# *Modelling the effects of PV module polymer thermal and moisture diffusion properties on lifetime energy yield*

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# Outline

# 1. Introduction

# Introduction – EnergyVille

Thor Park

Energyville 2 (Imec)

imec

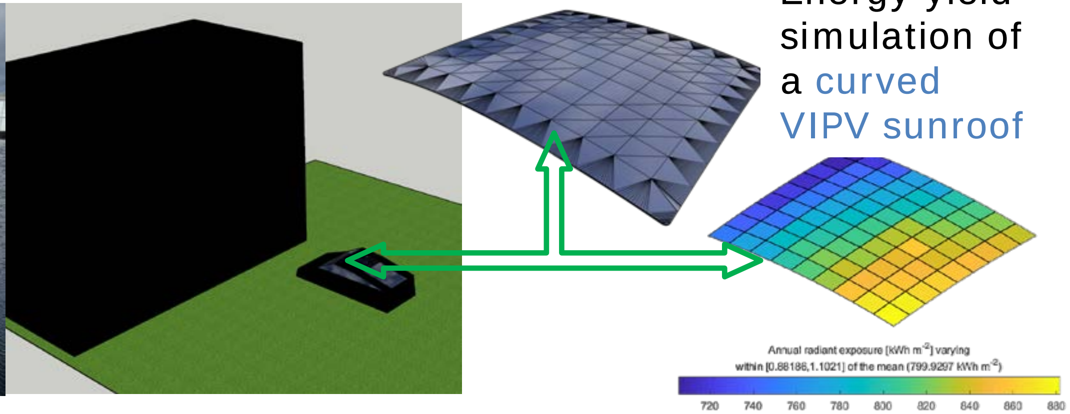
UHASSELT ← EnergyVille → vito

KU LEUVEN

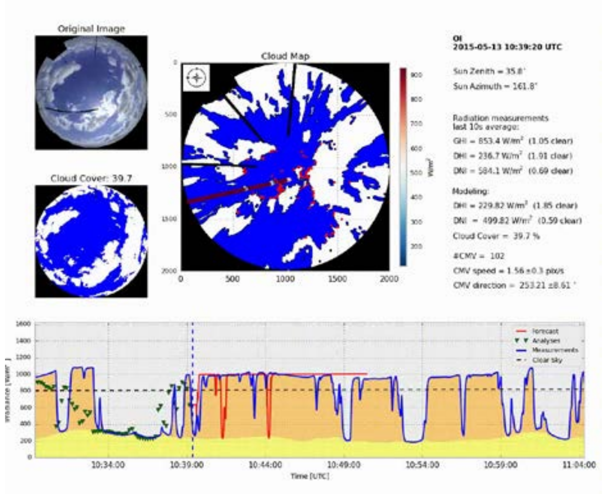

**sustainable energy** and **intelligent energy systems**

# Introduction – Energy yield simulation team

✓ Energy yield simulation framework: Different PV applications, PV system sizes and terrains




Energy yield simulation of a curved VIPV sunroof


Energy yield forecast

Combination of Artificial Neural Networks and physics-based PV model

- Low-cost sky camera image input
- Cloud classification

Higher accuracy and better spatial & temporal resolution than satellite based forecasts

