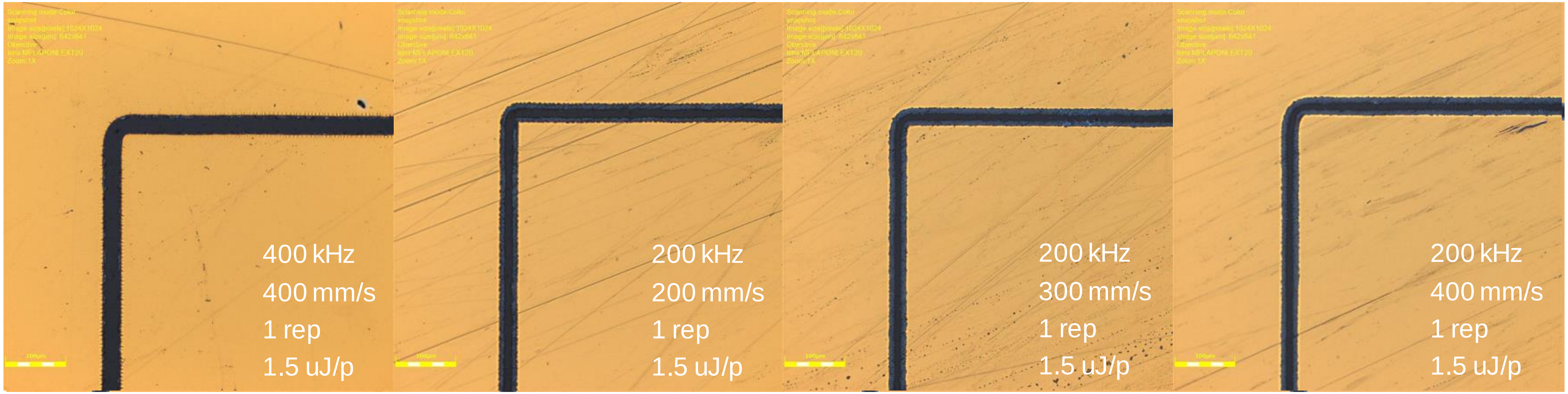


- Process optimization for damage reduction
- High repetition rate & low power helps
- Multiple passes to start seeing damage



WP3: DEPOSITION AND PATTERNING
T3.1: PATTERNING STEPS ON THIN FILMS

- Challenge of the project: no damage to CP1 films, especially for P1 &P4



  - All conditions explored are capable to ablate the front electrode
  - Condition with lowest damage is chosen to prevent potential risk of damage of the CP1
  - Infinite resistance measured between the 2 opposite sides of the ablated regions confirming the etching of the TCO

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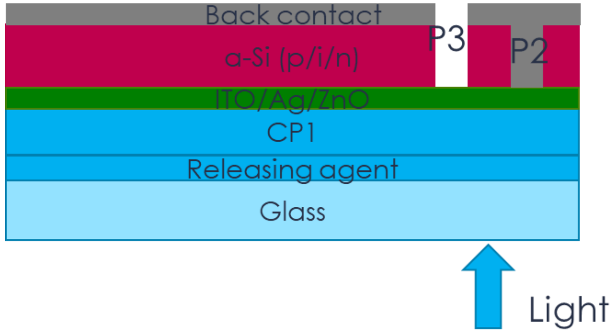
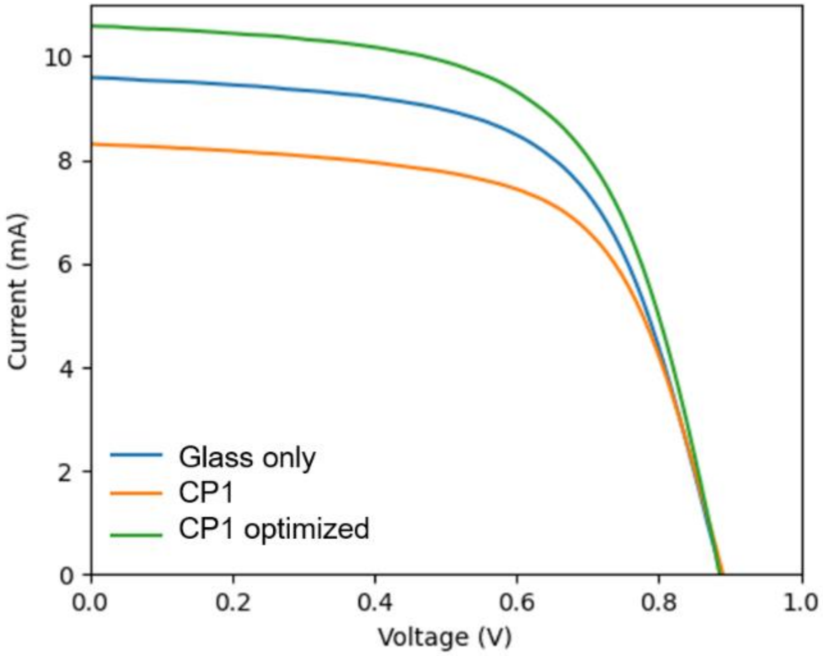
WP3: DEPOSITION AND PATTERNING
T3.2: SOLAR CELLS ON THIN FILM POLYMER



Substrate	Voc (mV) AM1.5	Jsc (mA/cm2) AM1.5	FF (%) AM1.5	Eff (%) AM1.5
Glass	888	9.2	61.5	5.1
CP1	890	8.0	63.1	4.5
CP1 optimized	886	10.18	61.2	5.74

