Measurement and simulation of moisture ingress in PV modules

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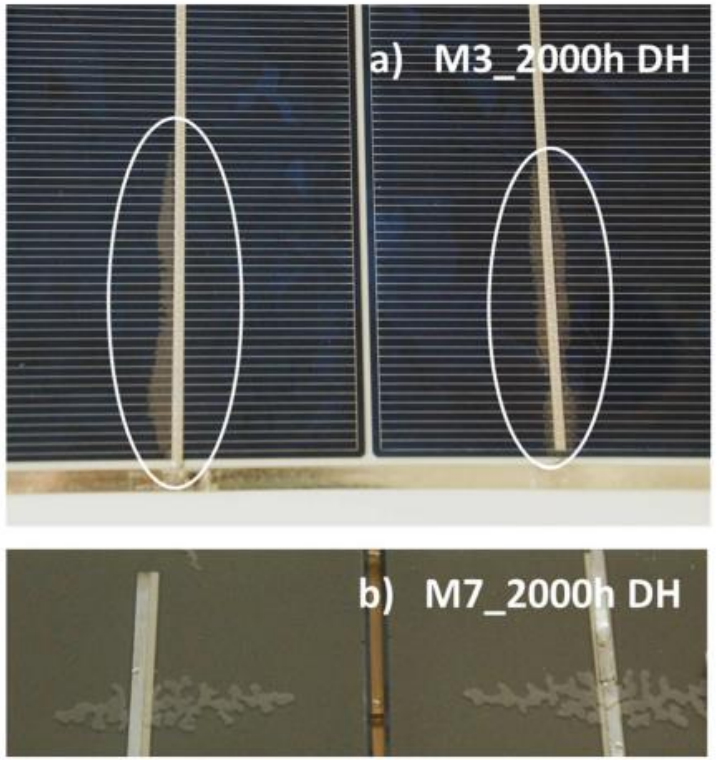
on PV Materials Durability

Outline

- **Motivation**
- **Measurement methods**
- **Simulation and calculation models**
- **Evaluation of encapsulated capacitive sensors**
- **Moisture sorption in the field**