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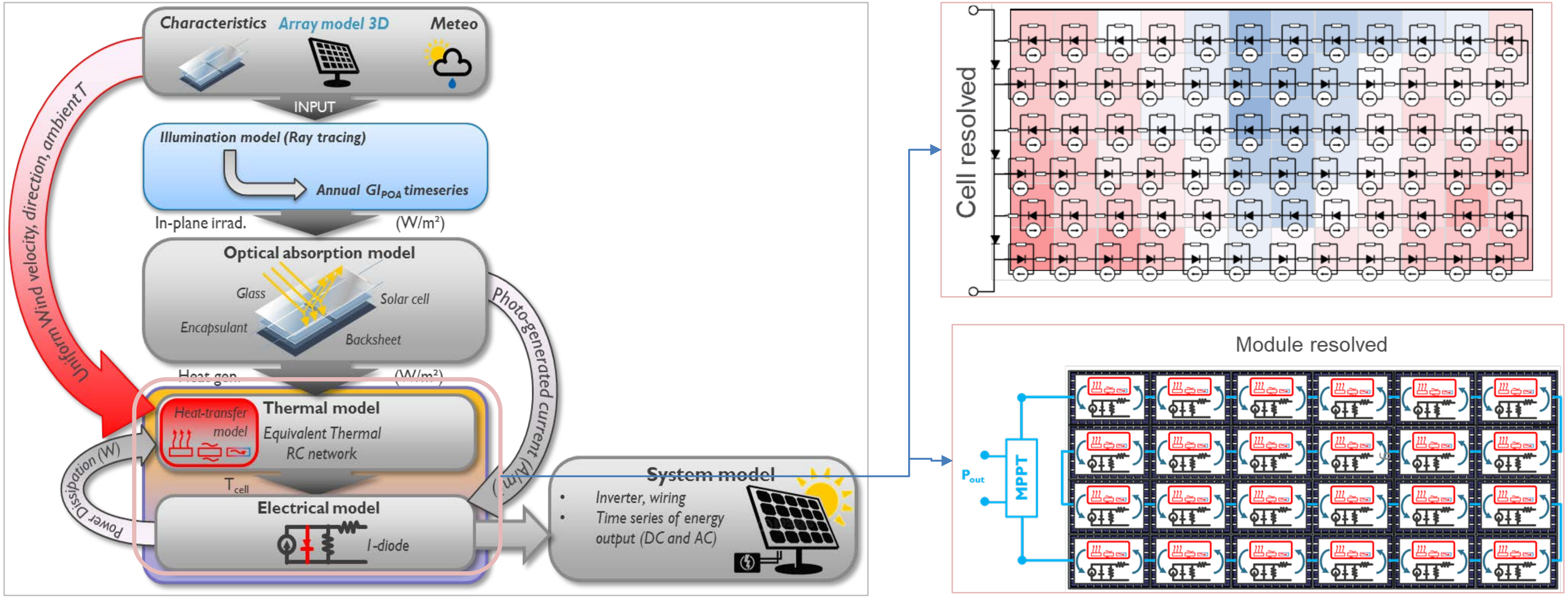
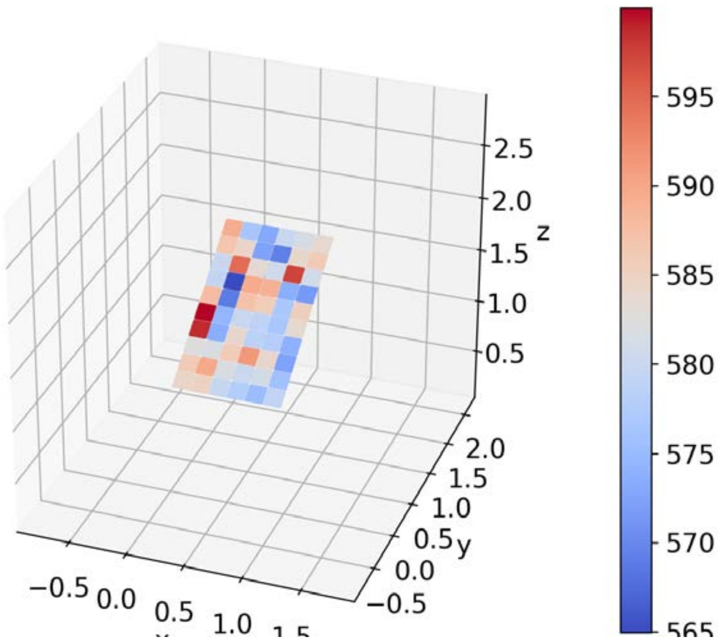
- ✓ Coupled thermal-electrical model
  - ✓ Directly model the interaction of module layers and heat exchange with environment
  - ✓ Include Non-uniformity: mismatch losses on cell or module level
  - ✓ Solve the thermal-electrical circuit



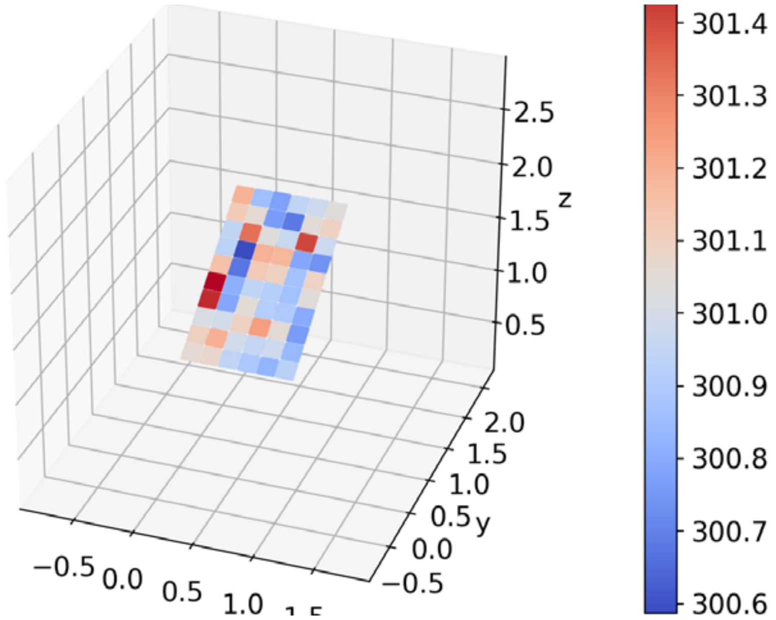
# Introduction - Energy yield simulation framework