- Initial test comparing process on glass and on CP1
- Efficiency loss due to CP1 absorption
- Optimized cell at project end (optimized front electrode and thin CP1)

➔ Process validated P2 and P3 validated (D5, D6)



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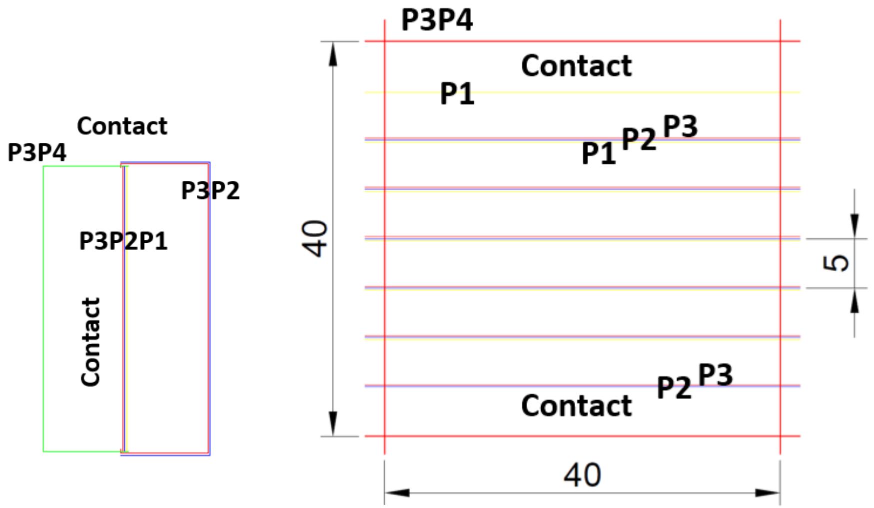
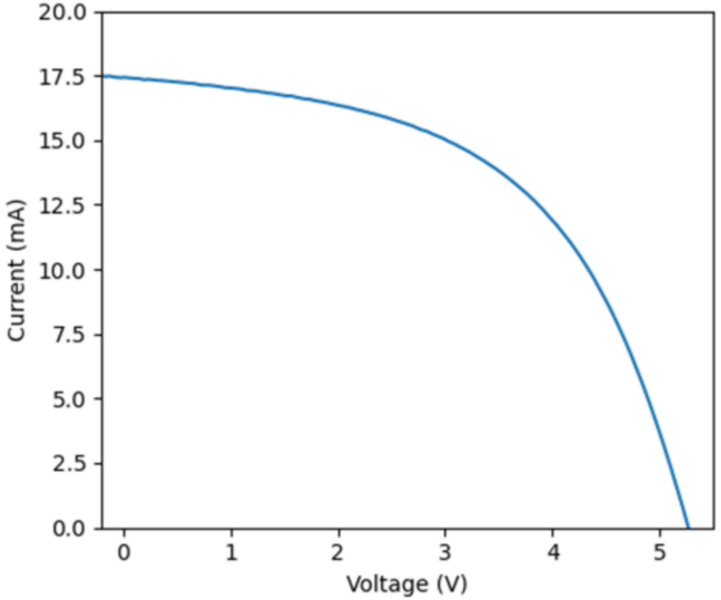
WP3: DEPOSITION AND PATTERNING
T3.3: INTERCONNECTION OF PV CELLS TO REALIZE A MINI-MODULE

- Developments of intermediate designs before realizing full size mini-module
- Issues with first design to test two cell interconnect. Move directly to intermediate size minimodule
- Successful demonstration of a 3×4 cm^2 active region minimodule

Voc (mV) AM1.5	Isc (mA) AM1.5	FF (%) AM1.5	Eff (%) AM1.5
5.27	17.43	53.01	4.05

→ Module interconnection process validated, P1 and P4 validated (D4, D7)





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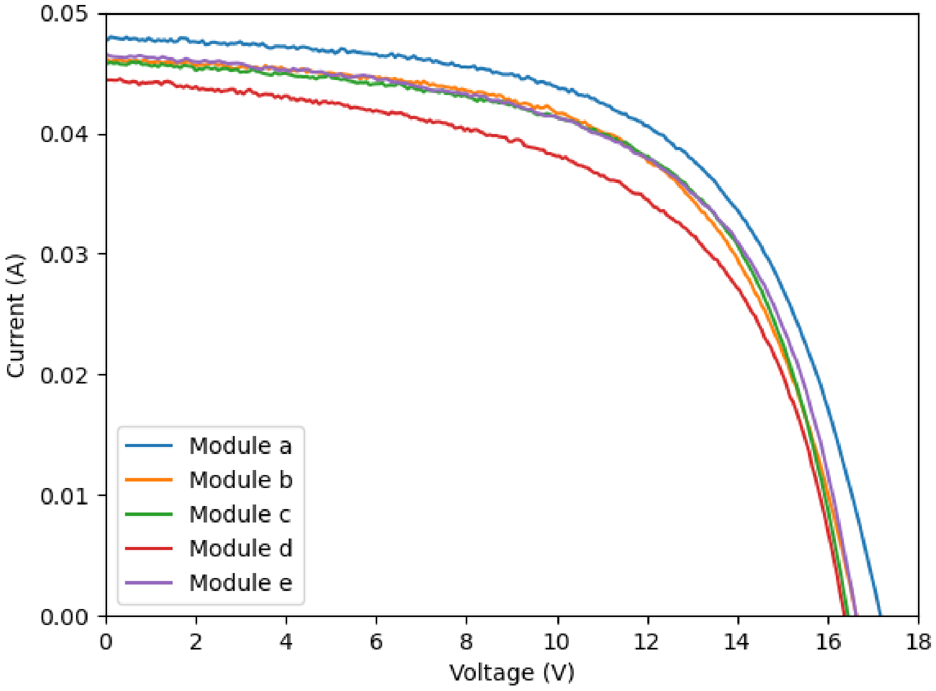
WP3: DEPOSITION AND PATTERNING
T3.3: INTERCONNECTION OF PV CELLS TO REALIZE A MINI-MODULE