Motivation

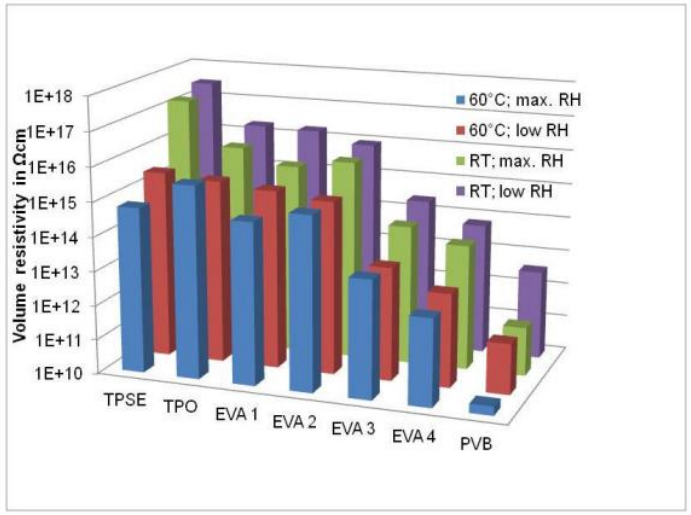
- **Degradation**



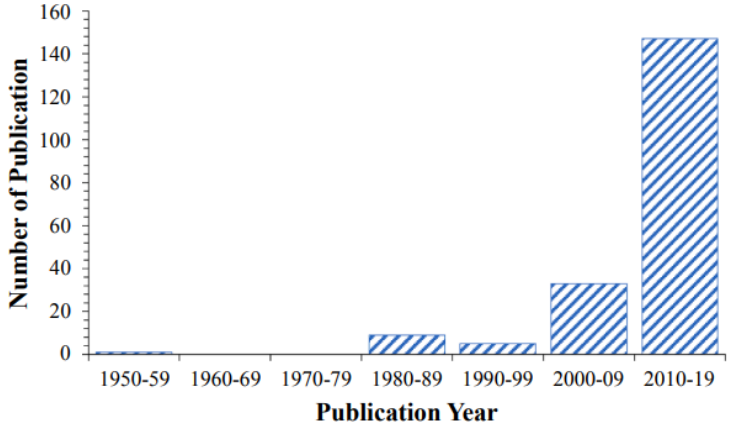
Voronko et al, PiP, 2015

IEA PVPS Task 13 report, 2017

Owen-Bellini et al, PiP, 2021



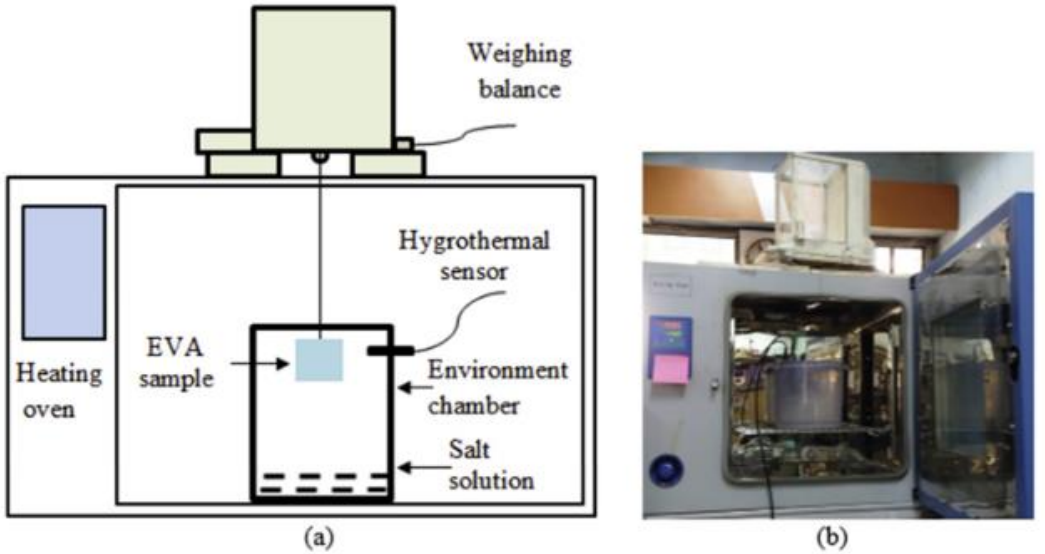
Berghold et al, IEEE PVSC, 2014



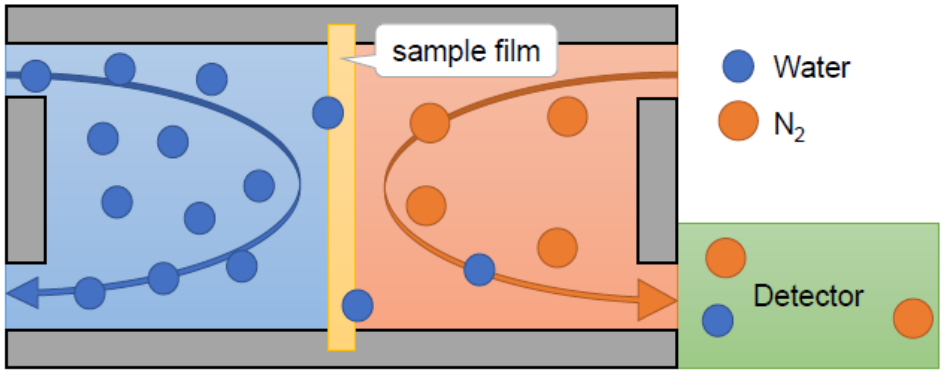
Segbefia et al, Solar Energy, 2021

Measurement methods

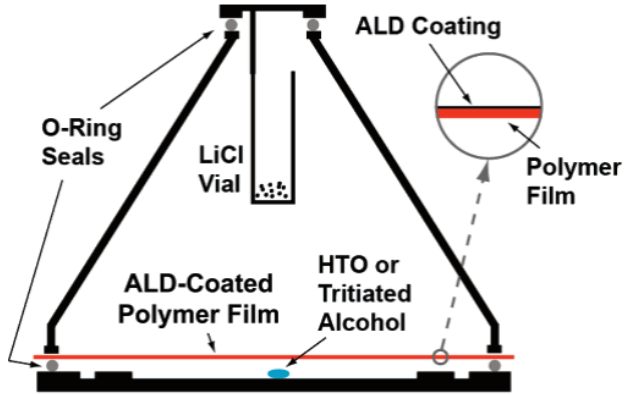
- **Moisture in the entire sample**
  - In-situ gravimetry
  - Karl-Fischer titration
- **Diffusion through a sample**
  - Gravimetric cup
  - MOCON method
  - Mass spectroscopy
  - Radioactive tracer
  - Cavity ring-down spectroscopy



Dadaniya et al, SolMat, 2019



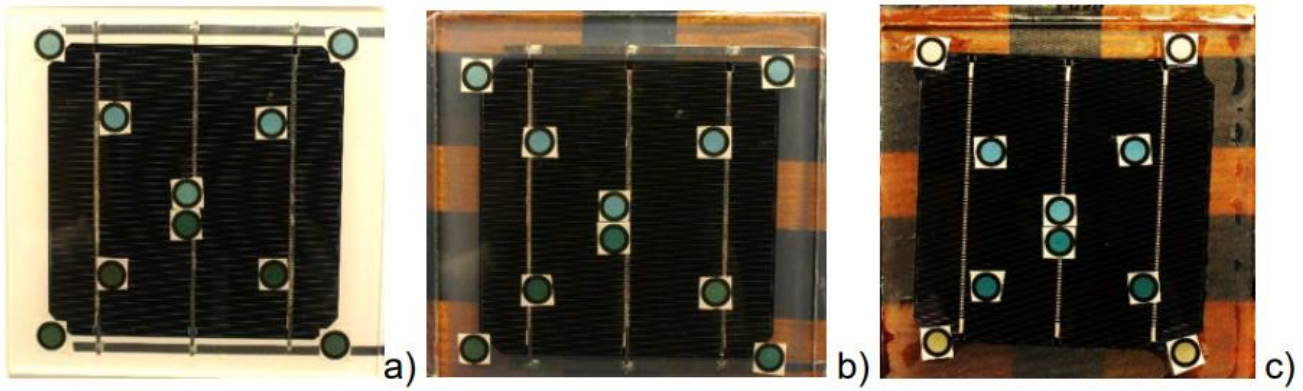
Mitterhofer, PhD thesis, Ljubljana, 2021