- ✓ Coupled thermal-electrical model – Example of cell level simulation for a single day
  - ✓ Include Non-uniformity: mismatch losses on cell or module level
  - ✓ Solve the thermal-electrical circuit – Thermal output for each module component (Backsheet, Encapsulant, Cell)

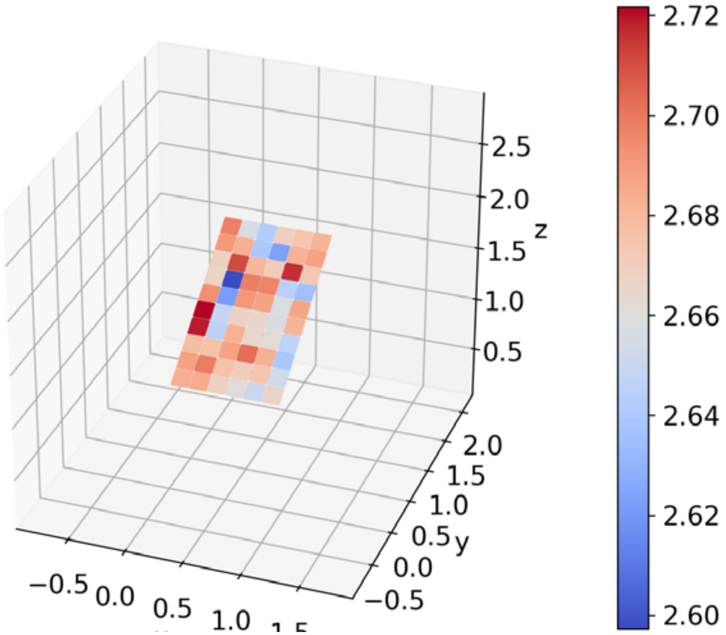
Gipoa [W/m2]




T-cell [K]




Pmpp [W]

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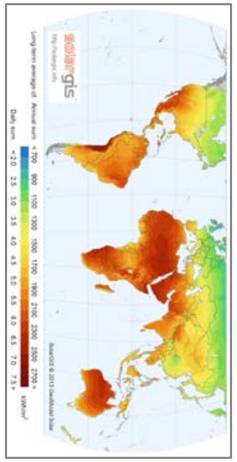
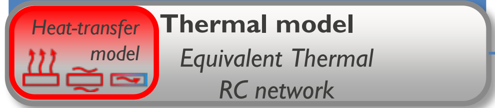
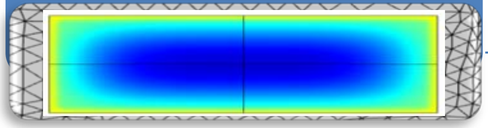
- ✓ Our modelling approach
  - ✓ Overview – How it works



Thermal model

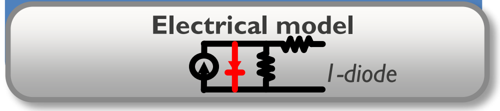



Moisture ingress model



UV

Electrical model




Degration models
- Effect of climate
- Effect of BoM

Varry material properties
- Thickness, Thermal properties, diffusion properties

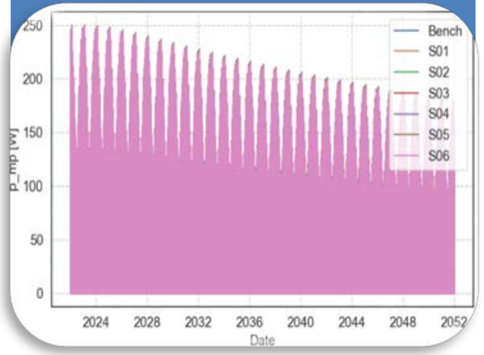
Output

Degradation rate

DC power time series

Energy yield

Other electrical parameters (Impp, Vmpp etc

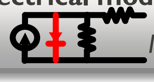


# Introduction – Degradation model: Another physics based layer on yield model

- ✓ Our modelling approach
  - ✓ Model degradation of I-V characteristic parameters as function of time and environmental conditions

Electrical model

Electrical model




Degration models
- Effect of climate
- Effect of BoM

$$I(t) = I_{pv}(t) - I_0\left[\exp\left(\frac{V + R_S(t)\cdot I}{V_t \cdot a}\right) - 1\right] - \frac{V + R_S(t)\cdot I}{R_P(t)}$$

$$I_{pv}(t) = (I_{pv,n} + K_I \Delta T)\frac{G(t)}{G_n}$$

$$I_0 = \frac{I_{sc,n} + K_I \cdot \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \cdot \Delta T}{a \cdot V_t}\right) - 1}$$

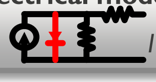
$$G(t) = \tau(t)\cdot G_0$$

# Introduction – Degradation model: Another physics based layer on yield model

- ✓ Our modelling approach
  - ✓ Model degradation of I-V characteristic parameters as function of time and environmental conditions

