# Reliability of PV modules and long-term performance prediction

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# PV research in Neuchâtel



- **Two neighboring institutions**

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

- Fundamental research
- Advanced devices

csem

- CSEM PV-Center founded in 2013
- Technology transfer center for PV
- Applied research, industrial mandates


Different missions but strong collaboration and complementary competences

- **Modules activities**

**Module reliability**

- Module reliability testing and modeling
- Module components and materials accelerated reliability testing
- Module testing tools (encapsulation quality and reliability) development
- Participation in work groups for PV standards development

**Modules & system integration**

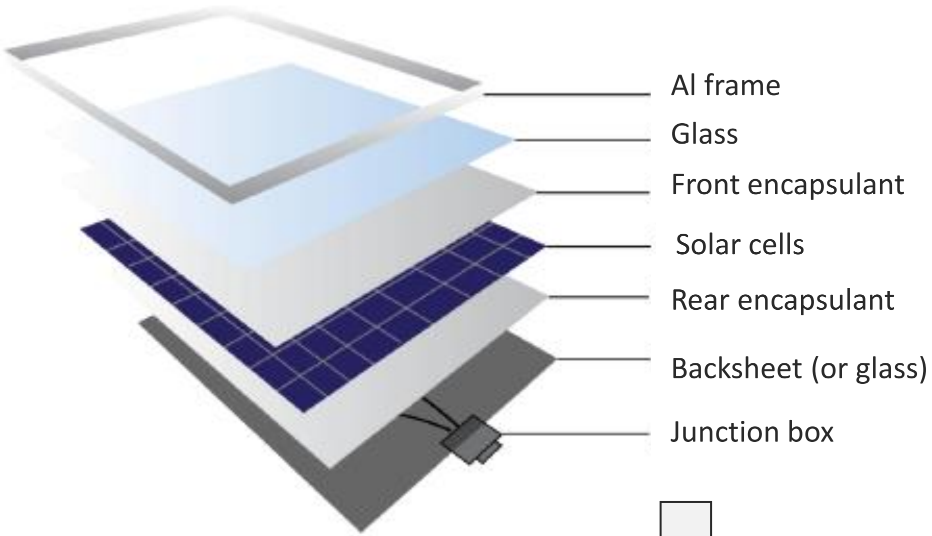
- New PV module encapsulation materials and interconnection techniques
- Novel encapsulation process development
- Innovative module design
- Architectural projects with PV

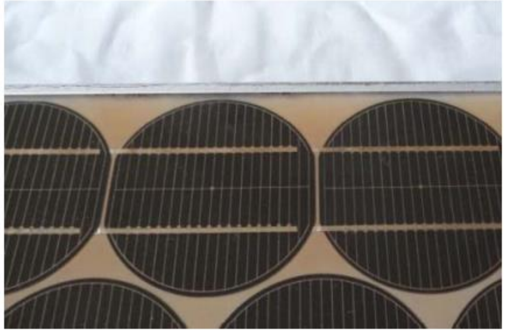
**System**

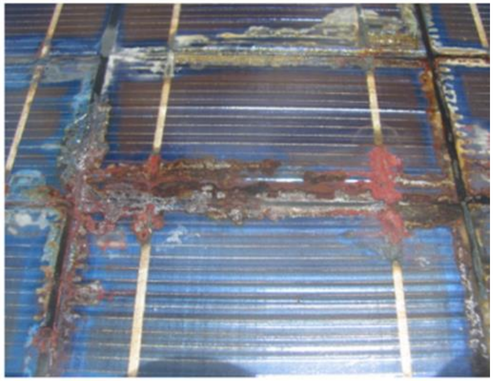
- Integration to variable grid conditions
- Batteries interfacing to PV