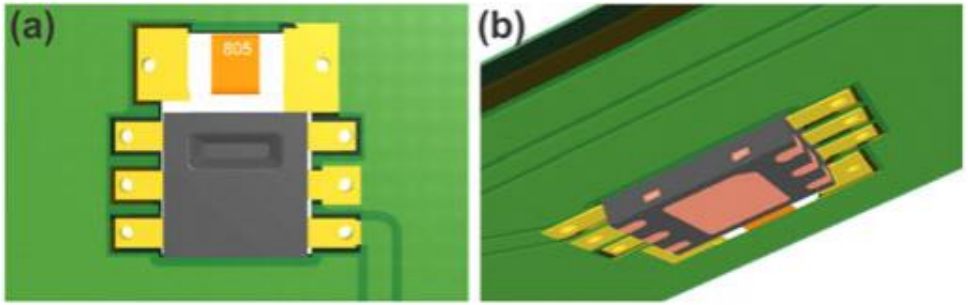
Dameron et al, J. Phys. Chem. C, 2008

Measurement methods

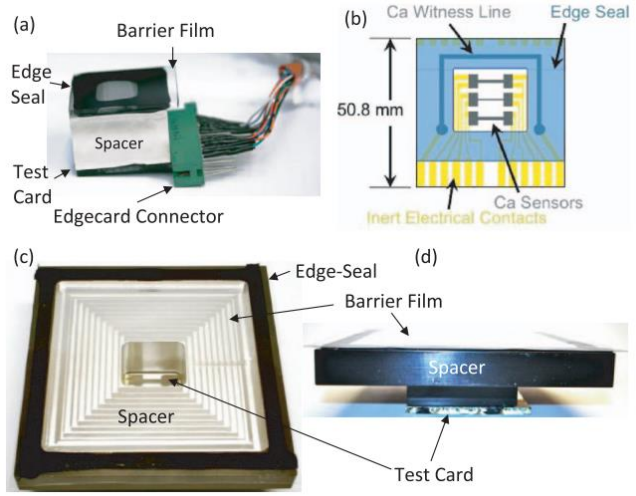
- **Encapsulated sensors**
  - $CoCl_2$ strips
  - Ca film
  - Miniature capacitive RH sensors
- **Non-invasive**
  - IR absorption
  - SWIR
  - FTIR
  - Neutron scattering



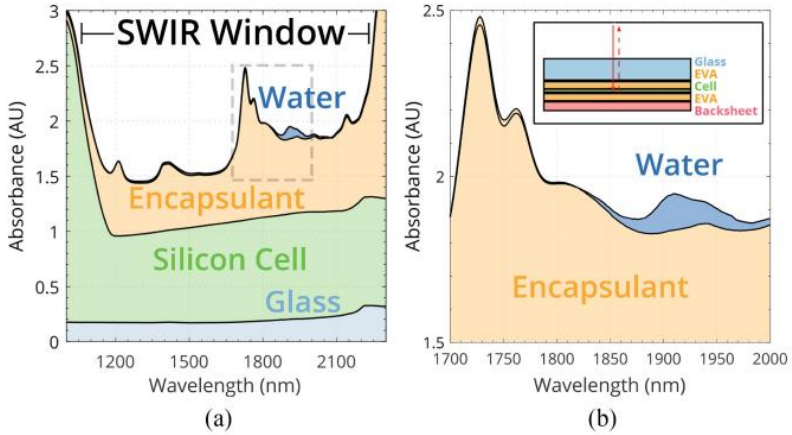
Kyranaki, PhD thesis, Loughborough, 2020



Jankovec et al, IEEE JPV, 2016



Kempe et al, Rev. Sci. Inst., 2013

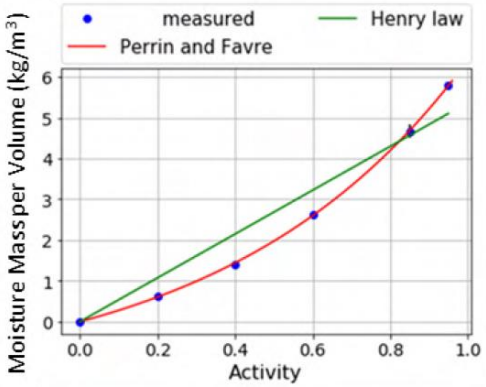


Kumar et al, IEEE JPV, 2019

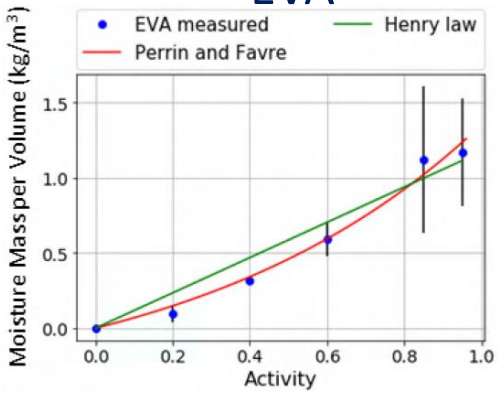
Calculation models

- **Sorption models**
  - Henry
  - Langmuir
  - Dual sorption
  - Flory-Huggins
  - BET
  - ENSIC
  - …