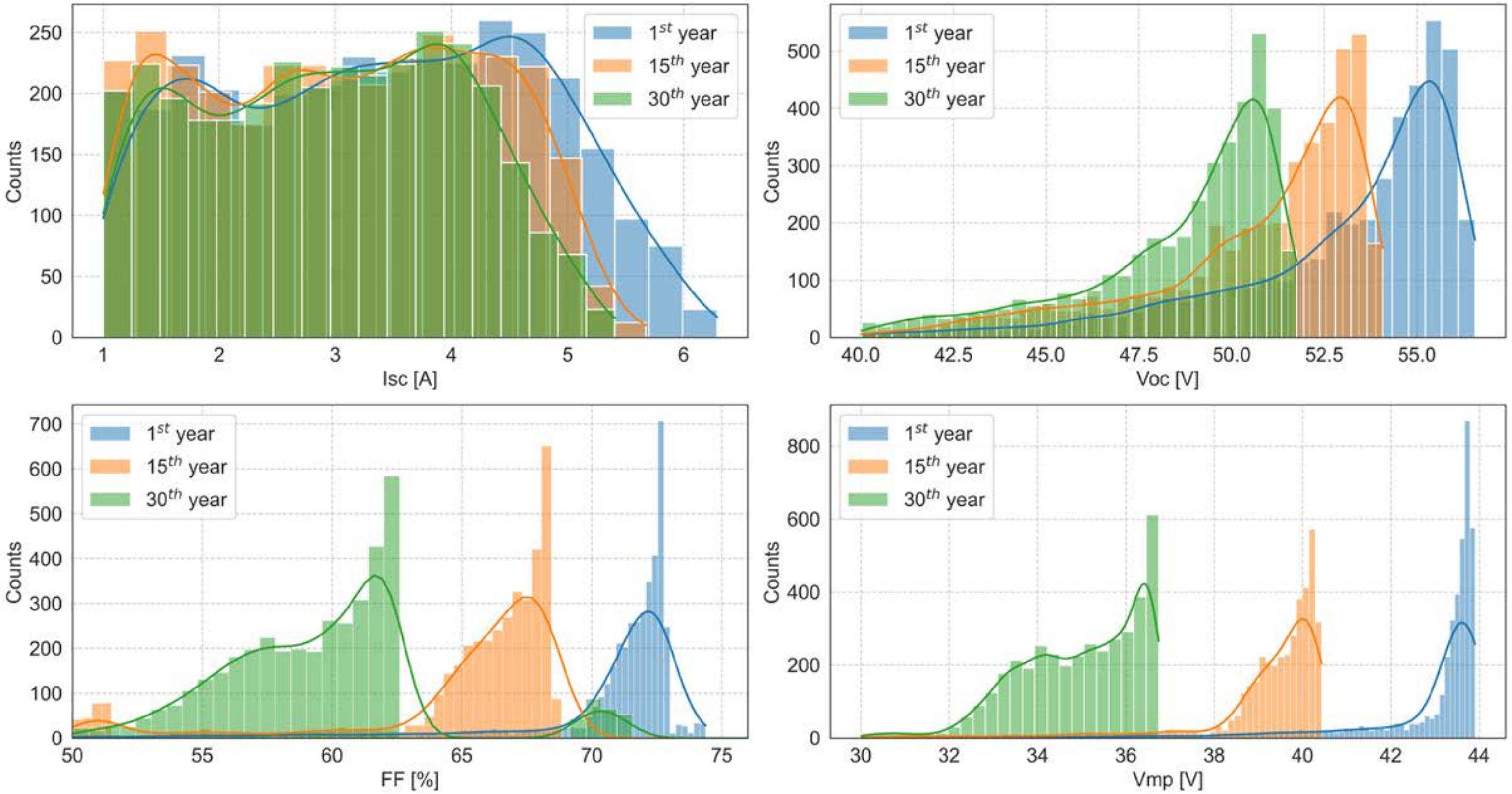
**Electrical model**

Electrical model



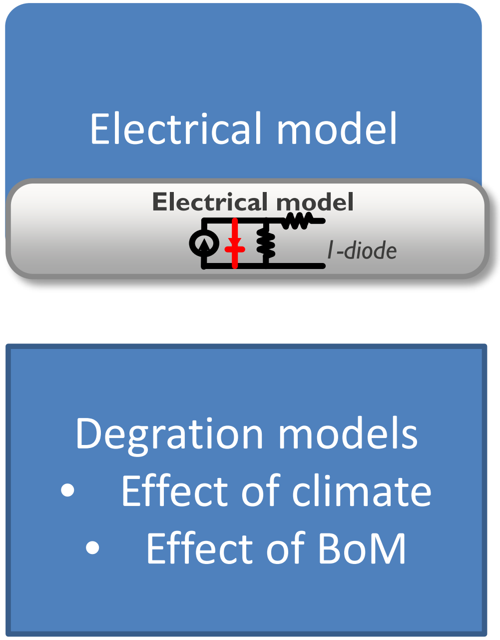

**Degration models**

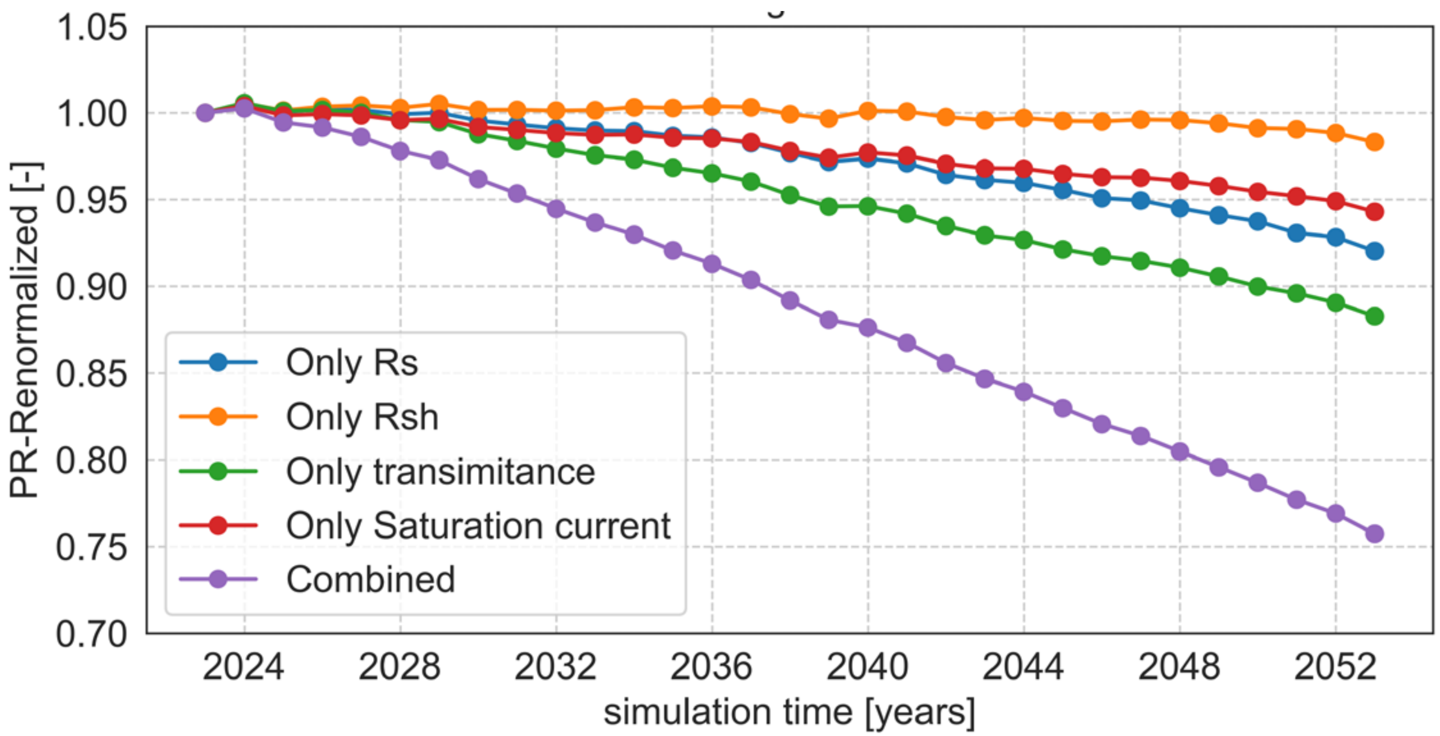
- Effect of climate
- Effect of BoM



# Introduction – Degradation model: Another physics based layer on yield model

- ✓ Our modelling approach
  - ✓ Model degradation of I-V characteristic parameters as function of time and environmental conditions





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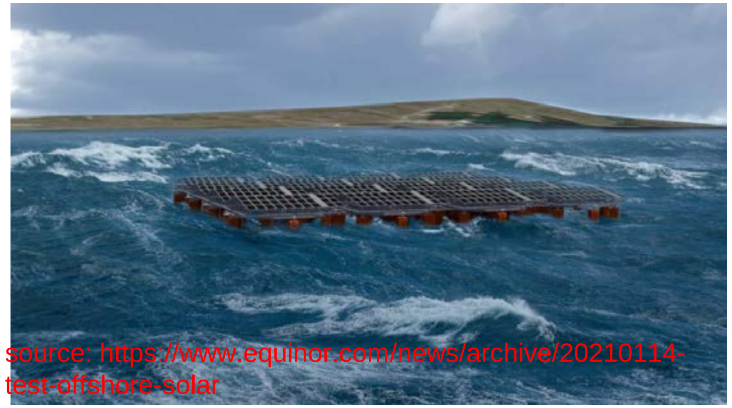
# Introduction – Needs and challenges

