Analytical calculation of encapsulation-induced variation of PV modules efficiency

Maider Machado[1], Tomás Baenas[2], Naiara Yurrita[1]

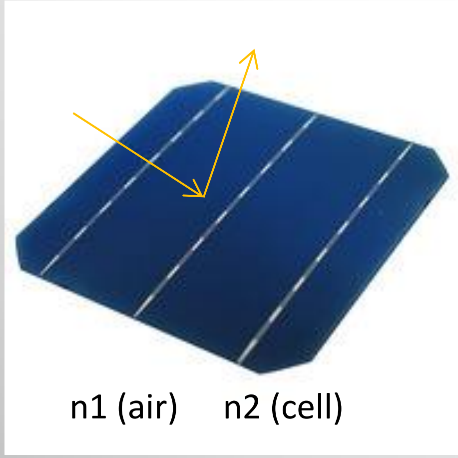
[1]Solar Energy group, Tecnalia Research and Innovation (Spain)
[2] Applied Mathematics Dept., University of Alicante (Spain)

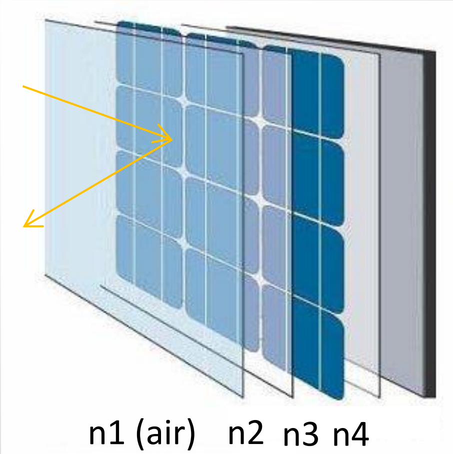
Universitat d'Alacant
Universidad de Alicante

- Multiple encapsulation configurations can be conceived in the design phase of PV modules (specially BIPV modules).
- Evaluation of performance of encapsulation materials in terms of their effect on module efficiency is required.
- Manufacturing and experimental characterization of every possible combination (superstrate and polymer interlayer types, thickness, colour, etc.) is costly and time demanding.

- Short-circuit current density is directly related with spectral absorptivity of the PV cells in encapsulated conditions.

- Absorptivity of encapsulated PV cells is not accessible from spectrophotometry. Calculation needed.

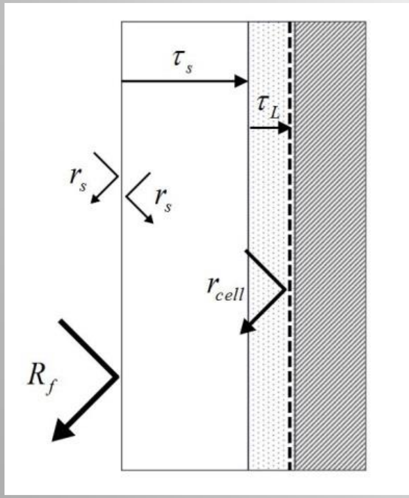




Calculation of layer-by-layer absorption in a PV module

- Literature: numerical ray-tracing, multidirectional numerical net radiation methods, etc.

- This work: separation in optical components, each of them defined through a transfer matrix connecting energy fluxes.



Optical model:

T. Baenas, M. Machado, Solar Energy 125 (2016) 256 – 266

http://authors.elsevier.com/a/1SKRE,tRcw4aW

- The reflectivity of the cell, r_{cell}, is introduced through a virtual opaque coating component.

- Singular solution to the equation system for the energy coefficients of the optical system:

$$r_{cell} = \frac{R_f - r_s}{\tau_S^2 \tau_L^2 (1 - 2r_s + R_f r_s)}$$

- R_f, r_s, τ_s, τ_L are obtained from spectrophotometry and well-known, standardized calculations (EN 410).

- Once determined, r_{cell} may be applied to any other config.