PET

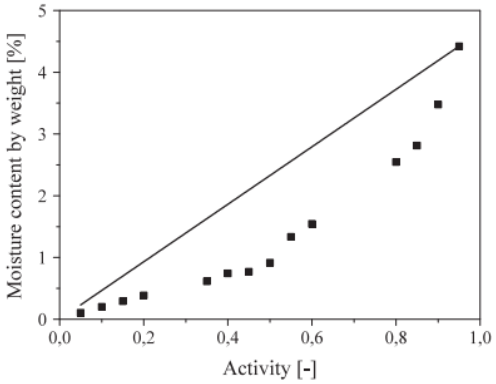


EVA

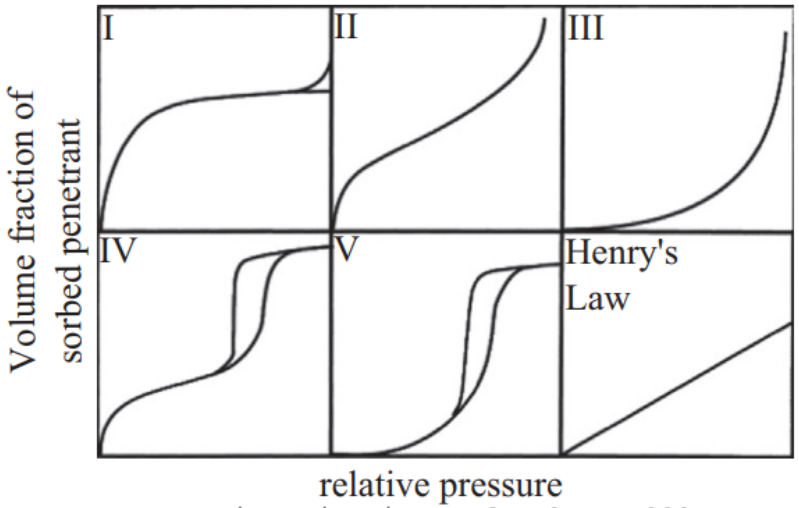


Kyranaki, PhD thesis, Loughborough, 2020

PVB

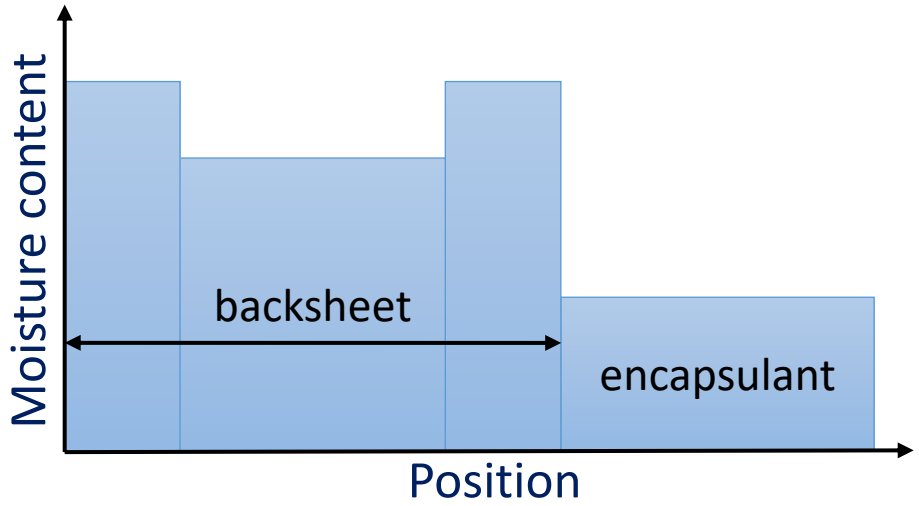


Meitzner et al, SolMat, 2016



Van der Wel et al, Prog. Org. Coat., 1999

$$C = H \cdot p$$



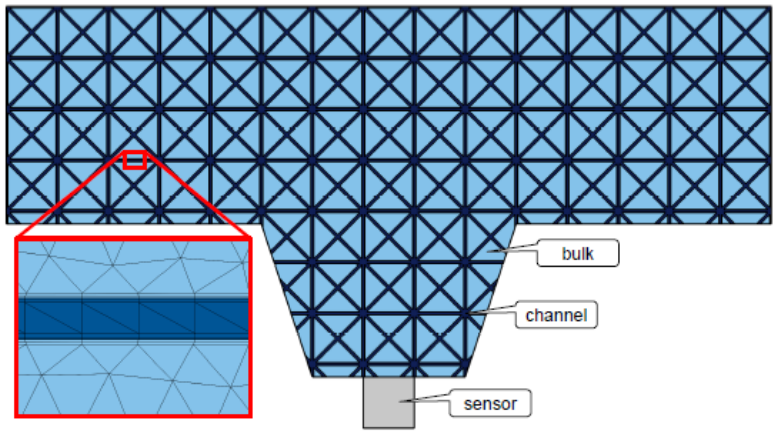
Calculation models

- **Diffusion**
  - Fickian
  - Concentration-dependent diffusion coefficient
  - Two material phases
  - Dual sorption
  - Molecular simulations
  - Three states of water
  - …