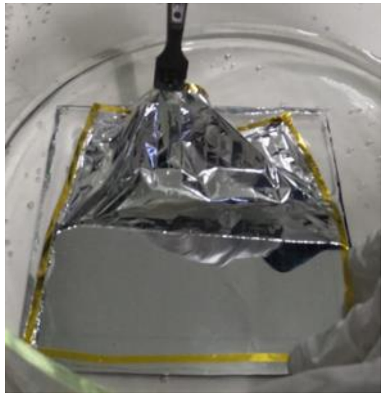
- Deposition of full-size prototype mini-modules
- 10×10 cm^2 active region 20 segments ~10% dead area
- Successful fabrication of several working minimodules

Voc (mV) AM1.5	Isc (mA) AM1.5	FF (%) AM1.5	Eff (%) AM1.5	Pmpp (W) AM 1.5
17.18	47.91	59.81	4.92	0.49
16.64	46.12	59.33	4.55	0.46
16.46	45.84	61.01	4.60	0.46
16.37	44.48	56.82	4.14	0.41
16.64	46.47	59.29	4.58	0.46



- Successful release from substrate and ultralight weight confirmed (85 mg)
- **Best performance 5591 W/kg (AM 1.5g)**

➔ **Successful demonstration of ultralight weight solar module. HW validated**



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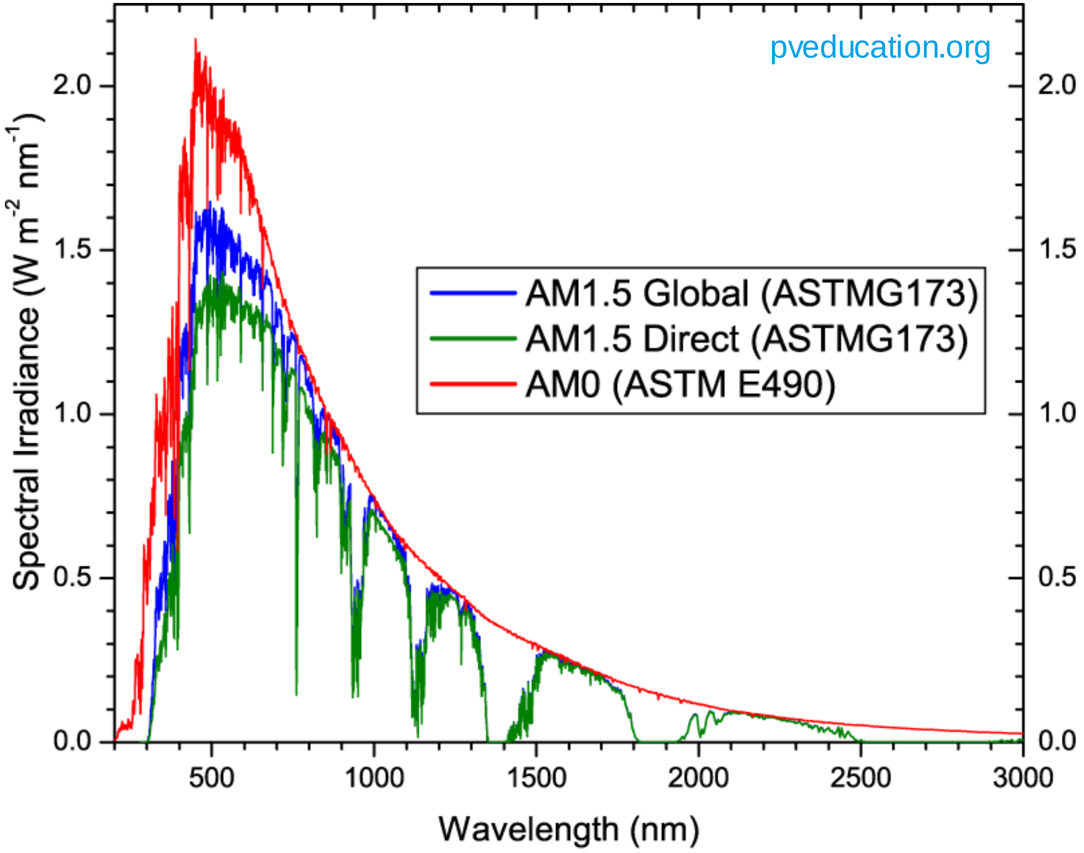
WP4: CHARACTERIZATION AM0 EVALUATION



INTENSITY

AM0: 1'367 W/ m^2

AM1.5: 1'000 W/ m^2

➔ 37% increase in intensity

SPECTRAL

AM0: APE (350-820 nm) = 2.373 eV

AM1.5g: APE (350-820 nm) = 2.268 eV

➔ 4.6% blue shift in APE

a-Si:H SJ solar cells have spectral response between (roughly) 350 nm (TCO bandgap) and 820 nm (~end of a-Si:H absorption edge)

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WP4: CHARACTERIZATION
AM0 EVALUATION

- Matter of fact: at CSEM we have a class AAA AM1.5 Solar Simulator
- We do not have a readily available AM0 Solar Simulator
- We can use a Fresnel lens to increase the intensity of the AM1.5 SolSim

Open Questions:

- Can we measure under AM0 conditions (intensity, spectrum) ?
- To what extent are AM0 and AM1.5 measurements comparable ?
- To what extent should cells be optimized the same way for both spectra ?