- The model also provides simple analytical expressions for layer-by-layer absorptance:

$$A_{mod} = (1 - r_s)\frac{1 - r_{cell}\tau_s^2\tau_L^2}{1 - r_s r_{cell}\tau_s^2\tau_L^2},$$

$$A_{cell} = (1 - r_s)(1 - r_{cell})\frac{\tau_s\tau_L}{1 - r_s r_{cell}\tau_s^2\tau_L^2},$$

$$A_{enc} = (1 - r_s)\,(1 - \tau_s\tau_L)\frac{1 + \tau_s\tau_L r_{cell}}{1 - r_s r_{cell}\tau_s^2\tau_L^2},$$

$$A_{mod} = 1 - R_f = A_{cell} + A_{enc}$$

Relationship between A_{cell} and short-circuit current

Short-circuit current of a bare cell

$$J_{sc,\,bare} = q\int_{\lambda_1}^{\lambda_2} \phi(\lambda) EQE_{bare}(\lambda) d\lambda$$

Short-circuit current encapsulated cell

$$J_{sc,\,mod} = q\int_{\lambda_1}^{\lambda_2} \phi(\lambda) EQE_{mod}(\lambda) d\lambda$$

$$IQE_{mod}(\lambda) = \frac{EQE_{mod}(\lambda)}{A_{cell}(\lambda)}$$

$A_{cell} \equiv$ Encapsulated cell absorptivity

Solar Energy 125 (2016) 256-266

- IQE of a bare cell is easily determined from air-cell spectral response and reflectance measurements.

- It is assumed here that this magnitude is intrinsic to the cell, so that,

$$IQE_{bare}\,(\lambda) = IQE_{mod}\,(\lambda)$$

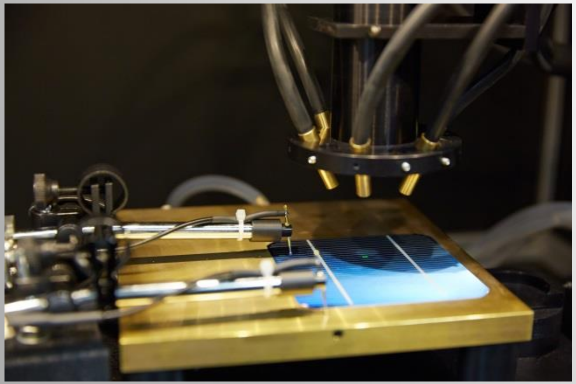
Short-circuit current of encapsulated cell

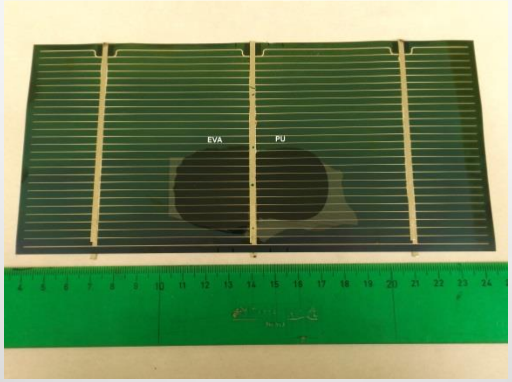
$$J_{sc,\,mod} = q\int_{\lambda_1}^{\lambda_2} \phi(\lambda) IQE_{bare}(\lambda)\, A_{cell}(\lambda) d\lambda$$