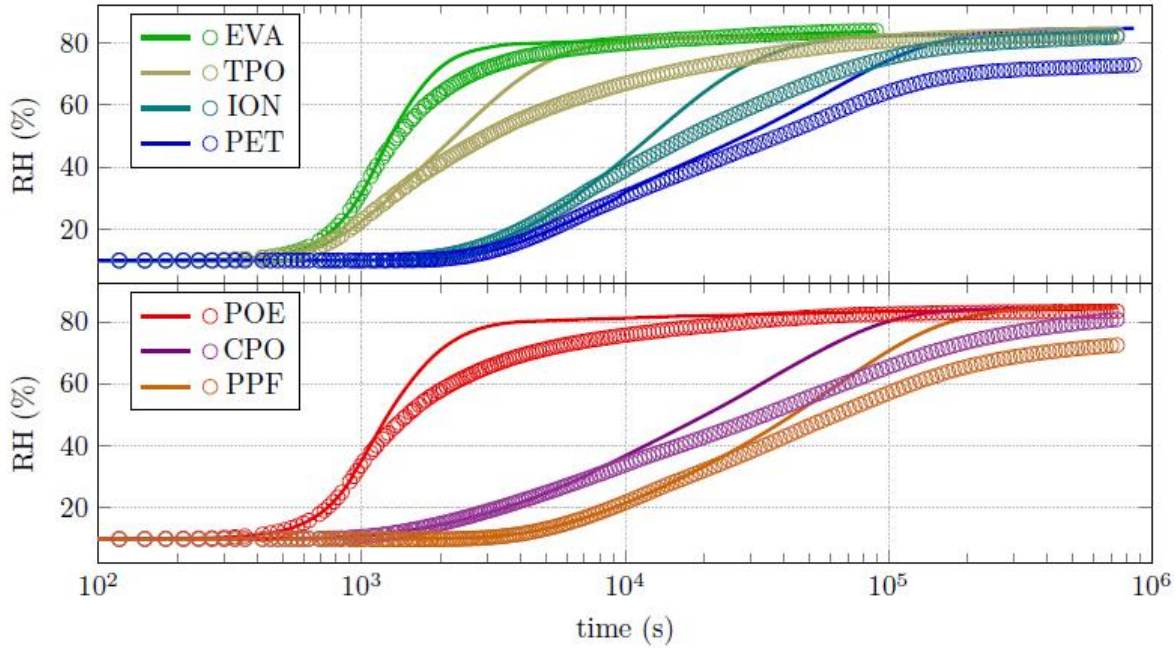
$$\frac{\partial C}{\partial t} = D \cdot \Delta C$$

$$\frac{\partial C_{free}}{\partial t} = D \cdot \Delta C_{free} - \frac{\partial C_{imm}}{\partial t}$$

$$\frac{\partial C_{imm}}{\partial t} = \alpha C_{free} - \beta C_{imm}$$



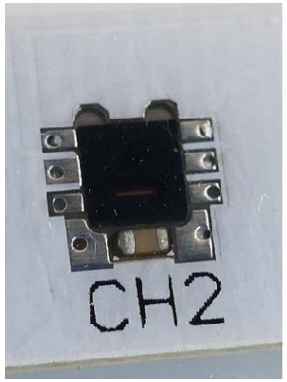
Mitterhofer, PhD thesis, Ljubljana, 2021
Mitterhofer et al, IEEE JPV, 2020