# Reliability of PV modules

- **PV module: a multi-layer system…**



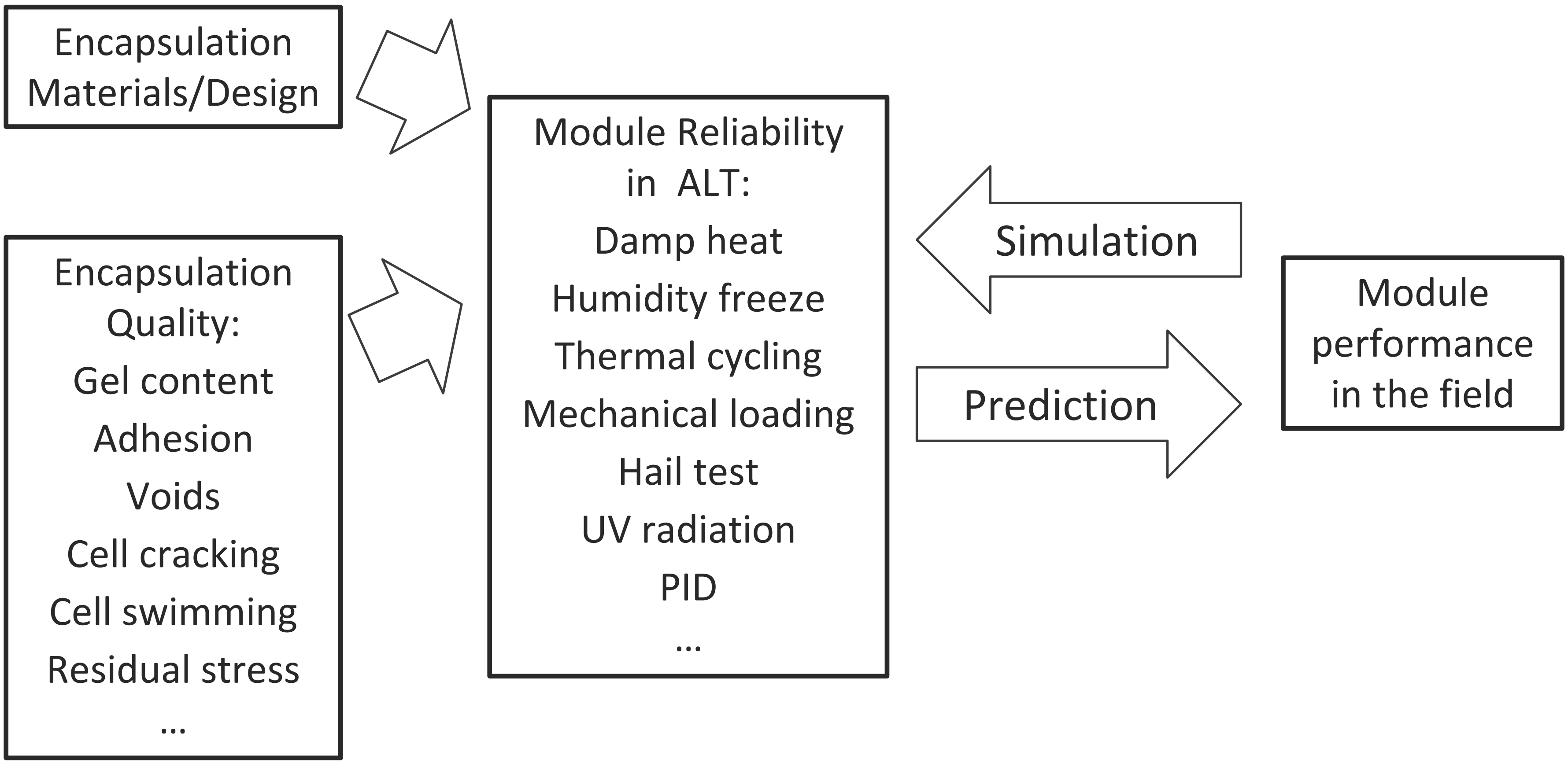



# Reliability of PV modules: many parameters



- **…with lots of impacts & interactions**



# Lifetime & long-term performance prediction



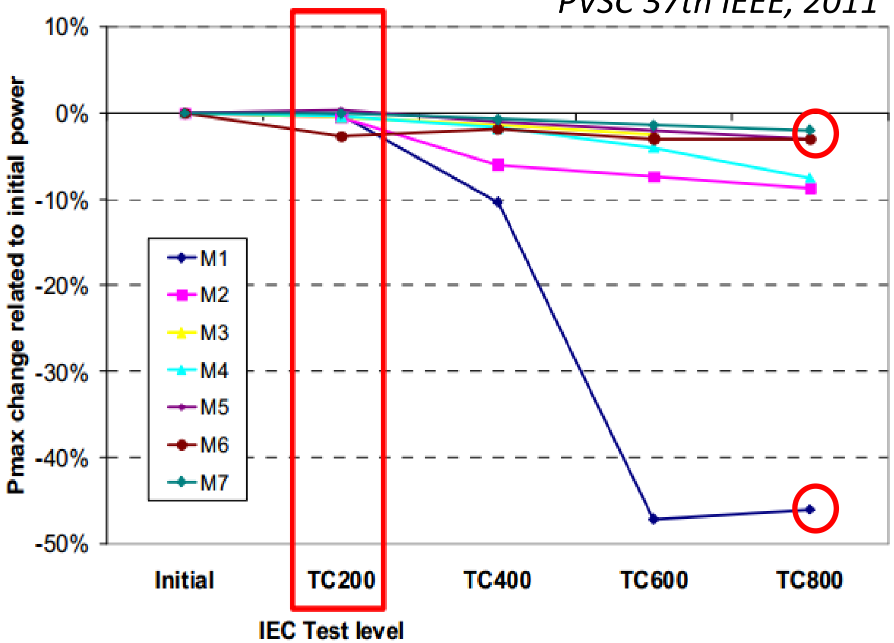
**Aim: predict the module lifetime and long-term performance for a given set of conditions**

- **Method: build a model based on**
  - A *failure mode and effects analysis* based on literature and field data (!)
  - Dedicated sets of *accelerated life tests (ALTs)* to reproduce predominant failure modes as a function of:
    - Climate where the module operates
    - Stand alone installation vs BIPV
    - Technology specificities (interconnects,..)
  - In literature, most authors consider one failure at a time with an Arrhenius type behavior, sometimes extended to take into account irradiance and/or humidity

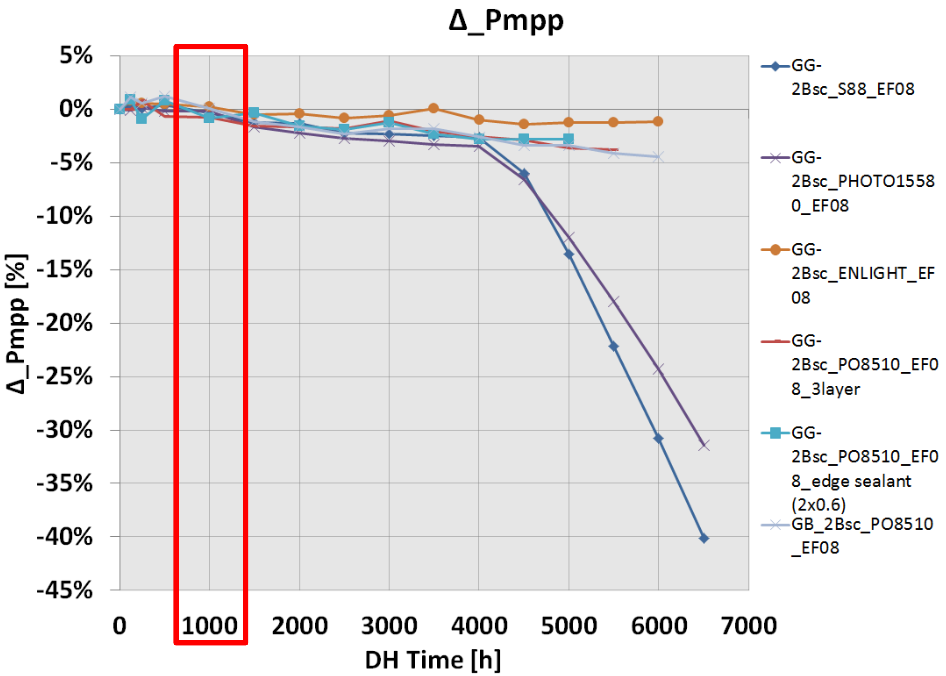
**Challenge** here is to be able to predict impacts of **inter-related failure mechanisms** on lifetime and performance !