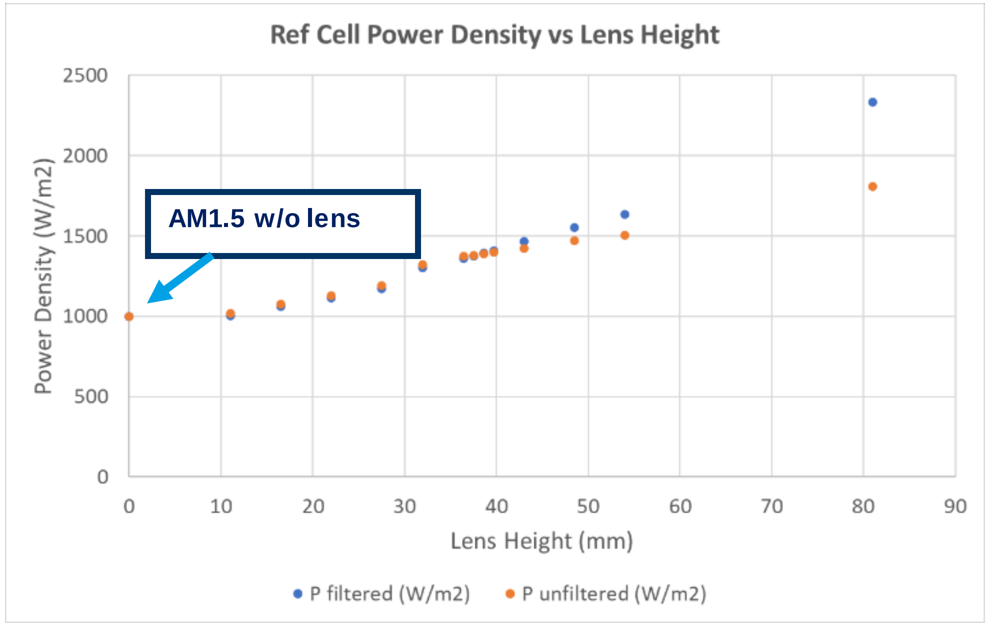
WP4: CHARACTERIZATION AM0 EVALUATION

Fresnel lens above (ref) cell under solar simulator

with controllable height adjustment

WP4: CHARACTERIZATION
AM0 EVALUATION

Height (mm)	Relative Isc filtered ref cell vs AM1.5	Relative Isc unfiltered ref cell vs AM1.5	Relative Ratio Filtered/Unfiltered
w/o lens	1.001	0.999	1.00
32.0	1.303	1.320	0.99
36.4	1.358	1.373	0.99
37.5	1.377	1.381	1.00
38.6	1.393	1.391	1.00
39.7	1.409	1.397	1.01



Unfiltered cell: monocrystalline Si SJ solar cell

Filtered cell: monocrystalline Si SJ solar cell with spectrally matched optical filter to mimic a-Si:H cell

➔ no significant spectral shift when using Fresnel lens up to 1.4 Sun, blueshift for higher concentration

➔ Estimated difference between ref cell height and a-Si:H cell height: 1-2 mm (approx 1% error)

WP4: CHARACTERIZATION
AM0 EVALUATION

- ‘Rough cell’: CSEM baseline

  Structure: Glass / ZnO:B / pin a-Si:H / ITO / Ag

- ‘Flat cell’: Rather representative structure for Powersail

  Structure: Glass / ITO / ZnO:Al (thin barrier) / pin a-Si:H / ITO / Ag

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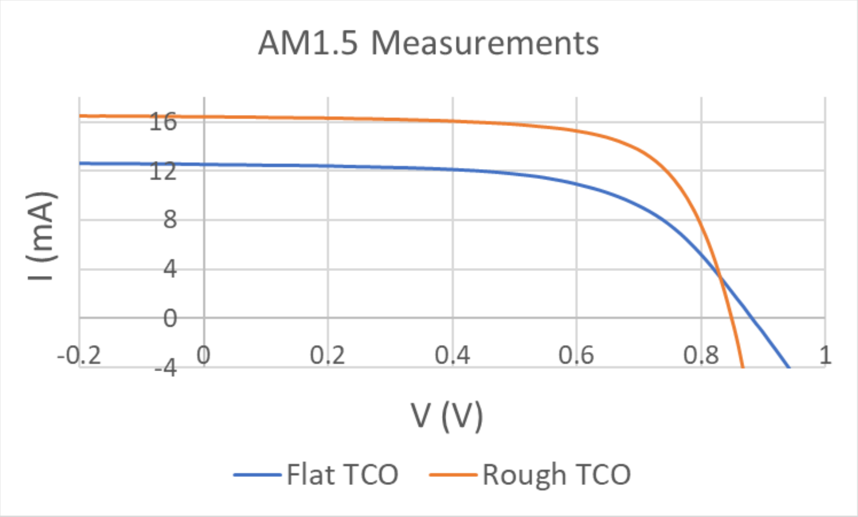
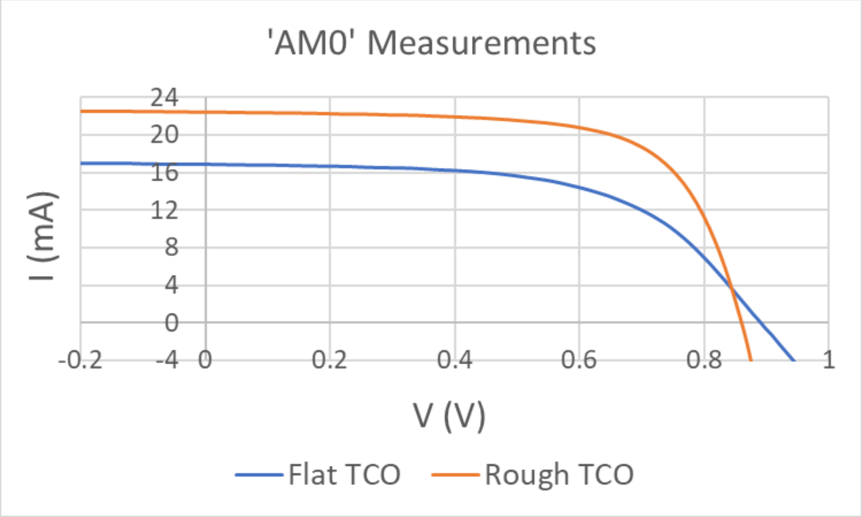
WP4: CHARACTERIZATION
AM0 EVALUATION