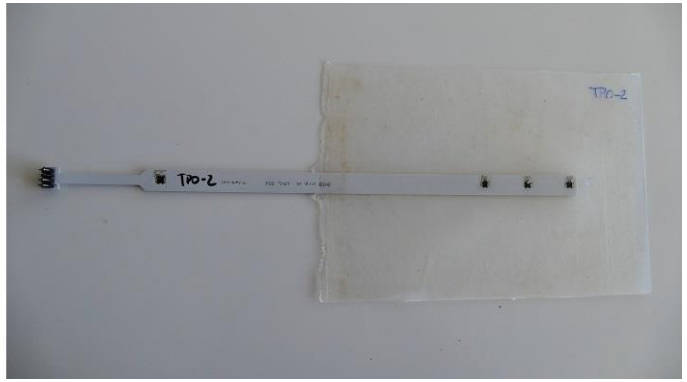


Mitterhofer, PhD thesis, Ljubljana, 2021

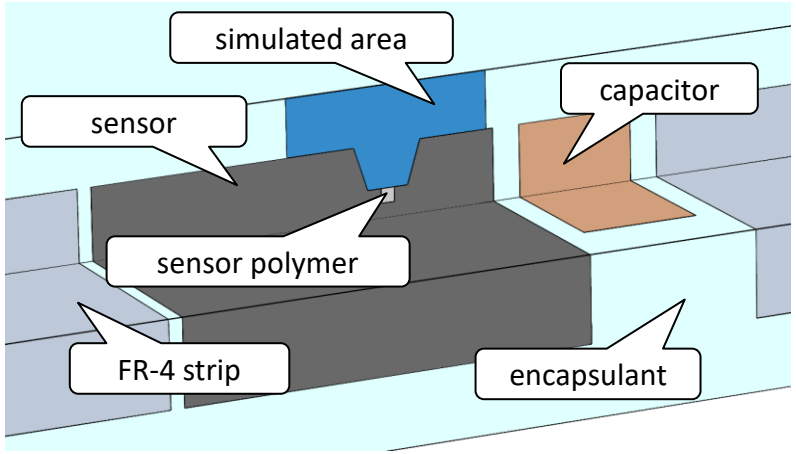
Evaluation of encapsulated sensors

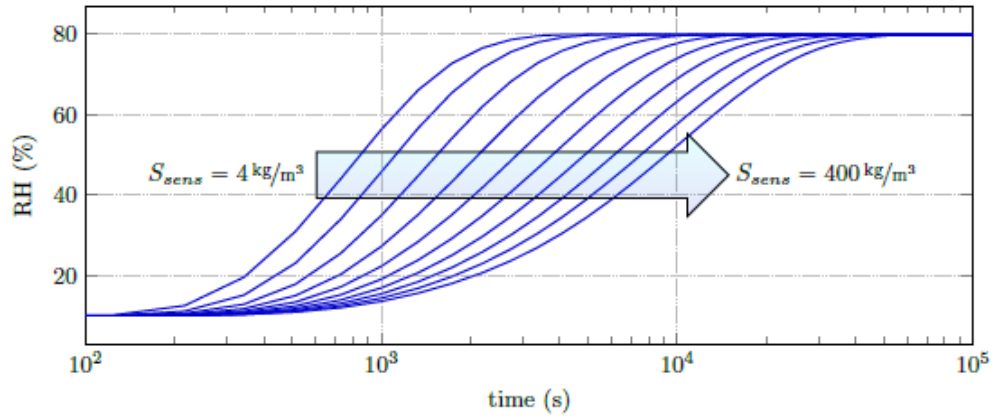
- **Sensors in material: How do they affect their measurement?**
- **Evaluated via FEM simulations and comparison with in-situ gravimetry**