Experimental validation: short-circuit current

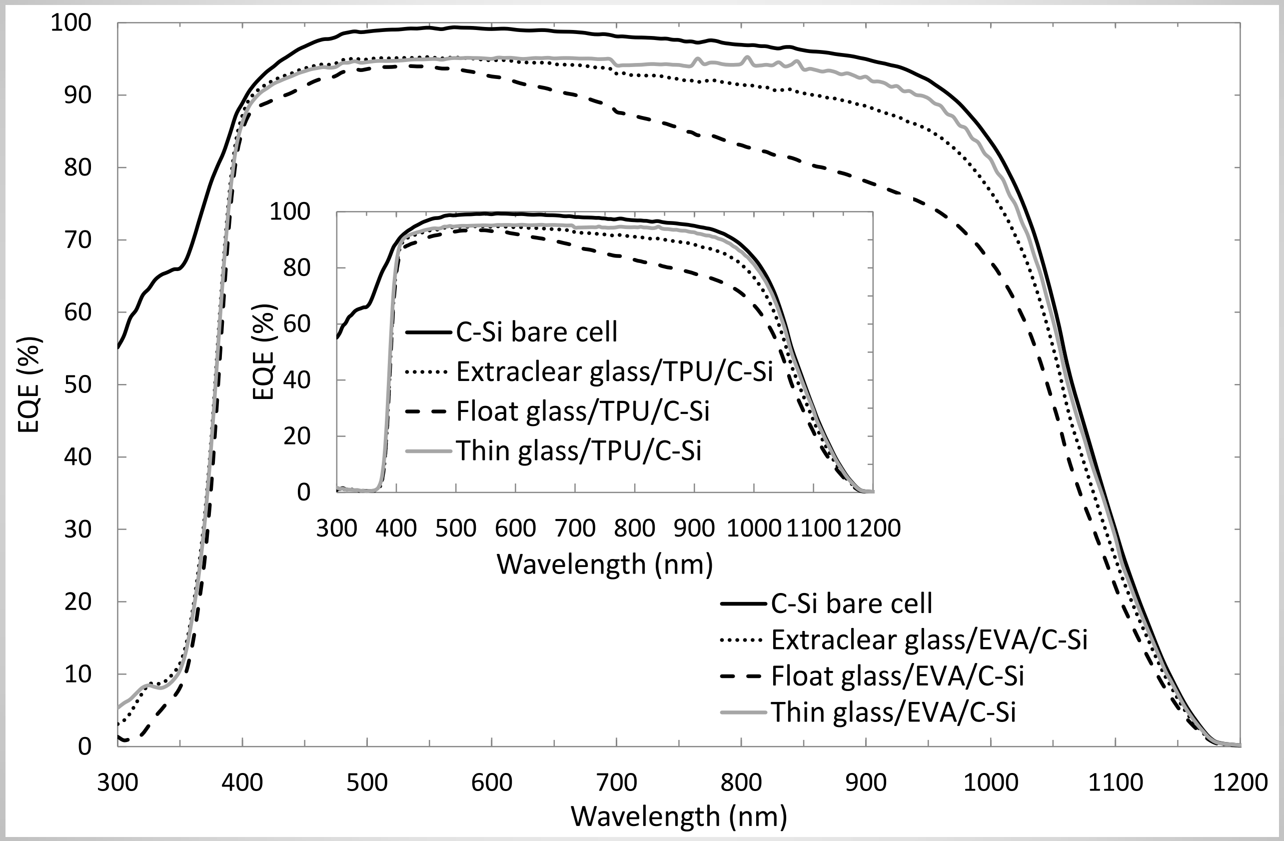
- Experimental and calculated short-circuit current for 12 encapsulation configurations have been compared.

- All combinations of commercial c-Si and CIGS cells with extraclear, float and thin glass superstrates, EVA and TPU encapsulation materials tested.