- **Examples of ALT**

*Ref: Herrmann et al., PVSC 37th IEEE, 2011*




Thermal Cycling test (IEC 61215):
200 cycles with T between -40°C and 85°C




Damp Heat test (IEC 61215):
T=85°C, RH=85% for 1000 hours

- Clear necessity to define qualification test beyond IEC 61215 to evaluate long-term performance as a function of climate

Moisture ingress into PV modules

- **Problematics of moisture ingress:**
  - Delamination (mechanical stability loss, optical loss, water accumulation, …)
  - Corrosion ($R_s$ increase, could accelerate EVA yellowing, …)
  - Enhanced probability of PID ( due to reduced volume resistivity of encapsulants)
  - Encapsulant degradation (in combination with heat and UV)



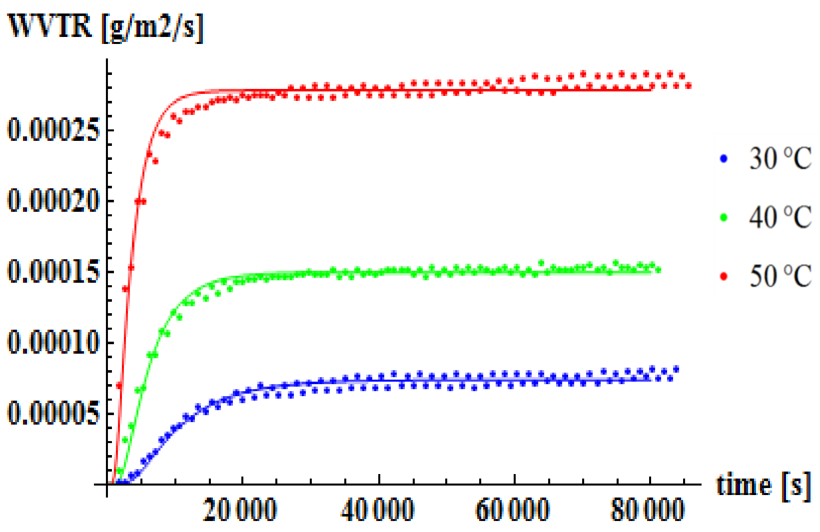
- **Different techniques can be used to minor and study water ingress:**
  - Permeation WVTR Mocon, Fourier Transform Infrared Spectroscopy (FTIR),..
  - Humidity sensor

# Modeling with Finite Element Method (FEM)



- **Acquire input material properties – WVTR data treatment:**
- WVTR characterization of different commercial backsheets (BS) and EVAs formulations measured at various temperatures (30°C, 40°C, 50°C)

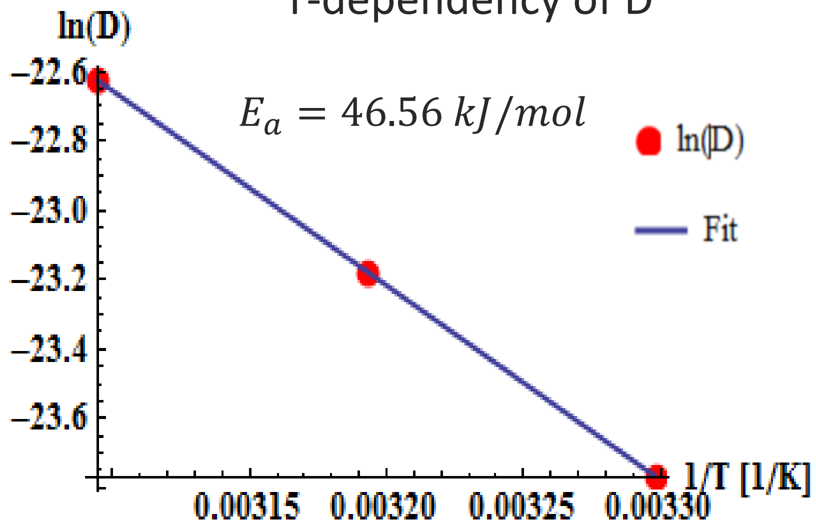
WVTR data fitting




$$WVTR(t) = \frac{DC_s}{l}\left[1 + 2\sum_{n=1}^{\infty}(-1)^n e^{\left(-\frac{Dn^2\pi^2 t}{l^2}\right)}\right]$$

$C_s$ saturation concentration, $l$ film thickness, $t$ time

T-dependency of D




D shows an Arrhenius dependency on temperature

$$D(T) = D(T_{ref})e^{\frac{-E_a}{R}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)}$$

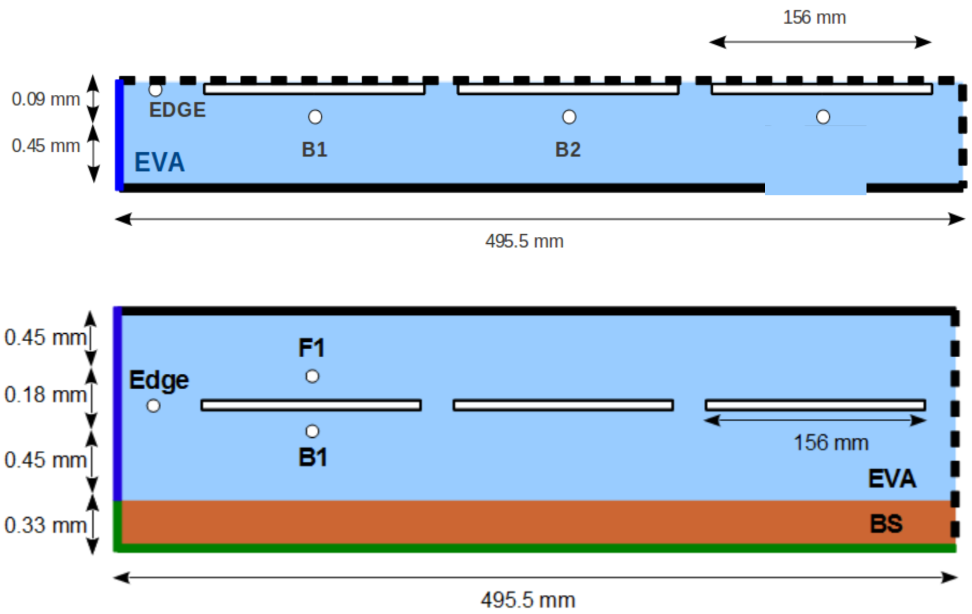
# Modeling: geometry



- **2D FEM modeling geometry**
  - A model was built in COMSOL to solve Fick's Second Law of diffusion:

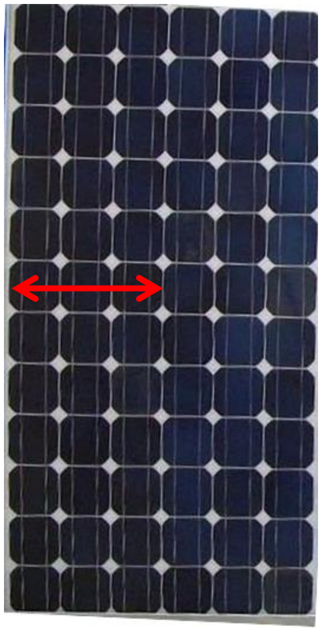
$$\frac{\partial c(\vec{x},t)}{\partial t} - div\left(D \cdot \overrightarrow{grad}\, c(\vec{x},t)\right) = 0$$

  - Boundary Conditions (Henry's law): $c_{surf}(T,RH) = S(T) \cdot p_{H_2O}(T,RH)$




Glass/Glass

Glass/Back Sheet

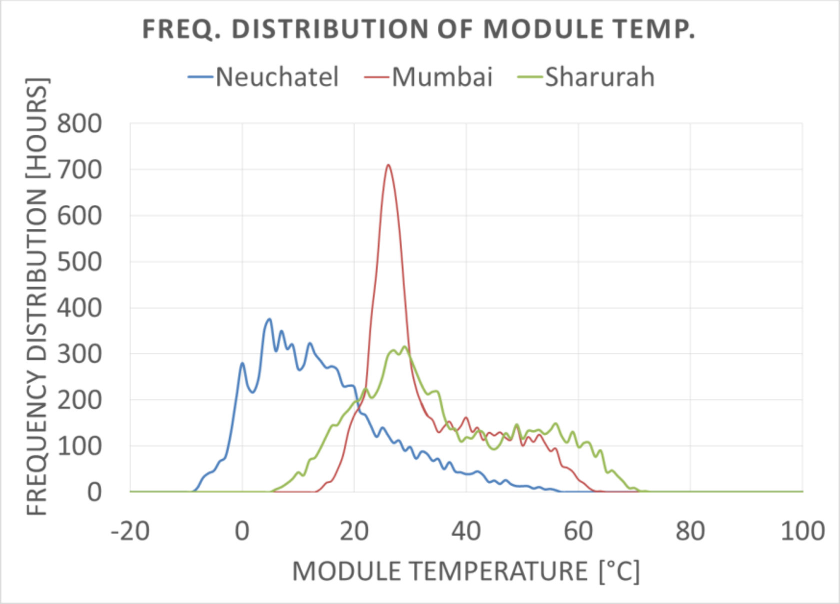


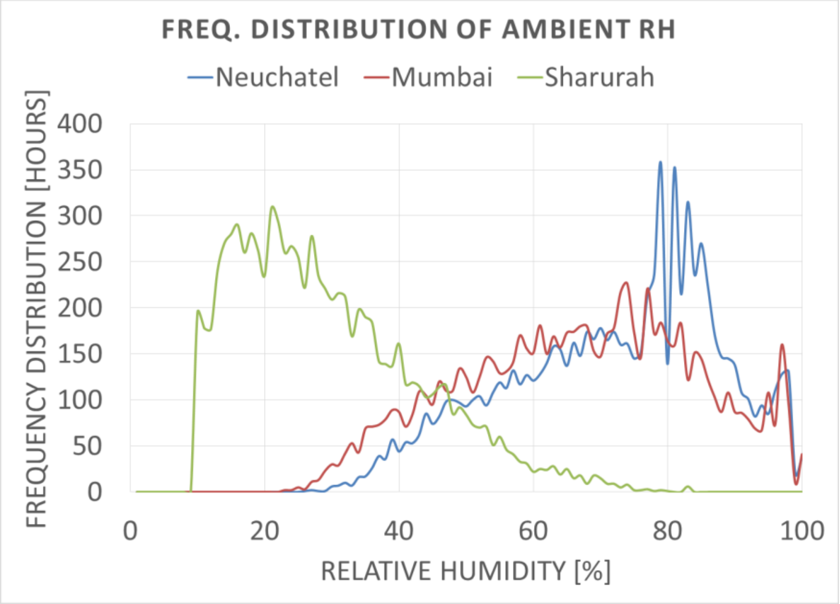
# Modeling: climates



- **Three climatic conditions**

| Climatic zone | "Cool & Humid" (Temperate) | "Hot & Humid" (Tropical) | "Hot & Dry" (Desert) |
|---|---|---|---|
| **Location** | Neuchâtel (Switzerland) | Mumbai (India) | Sharurah (Saudi Arabia) |



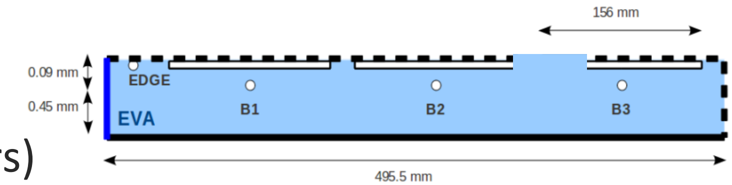




- The module temperature was estimated using King's model: $T_{mod} = T_{amb} + E \cdot e^{-a-b \cdot v}$ with an open-rack mounting configuration

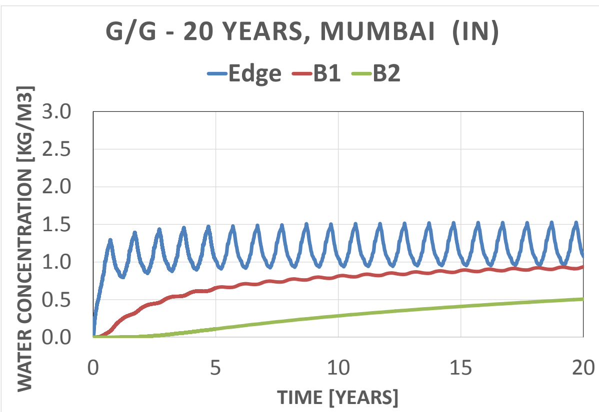
# Moisture ingress into PV modules - Modeling