AM1.5	Voc (mV)	Isc (mA)	FF (%)	Pmpp (mW)	Roc (Ohm)	Rsc (Ohm)	Eff (%)
Flat	883	12.6	60.1	6.67	15.1	1637	6.41
Rough	850	16.4	69.2	9.65	5.0	2486	9.26
«AM0»	Voc (mV)	Isc (mA)	FF (%)	Pmpp (mW)	Roc (Ohm)	Rsc (Ohm)	Eff (%)
Flat	892	16.9	58.1	8.77	13.2	1584	6.21
Rough	861	22.4	68.2	13.15	4.1	1507	9.30

Flat:

Jsc ratio = 1.34

Rough:

Jsc ratio = 1.37

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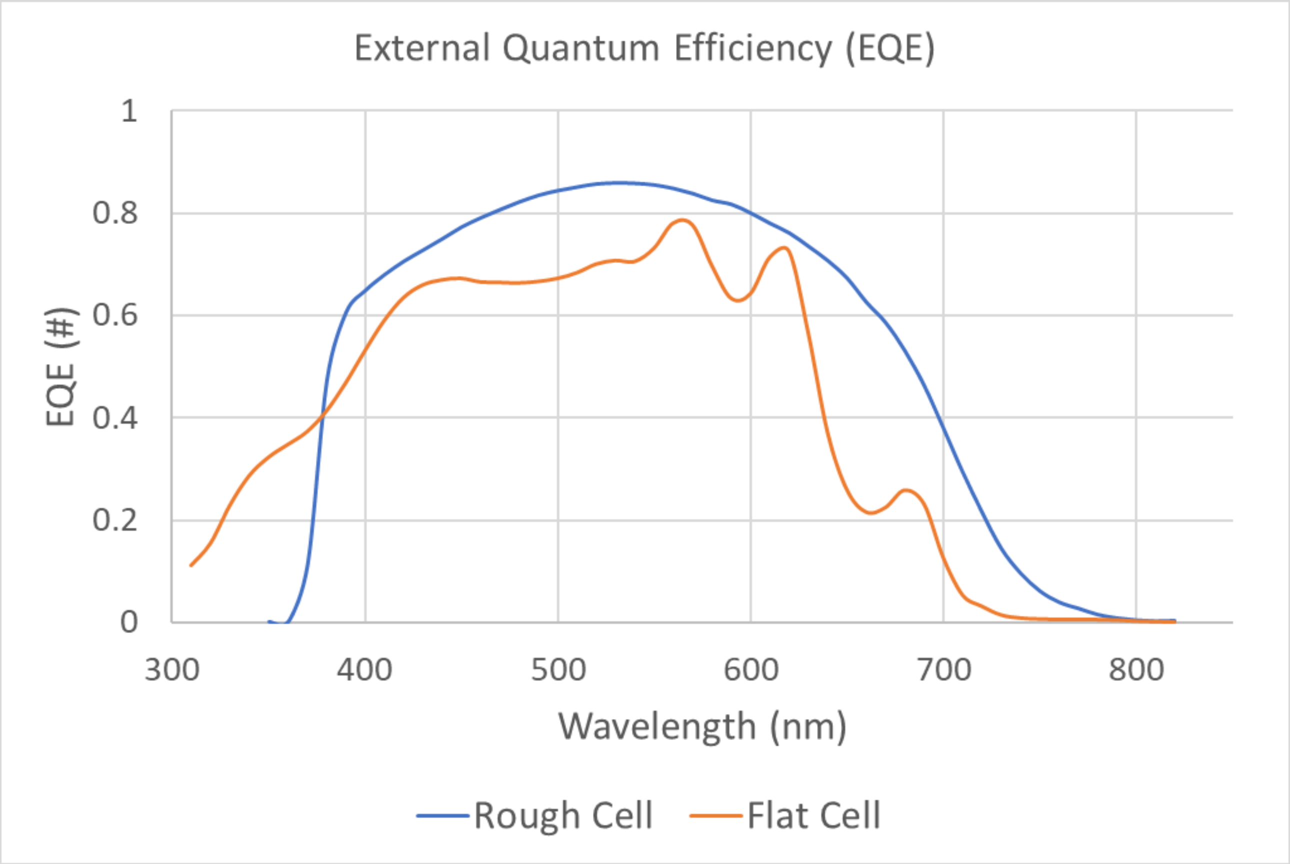
WP4: CHARACTERIZATION AM0 EVALUATION