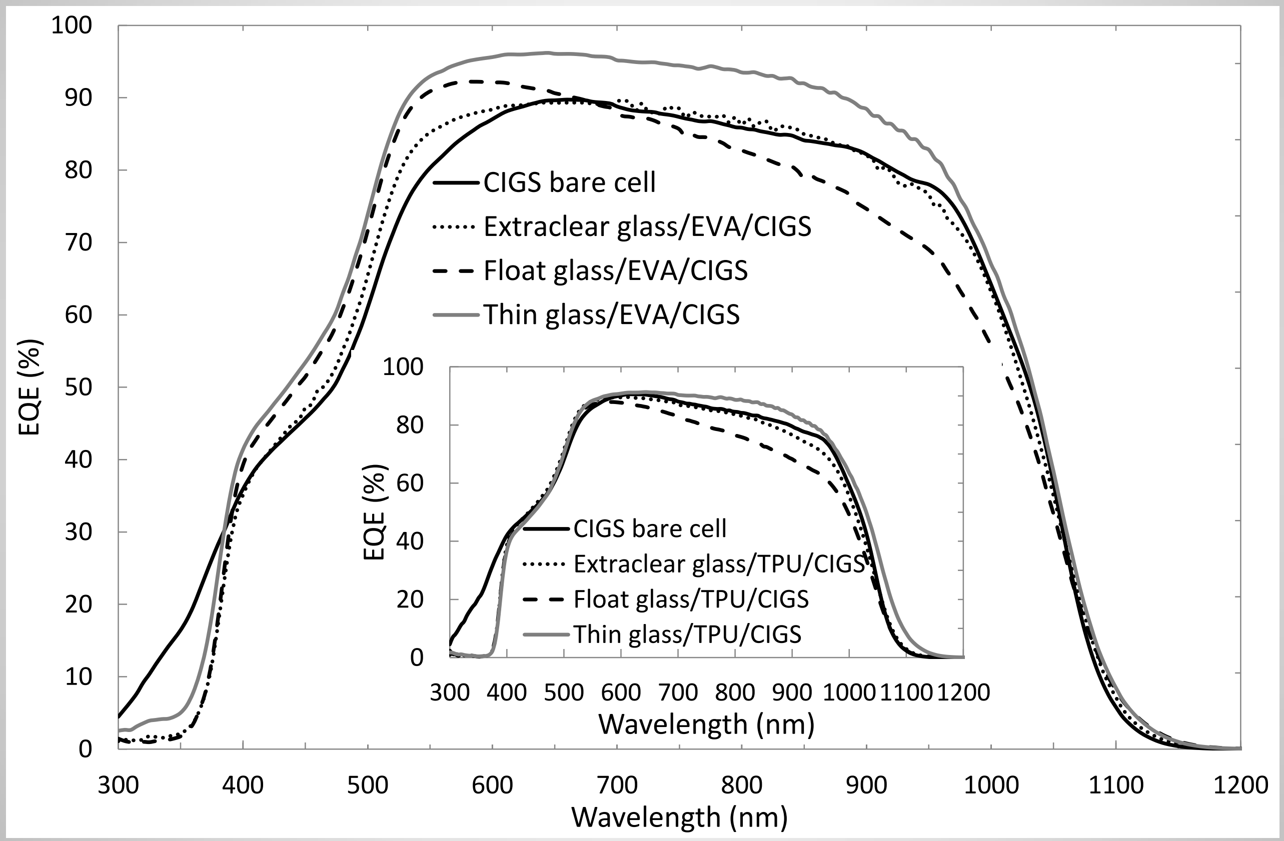
Experimental External Quantum Efficiency- Silicon cell