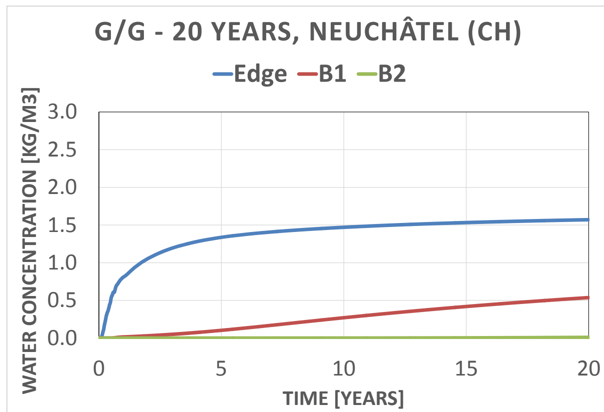
- **Glass/Glass module (G/G)**
  - Water concentration as a function of time (years)



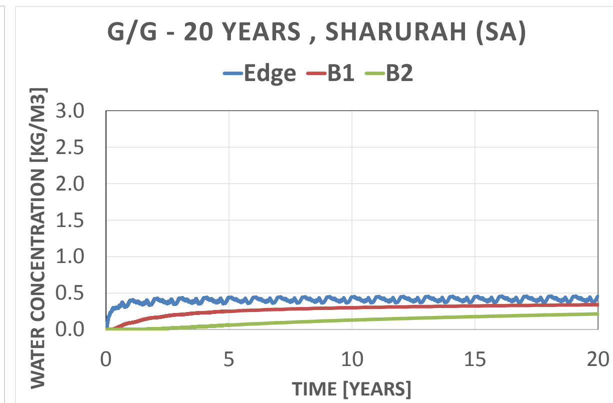

Tropical




Cool & humid




Desert

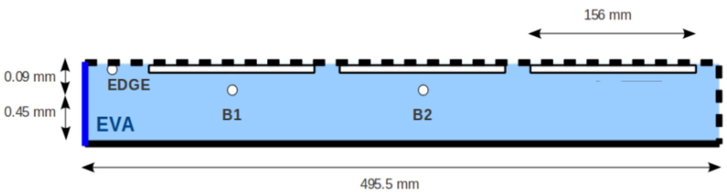


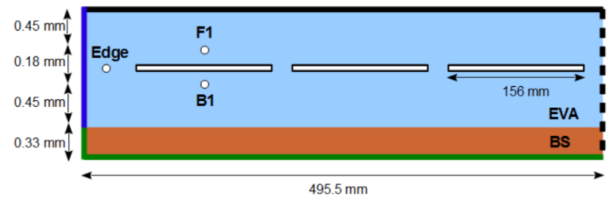

- As expected the moisture ingress is the fastest in tropical climate, with clear seasonal variations, particularly at the edge
- In the cool and humid environment, saturation is reached after 10 years at edge, very slow ingress at back of the cells
- In the desert climate saturation at edge quickly achievedas a result of higher T and low RH%

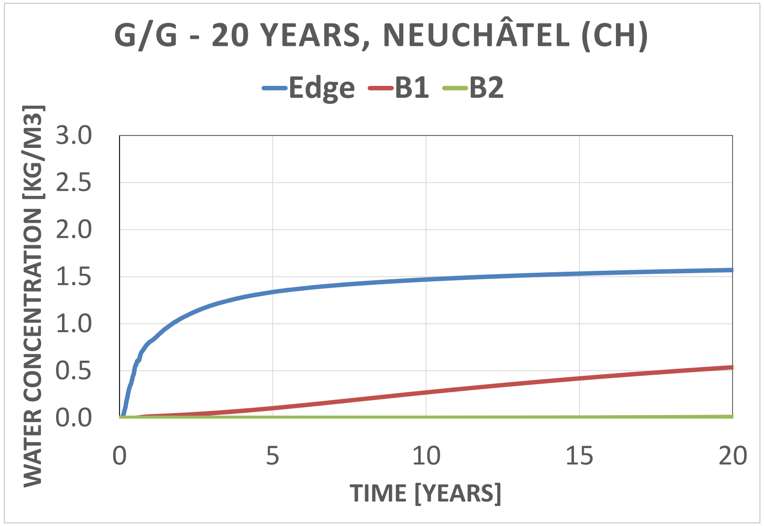
# Moisture ingress into PV modules - Modeling

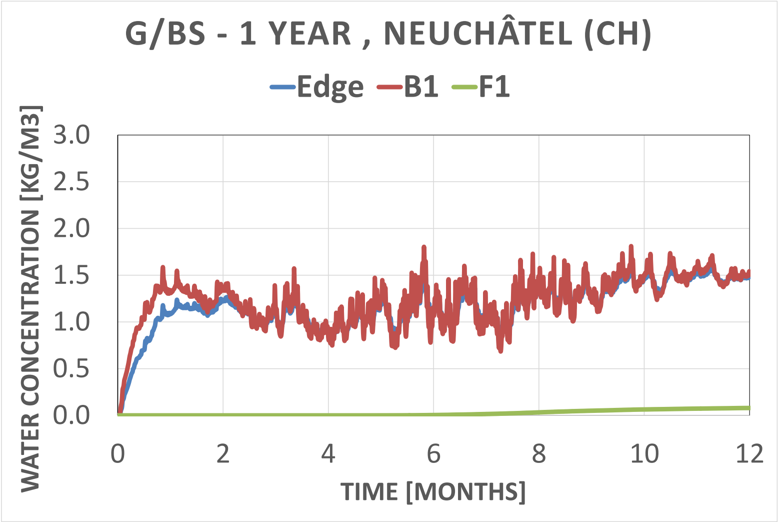


- **Module configuration**:
  - Glass/glass (G/G) vs glass/backsheet (G/BS) in temperate climate (cool and humid)