Flat cell: high reflection, and interference fringes

Higher response in the far blue (ITO vs thick ZnO:B)

Jsc values as determined from EQE measurements in mA/cm^2

Type	AM0	AM1.5	Ratio EQE	Ratio I-V
Rough	18.86	15.32	1.23	1.37
Flat	14.54	11.54	1.26	1.34

EQE Jsc Ratio lower than 1.37 for spectral density, mostly due to spectral losses in the blue

-> Previous IV measurements overestimate power output by approx 10%

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WP4: CHARACTERIZATION
AM0 EVALUATION

Efficiency Estimation (our best guess)

According to best practice, using Voc & FF from I-V, corrected Jsc from I-V

EQE gives 3-5% lower Jsc than I-V (calibration, bias light, spectrum, alignment, ….)

Isc values from I-V considered more reliable (more accurate calibration, area definition and illumination)

Correcting for AM1.5 Jsc ratio from SolSim

AM1.5	Voc (mV)	Jsc (mA/cm2)	FF (%)	Eff (%)
Flat	883	12.09	60.1	**6.41**
Rough	850	15.77	69.2	**9.26**
AM0	**Voc (mV)**	**Jsc (mA/cm2)**	**FF (%)**	**Eff (%)**
Flat	892	15.23	58.1	**5.81**
Rough	861	19.41	68.2	**8.34**

Our best guess

AM1.5: Parameters from I-V measurement

AM0: Voc, FF from I-V, Current scaled to ratio from EQE to take spectral shift into account

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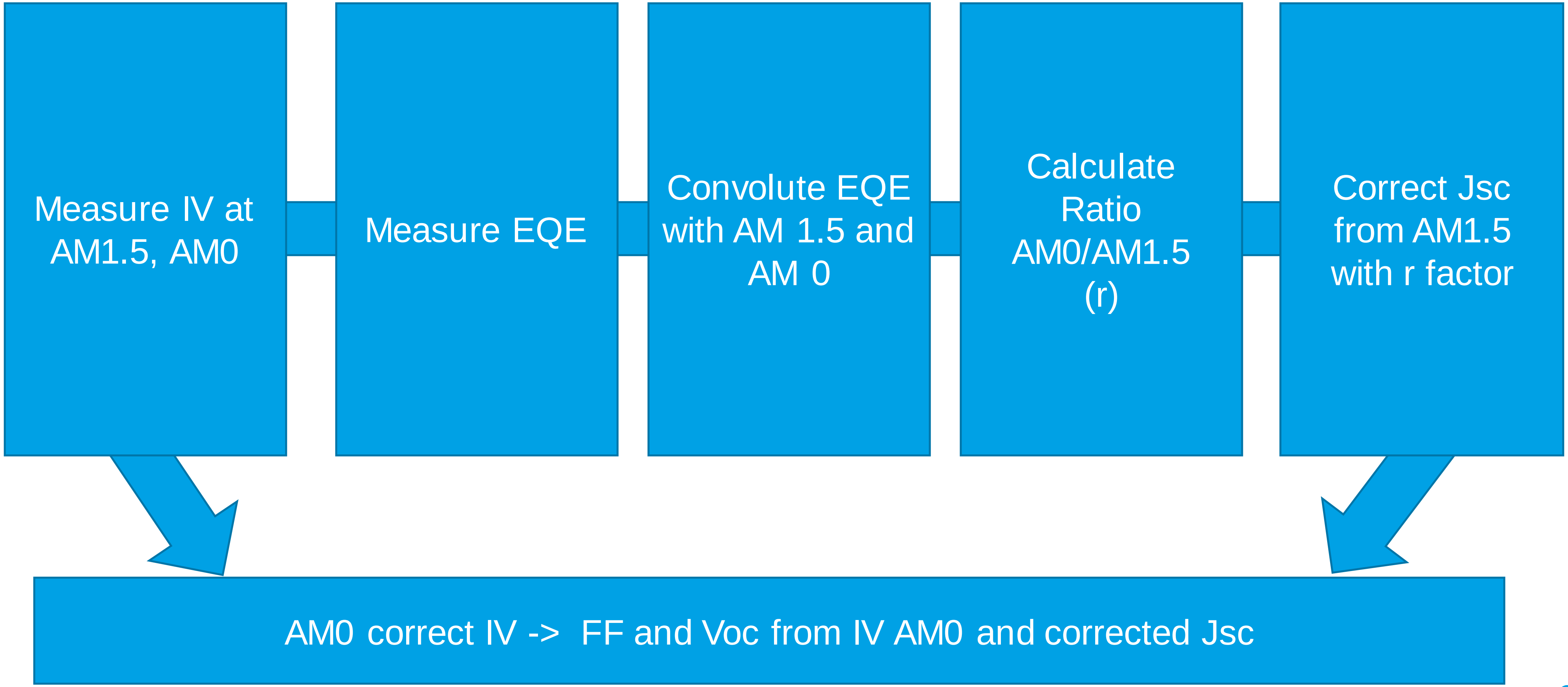
WP4: CHARACTERIZATION AM0 EVALUATION