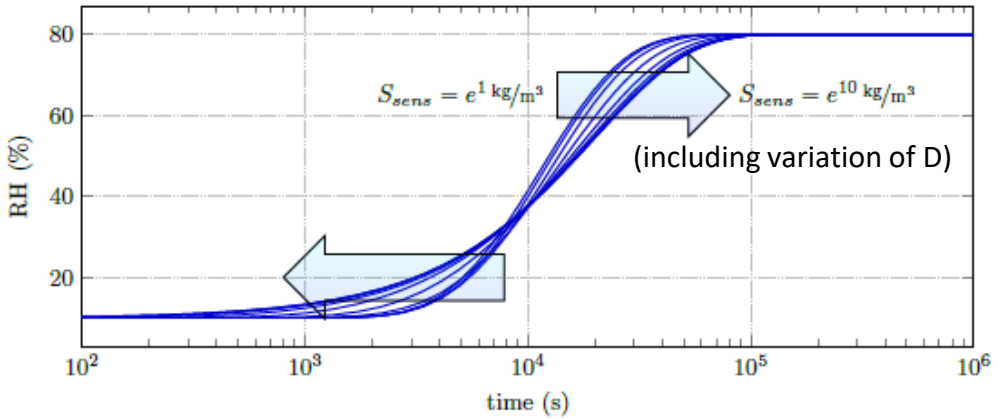




Mitterhofer et al, IEEE JPV, 2020

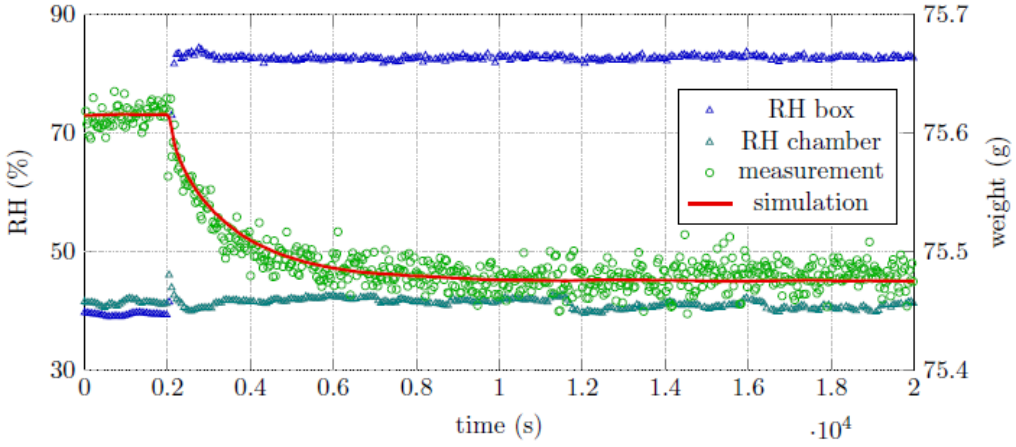


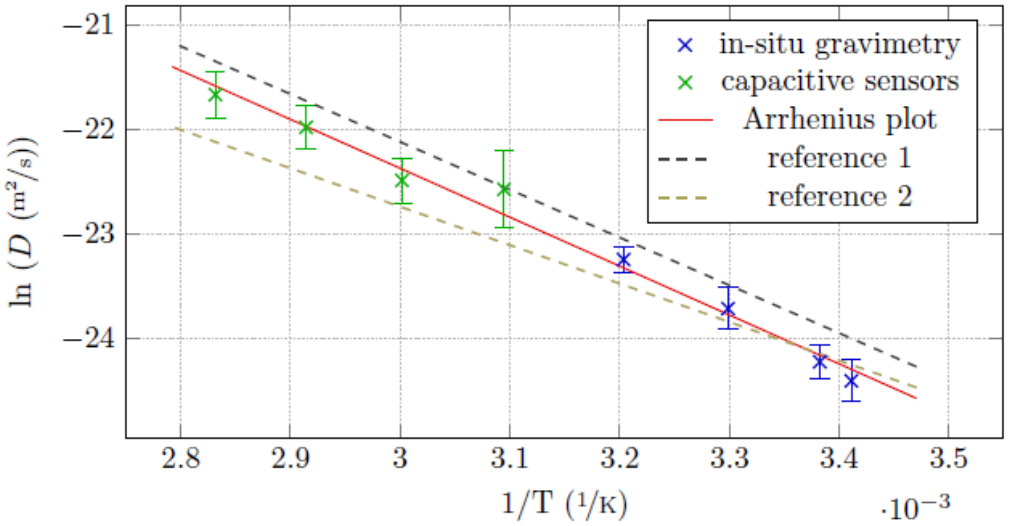




Mitterhofer, PhD thesis, Ljubljana, 2021

Evaluation of encapsulated sensors





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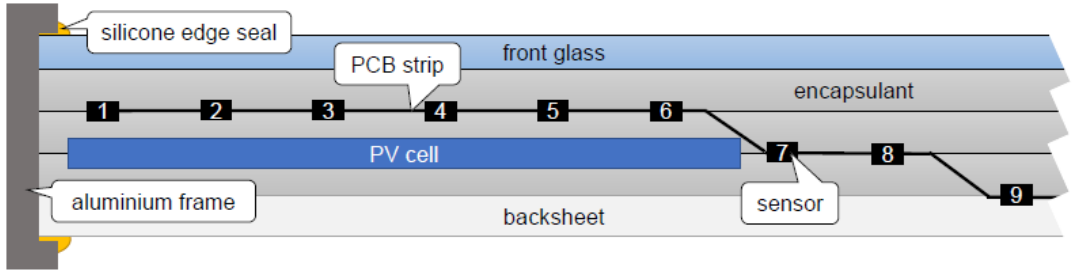
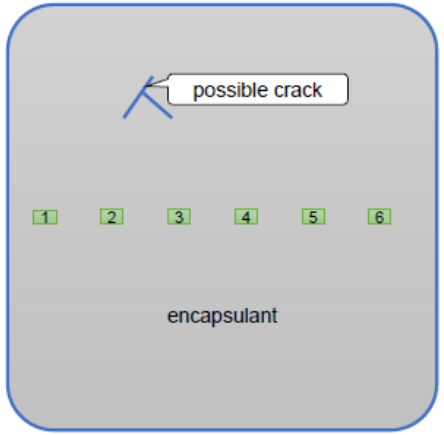
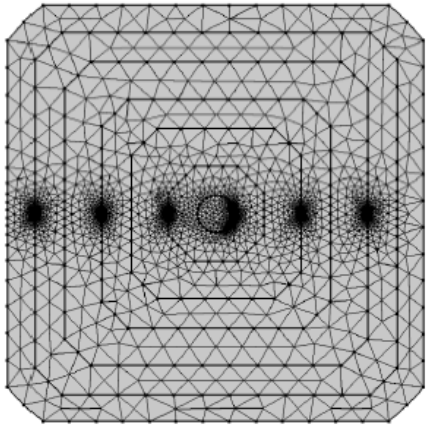
Measurements in the field

- **Measurements in similar modules in various climates**
- **Comparison with Fickian simulations**



location	climate
Bolzano, Italy	DM
Rome, Italy	DH
Singapore, Singapore	AH
Atacama, Chile	BK
Ljubljana, Slovenia	DH