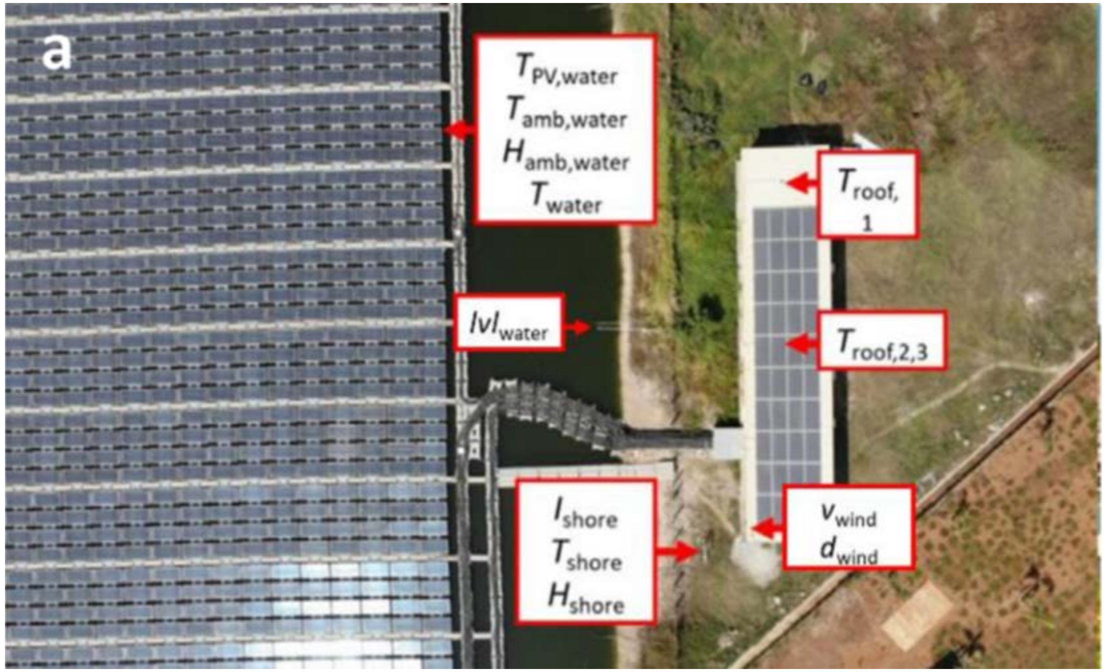
- ✓ Service Life Estimation for PV Modules
  - ✓ Overview – Different PV applications/Installations
    - ✓ These differences affect the microclimate conditions and hence the degradation rates/lifetime

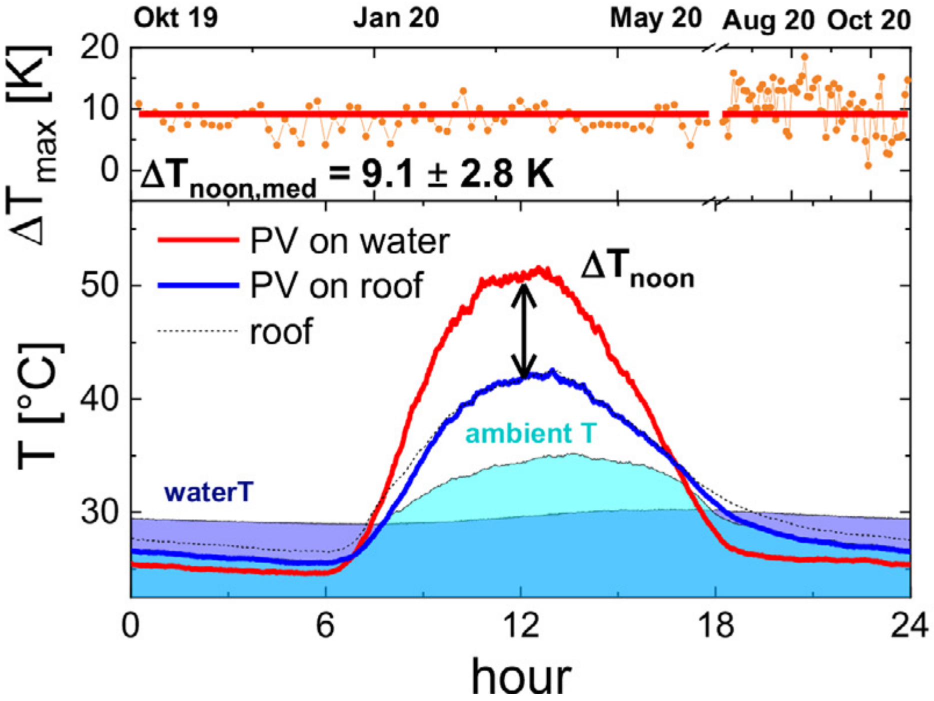


source: https://www.equinor.com/news/archive/20210114-test-offshore-solar


Source: https://www.pv-magazine-india.com/2020/10/05/agrivoltaics-for-pear-orchards/


https://www.pveurope.eu/solar-modules/solar-integration-solar-car-roof-both-evs-and-ice-vehicles