Diagram flow for best guess estimation solar cell performance under AM0



FINAL DISCUSSIONS

- After applying correction for AM0, test module has close to 7000 W/kg performance
- Process improvements based on current design are estimated improve output power by 10% without weight penalty
- Implementing light trapping schemes or multijunction may lead to significantly higher efficiency (10%+ possible), but gains may be offset by extra weight (cell already amounts to 36% of total weight)
- In the end the full system, including deployment will have to be considered. This will have a crucial impact on th

Material	Thickness (nm)	Density (g/cm^3)	Mass per area (mg/cm^2)
CP1	3000	1.54	0.462
ITO	45	7.14	0.032
Ag	12	9.32	0.011
ZnO:Al	120	5.61	0.067
Si	420	2.33	0.098
Al	200	2.7	0.054
		Total	0.724

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CONCLUSIONS

- Process flow to fabricate ultralight weight mini-modules established successfully
- Device conversion efficiency is rather low at this demonstrator stage (<5%)
- Measured power of 0.49 W for 10x10 cm2 module and weight of 85 mg under AM 1.5g (terrestrial).
- Estimated power of 0.58 W and weight of 85 mg under AM0 (space) illumination.
- Technology potential for large scale cheap solar power satellites demonstrated
- Next steps to develop the technology:
  - Improve module efficiency
  - Study module reliability in space
  - Develop deployment systems
  - Upscale fabrication to large area roll to roll process

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DELIVERABLES

Doc ID	Title	Milestone	No. of copies/format to be delivered to	e-copy to DMS (*)
PH	Photographic Documentation	Final Review	Two electronic images/graphics files. All material should be free of copyright restrictions and ready to be used by to agency for communication activities towards the public. File to be delivered to the ESA Technical Officer.	no
TAS	Technology Achievement Summary (mandatory only for Early Technology Development activities)	Final Review	Electronic file using the Technology Achievement Template to be delivered to the ESA Technical Officer.	no
FP	Final Presentation	Final Review	Electronic file in the form of a slide editor tool file (e.g. PowerPoint or compatible) to be delivered to the ESA Technical Officer.	yes
FPR	Final Presentation Recording	Final Review	A digital movie file between 1min and 3min length summarising the activity results. File to be delivered to the ESA Technical Officer.	no
ESR	Executive Summary Report (**)	Final Review	Electronic searchable, indexed and not encrypted PDF and native (WORD) file to be delivered to the ESA Technical Officer and Contracts Officer. In addition to the above, one (1) electronic searchable, indexed and not encrypted PDF and native (WORD) file shall be sent to the ESA Information and Documentation Centre – ESTEC Library (email: esa.ids@esa.int).	yes
FR	Final Report (**)	Final Review	Electronic searchable, indexed and not encrypted PDF and native (WORD) file to be delivered to the ESA Technical Officer and Contracts Officer. In addition to the above, one (1) electronic searchable, indexed and not encrypted PDF and native (WORD) file shall be sent to the ESA Information and Documentation Centre – ESTEC Library (email: esa.ids@esa.int).	yes

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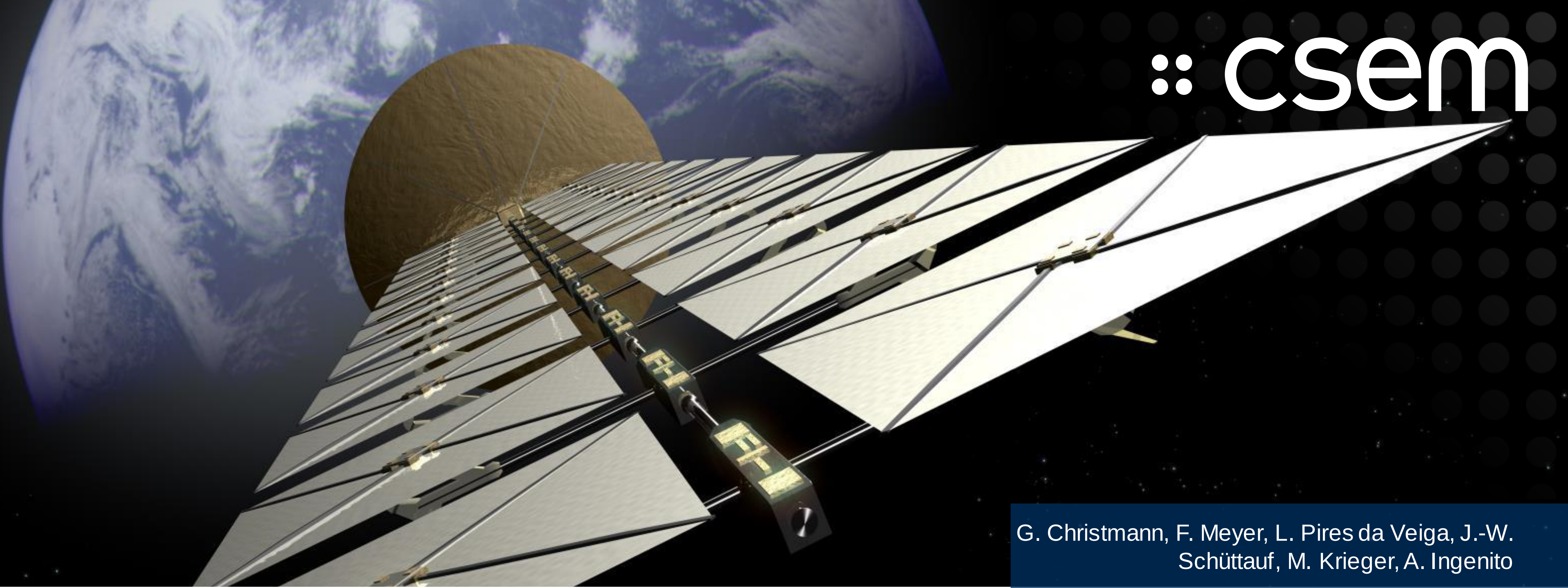
FACING THE CHALLENGES OF OUR TIME