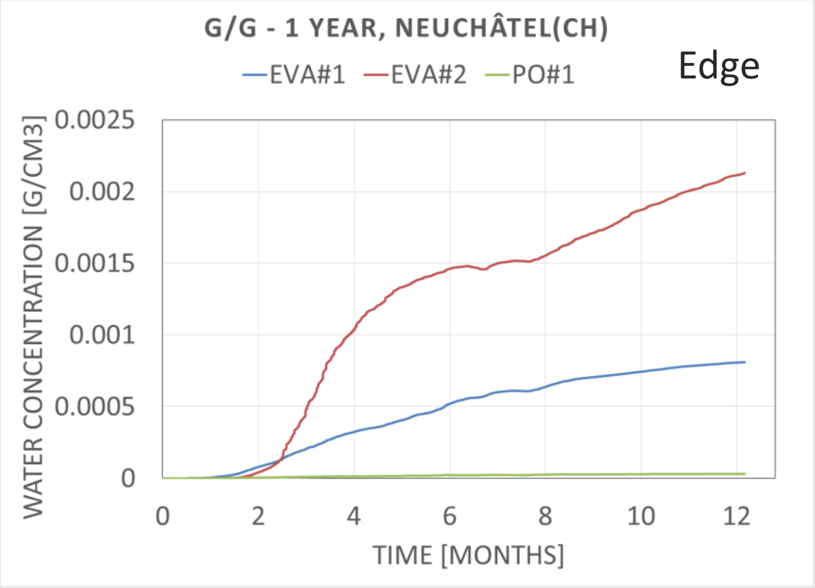




- In G/BS, saturation quasi reached at cell back after 1st year, then seasonal variations clearly visible; simulation to be extended for longer period
- G/G reduces moisture accumulation with respect to G/BS (moisture content at cell back already larger in G/BS after 1st year than in G/G after 20 years)

# Moisture ingress into PV modules - Modeling



- **Different encapsulants** in temperate climate
  - Water concentration in glass/glass (G/G) configuration for 3 encapsulants, simulated for 1 year




- PO#1, a commercial polyolefin-based encapsulant, shows significantly lower moisture ingress than the other 2 EVA encapsulants in one year
- For EVA#1 the water concentration is reduced by over 50% compared to EVA#2
  - EVA formulation plays an important role on water ingress

- These results demonstrate the ability to **predict** water ingress as a function of:
  - Module configuration
  - Encapsulant
- Care must be taken that not only diffusion coefficient but also solubility are important when choosing the proper material

# How to measure humidity within a module ?

- **Encapsulated capacitance sensor as moisture/T indicator**

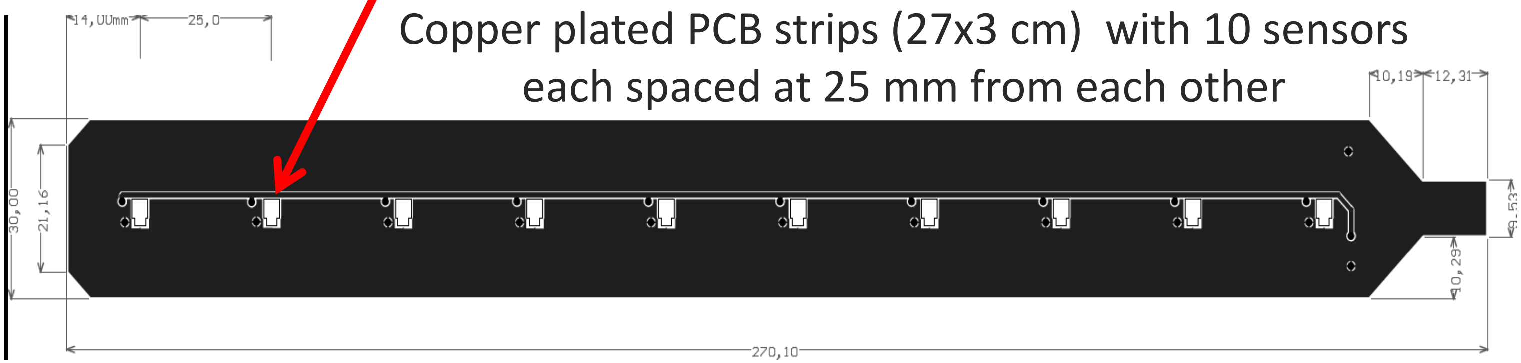
Capacitive sensor with digital output
Sensirion SHT25:
1.8 % RH, 0.2°C accuracy


Laboratory of Photovoltaics and Optoelectronics

University of Ljubljana
Faculty of Electrical Engineering

csem

Copper plated PCB strips (27x3 cm) with 10 sensors each spaced at 25 mm from each other




- The strip is laminated within the encapsulant in two configurations:
  - Encapsulant only
  - Glass/glass and glass/backsheet samples
- Then placed in various conditions (climatic chamber and outdoor)

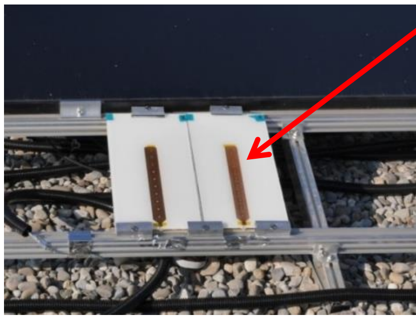
*Results to be presented at the next EU PVSEC (5DO10.3)*