Experimental validation

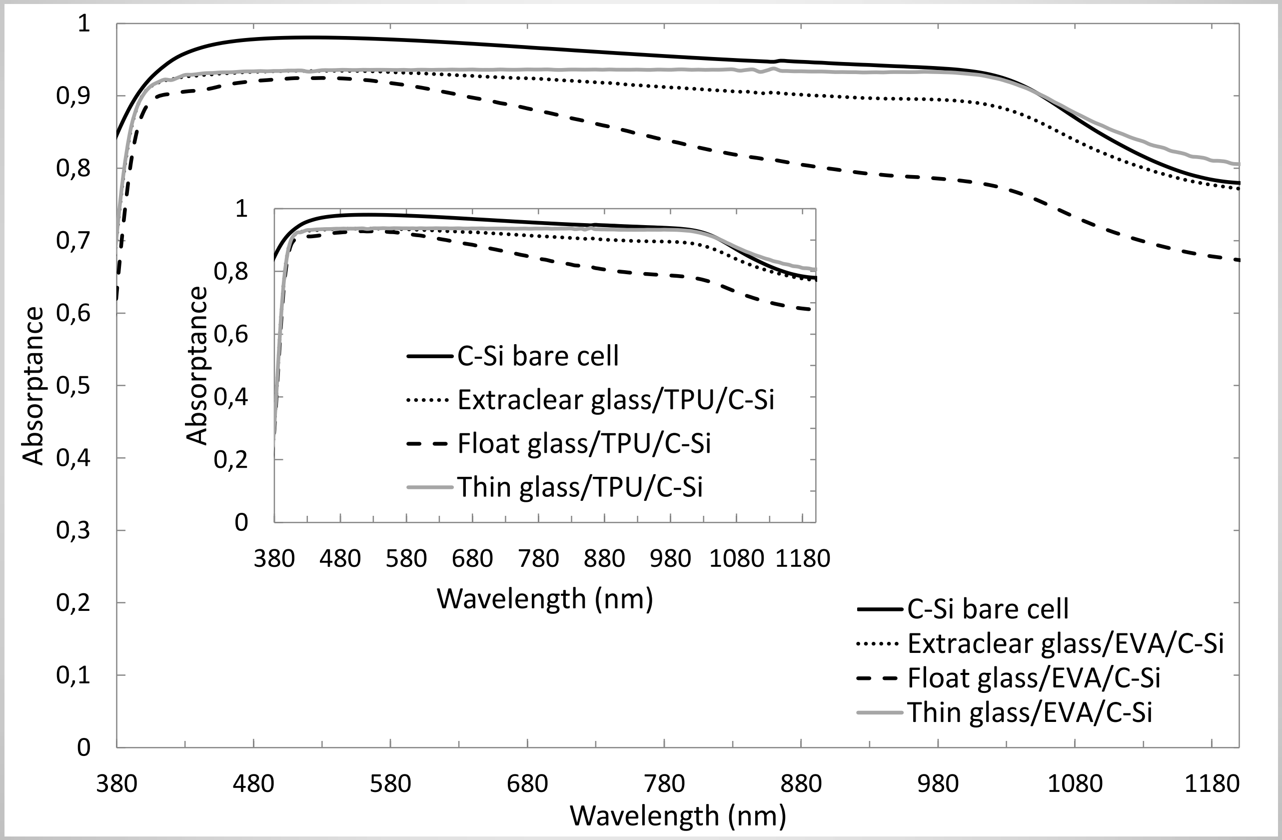
M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