G. Christmann, F. Meyer, L. Pires da Veiga, J.-W. Schüttauf, M. Krieger, A. Ingenito

14.07.2023

POWERSAIL

DISRUPTIVE PV POWER ARRAY TECHNOLOGY TO ENABLE ECONOMIC VIABILITY OF SPACE POWER SATELLITES

MOTIVATION: SPACE SOLAR POWER

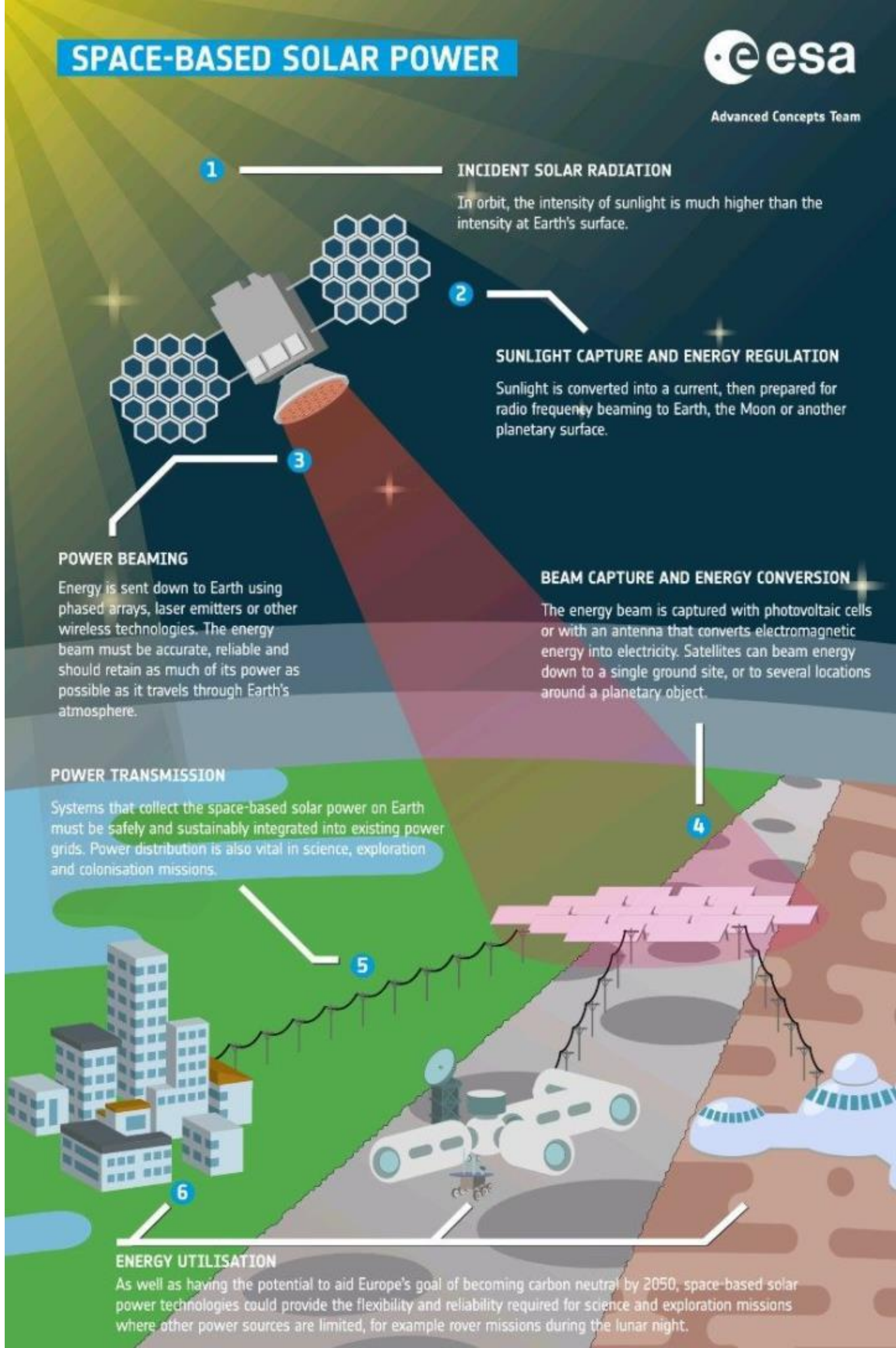
Exploiting the abundant stable solar energy in geostationary orbit 24/7 and 30% higher intensity

A lot of space in space

Large area deployable structures

Lightweight solar panels

➔ Demonstrator of a 10×10 cm^2 solar module on space grade polyimide for high power density



ULTRALIGHT DEMONSTRATOR MODULES

Successful fabrication of demonstrator modules

Based on cheap industrially proven technology

Low efficiency (<5%) but ultralight weight resulting in very high power density: 85 mg for 0.58 W. Deployment system will have an impact at satellite level

W/kg potential proven, next steps: improve efficiency, test reliability and upscale

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