- ✓ Our focus – Understand and model the different microclimate conditions and their impact on degradation rates/lifetime
  - ✓ Adaptable approach considering specific conditions

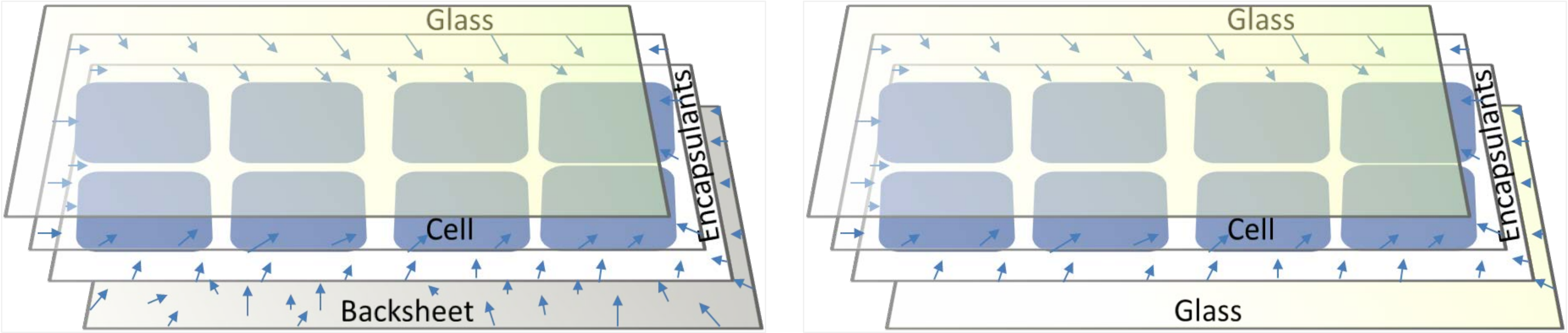



Figures from: I.M. Peters a , ∗ , A.M. Nobre b “Deciphering the thermal behavior of floating photovoltaic installations” 2022

# Introduction – Degradation model (application example)

- ✓ Considers PV module design aspects
  - ✓ E.g – Different PV designs (Glass- backsheet Vs Glass-Glass module)
    - ✓ These differences affect the microclimate conditions and hence the degradation rates/lifetime




- ✓ Arrows show possible moisture pathways
- ✓ Moisture circulation might take longer time for G-G compared to G-B modules
- ✓ Less pathways → More moisture accumulations inside the module over time