Experimental External Quantum Efficiency- CIGS cell



M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

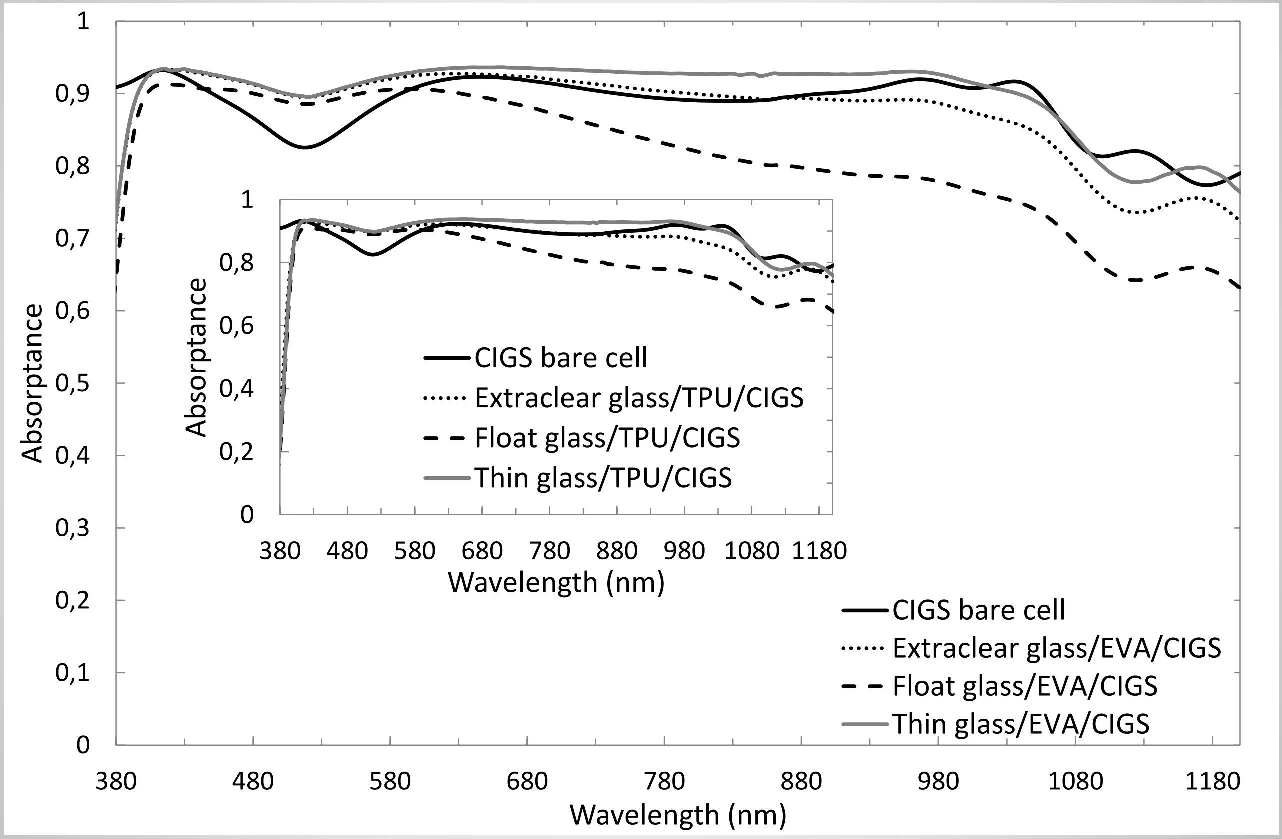
Calculated absorptance of encapsulated Silicon cell