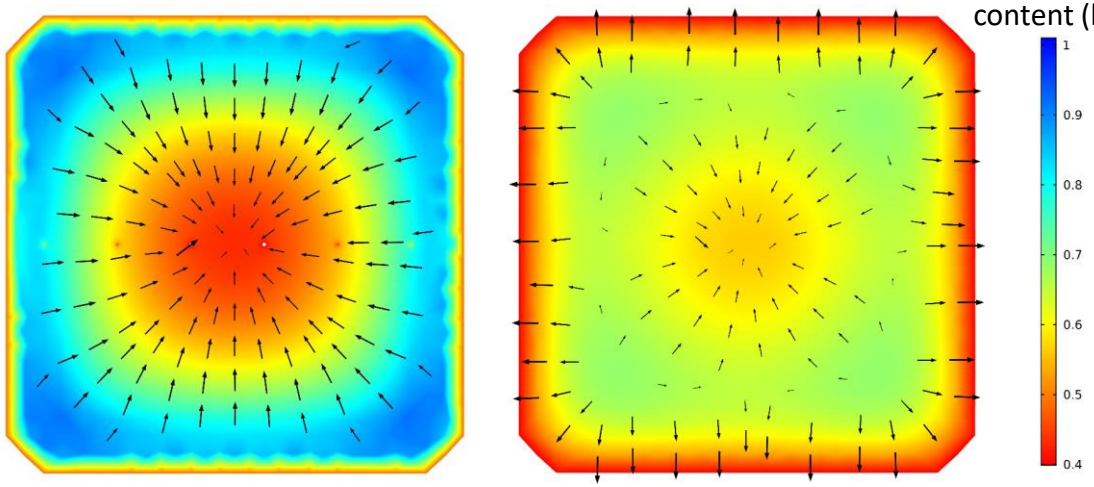


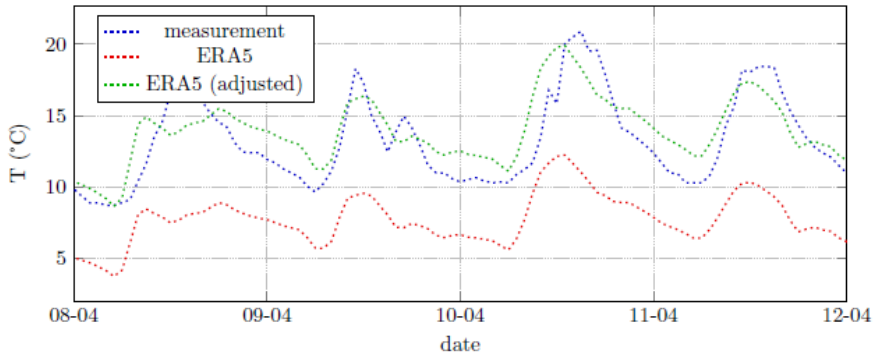


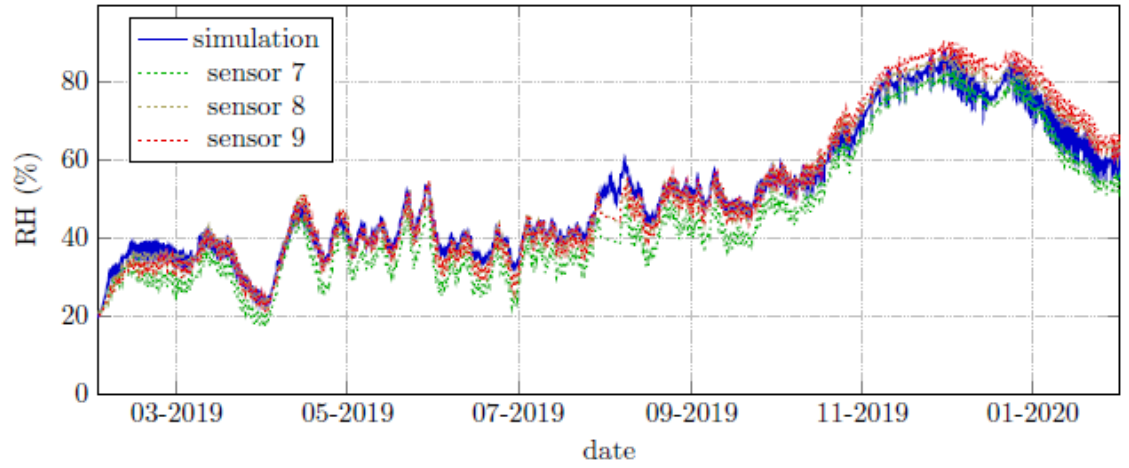
Mitterhofer, PhD thesis, Ljubljana, 2021
Mitterhofer et al, EUPVSEC 2020

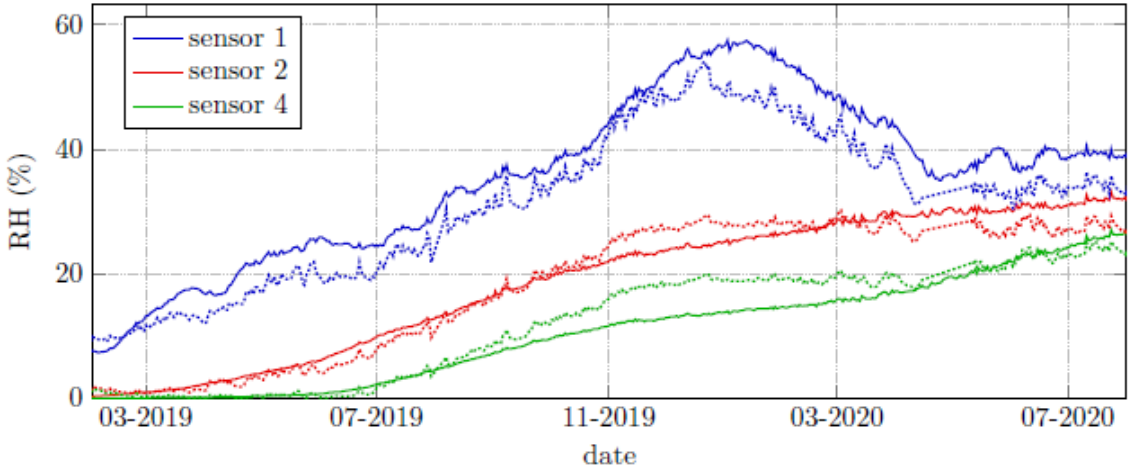
Measurements in the field

- **Good fits between measurements and simulations**









Mitterhofer, PhD thesis, Ljubljana, 2021
Mitterhofer et al, EUPVSEC 2020

Conclusions

- **Moisture ingress in PV is an increasingly important topic**
- **We have to better understand how moisture gets into the modules and how it affects them**
- **Many measurement methods and calculation models available**
  - Encapsulated sensors: High accuracy, spatial resolution, but can influence the measurements
- **Simulations can help us compare measurement methods, predict ingress in the future or in other climates and locations**
  - Require: Boundary conditions, material parameters, fitting model
- **Simulation models have to be verified by measurements**

Thank you for your attention!

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