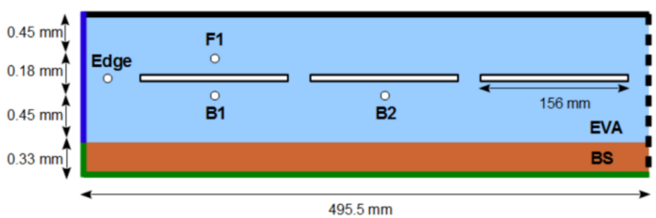
# Tool to validate our model

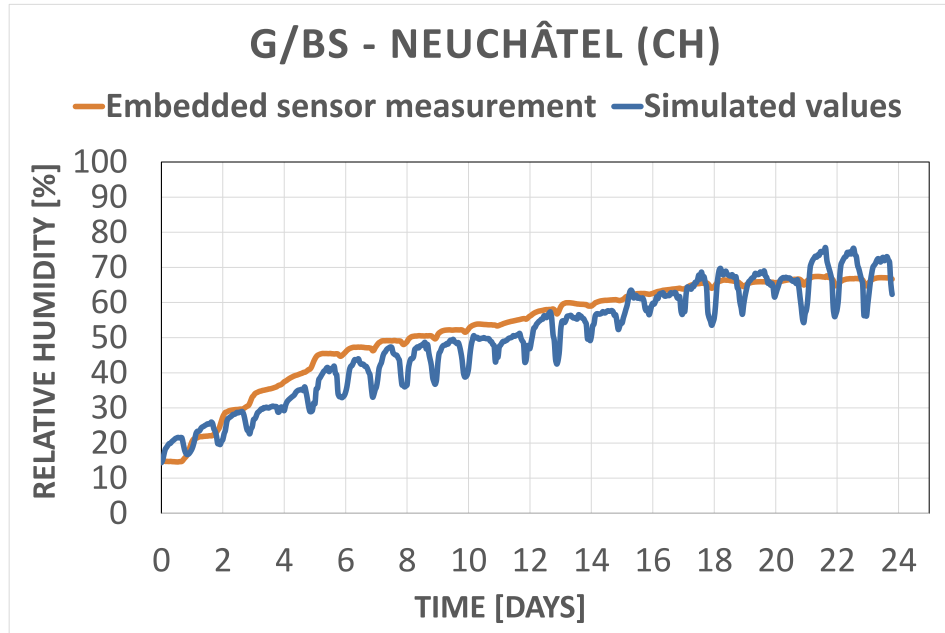


- **Comparison of simulated values with outdoor measurements (encapsulated sensors)**

$RH$ and $T$ sensors



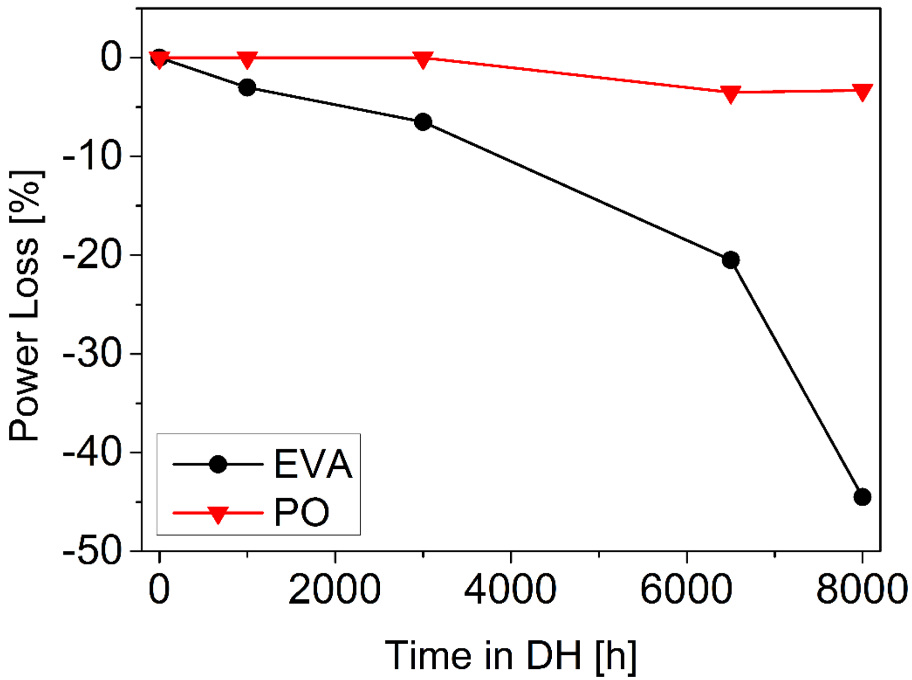


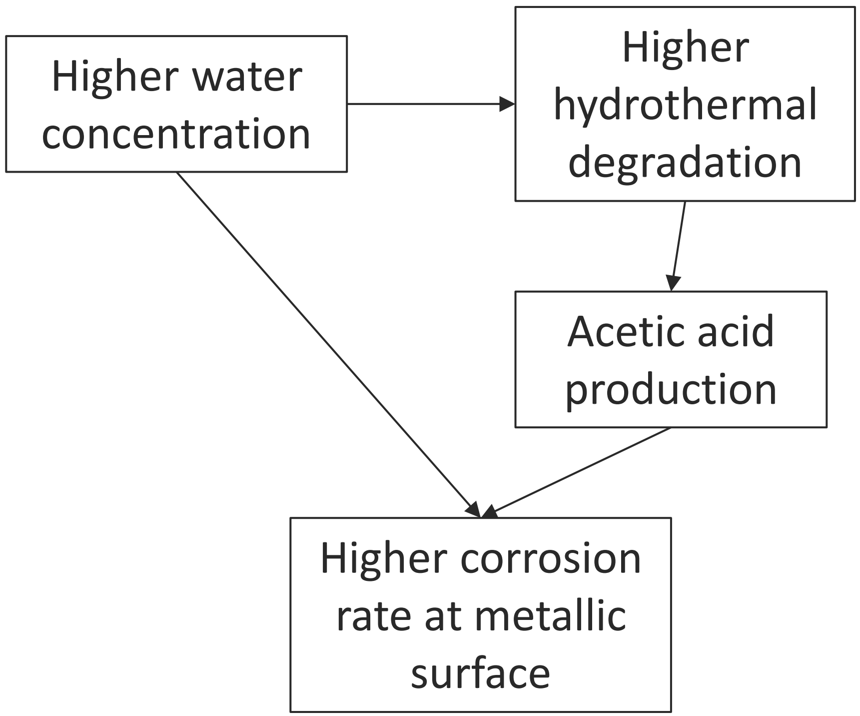




- Quite good agreement between measurement and simulation but:
  - Further simulations are required (longer time, controlled conditions)
  - RH value given by the sensor to be directly correlated with amount of water present in the polymer as assesse by an independent method (e.g. Karl Fischer)

# Example of link between moisture and reliability: corrosion

- **Different encapsulants in extended damp heat**
  - Standard solar cells, Glass/Backsheet module configuration, 85 °C / 85% RH, 8000 h.
  - Decrease in power loss corresponds to corrosion of metallic contacts