Experimental validation

M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

Calculated absorptance of encapsulated CIGS cell



Experimental validation

M. Machado et al., submitted to Solar Energy Mat. and Solar Cells

Calculated vs experimental short-circuit values

Silicon cells

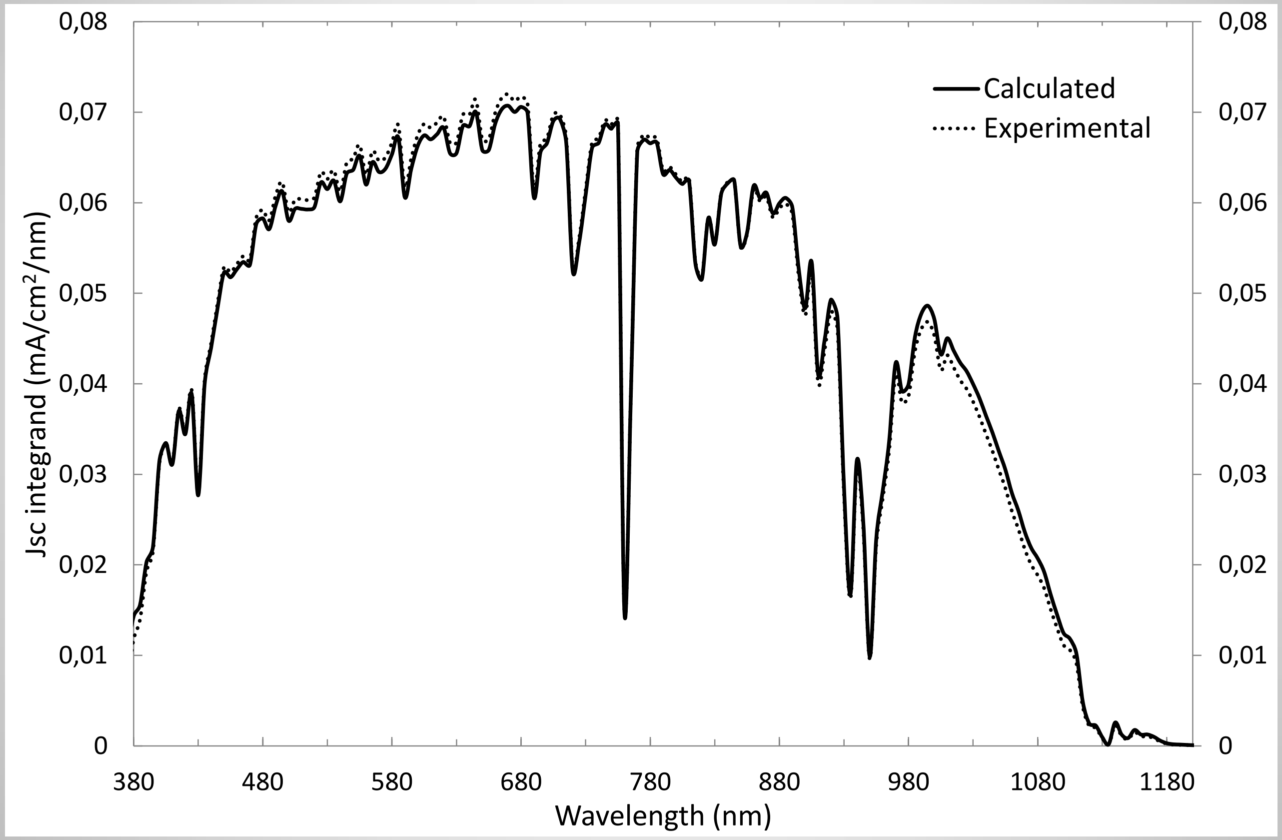
Encapsulation configuration	J_{sc} calc. (mA/cm^2)	J_{sc} exp. (mA/cm^2)	ΔJ_{sc} total (mA/cm^2)	*Error* (%)
Extraclear glass/EVA/Si cell	37.3	37.2	0.1	0.2
Float glass/EVA/Si cell	35.0	34.8	0.2	0.6
Thin glass/EVA/Si cell	38.0	38.0	0.0	0.0
Extraclear glass/TPU/Si cell	37.1	36.8	0.3	0.8
Float glass/TPU/Si cell	34.9	34.4	0.5	1.5
Thin glass/TPU/Si cell	37.9	37.9	0.0	0.0

CIGS cells

Encapsulation configuration	J_{sc} calc. (mA/cm^2)	J_{sc} exp. (mA/cm^2)	ΔJ_{sc} total (mA/cm^2)	*Error* (%)
Extraclear glass/EVA/CIGS cell	31.3	31.3	0.0	0.0
Float glass/EVA/CIGS cell	29.4	29.4	0.0	0.0
Thin glass/EVA/CIGS cell	31.8	32.2	-0.4	-1.3
Extraclear glass/TPU/CIGS cell	30.9	30.5	0.4	1.4
Float glass/TPU/CIGS cell	29.1	28.7	0.4	1.2
Thin glass/TPU/CIGS cell	31.8	32.2	-0.4	-1.1