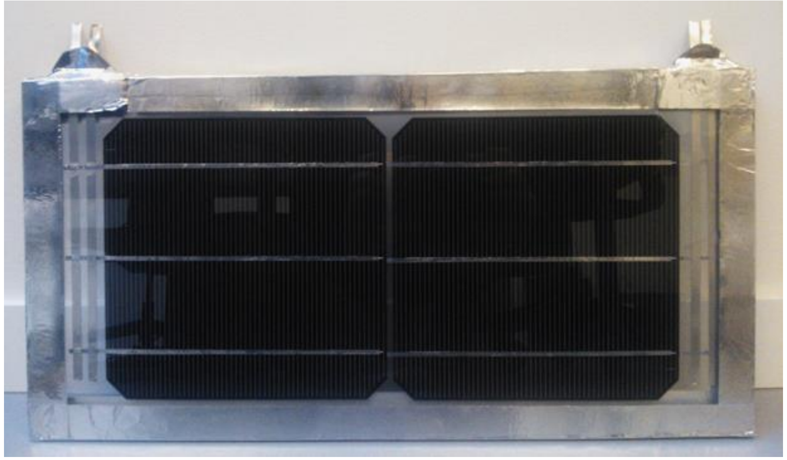


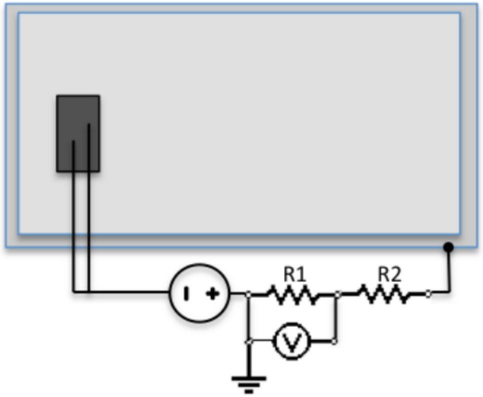




*Ref: G. Cattaneo et al.,*
*Proc of 29th EU PVSEC (2014)*

# Example of link between moisture and reliability: Potential Induced Degradation (PID)

- **Potential Induced Degradation (PID)**
  - One of the major failures observed in temperate climate
  - Power degradation due to increased shunt resistance
  - Stress factors: Voltage, Temperature, Humidity → can be mitigated at system but also module level
- **Mini-modules prepared with different encapsulant and configuration**
  - 2 cells mini-modules, Glass/Glass and Glass/Backsheet
  - Placed in climatic chamber at RH = 85% and T = 40°C/60°C/85°C for 96 hours
  - Leakage current monitored and mini-modules characterized with IV, EL

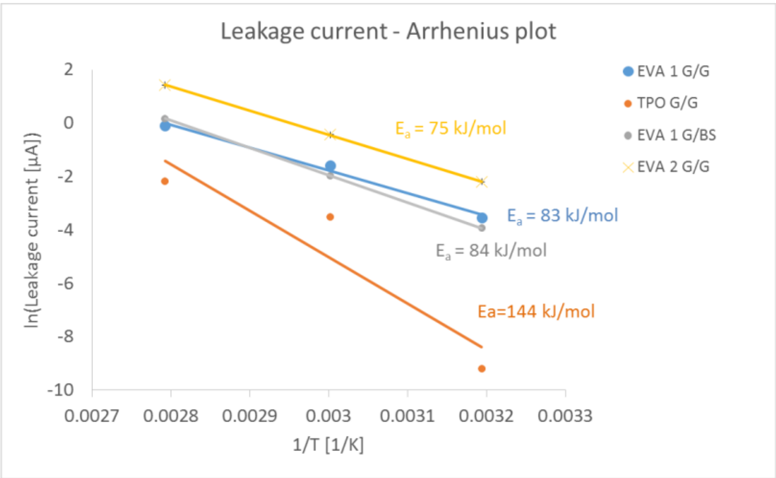




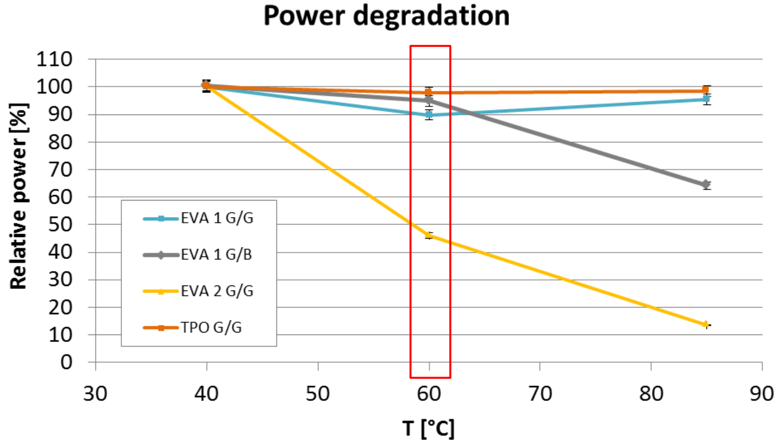
# Example of link between moisture and reliability: Potential Induced Degradation (PID)



- **First results at RH = 85% are in agreement with literature**:




- Leakage current increases with T → fit with an Arrhenius law
- Impact of encapsulant: for EVA activation energy ~ 80 kJ/mol (in line with literature), TPO well above




- Impact of encapsulant: almost no degradation for EVA 1 G/G and TPO, EVA 2 worst case
- Tests to be repeated at fixed temperature and various humidity, also with other c-Si based cells

# Summary/Outlook

- Moisture ingress has a strong impact on module reliability and lifetime
- A good model exist to simulate the moisture ingress into both G/G and G/BS modules, with which the effect of module configuration and packaging materials can be evaluated
- An in-situ RH/T sensor system embedded into PV modules was developed and applied, to measure the actual RH and T inside the module and was used to validate the model
- Results of outdoor data, water ingress simulations and ATLs provide first bricks to predictive modeling
- This predictive model must consider specificities linked to climate and operating conditions (e.g. integrated roof, façades vs stand-alone) based on reported major failure mechanisms
- The model is first develop for standard c-Si cells then should be extended to advanced c-Si based technologies (PERC, IBC, HJT)

# Thanks
# for your attention!

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