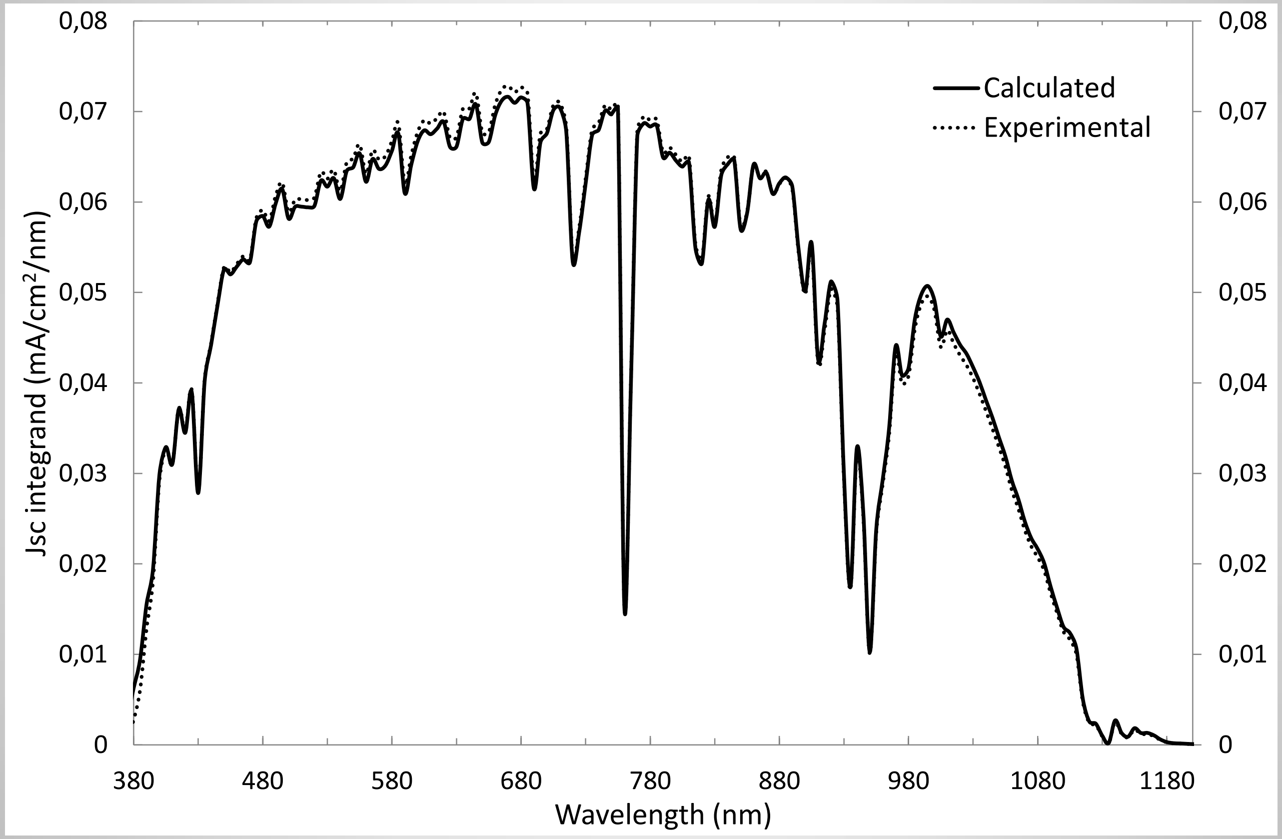
M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

Spectral comparison, extraclear glass/EVA/Si cell



M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

Spectral comparison, ultrathin glass/TPU/Si cell



M. Machado et al.,
submitted to Solar Energy Mat. and Solar Cells

Conclusions

- Transfer matrix method applied to deduce analytical expressions for encapsulated solar cells absorptivity.

- Simple method to evaluate the influence of encapsulation materials on cell efficiency.

- The experimental determination of a single configuration allows the prediction of multiple other configurations in terms of short-circuit currents.

- Very good agreement shown between theoretical calculation and experimental measurements.

Thank you for your attention

maider.machado@tecnalia.com