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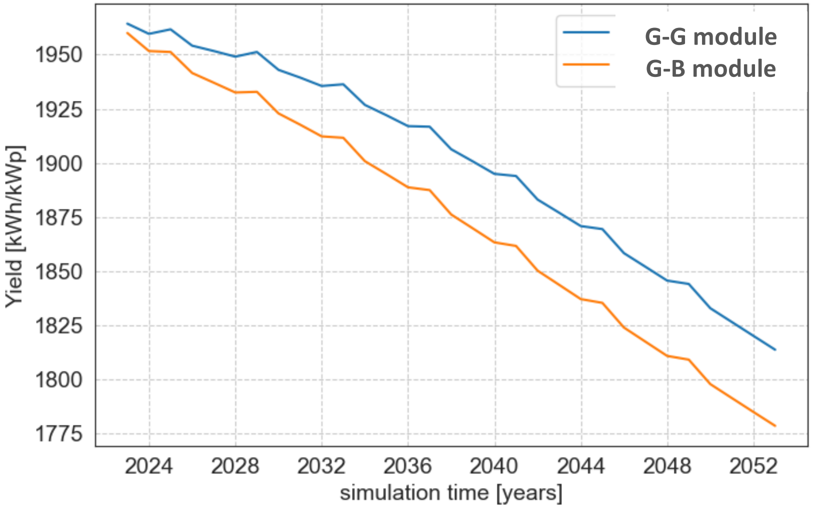
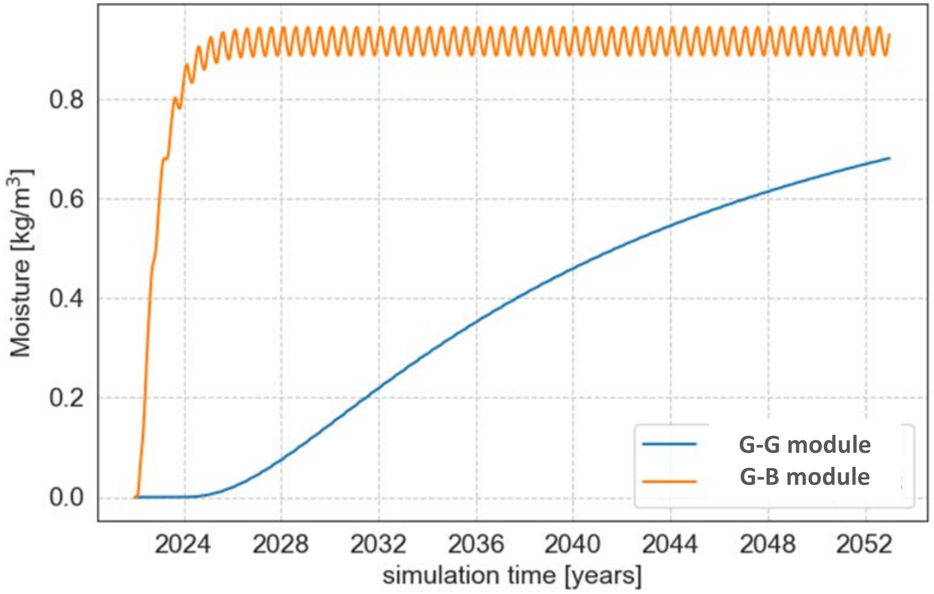
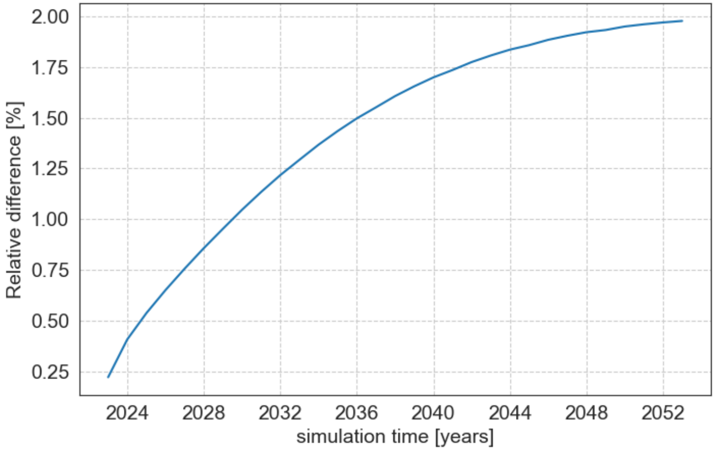
✓ Simulation of moisture effects for a Glass-glass and Glass-backsheet module




Climate dependent variations

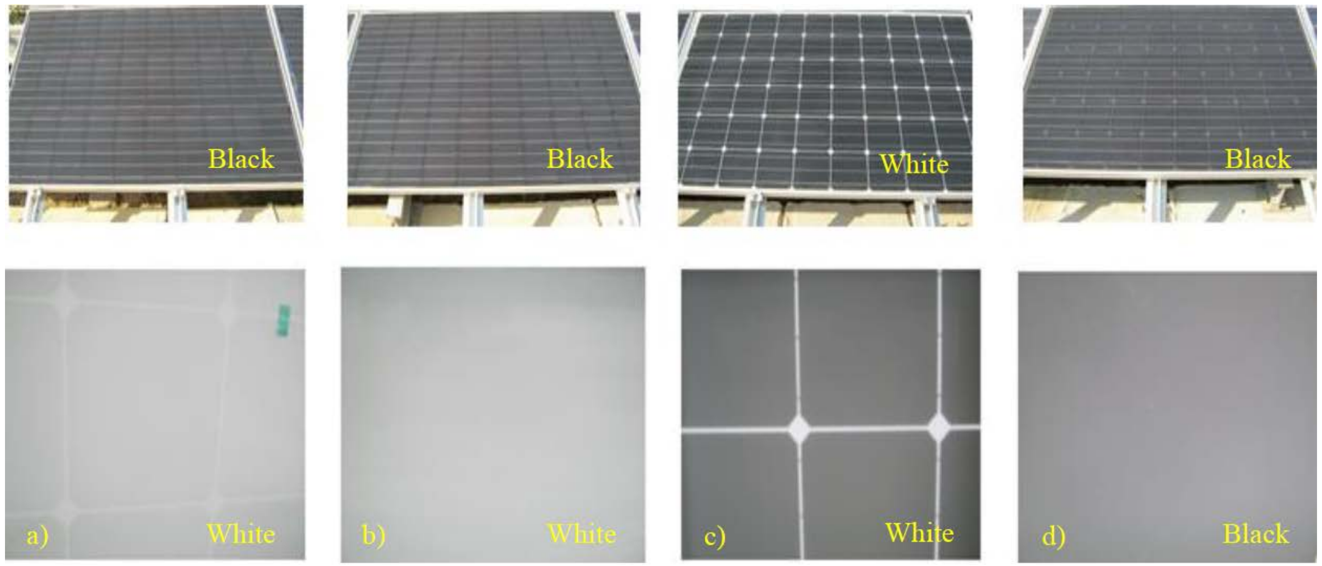


# 2. Motivation

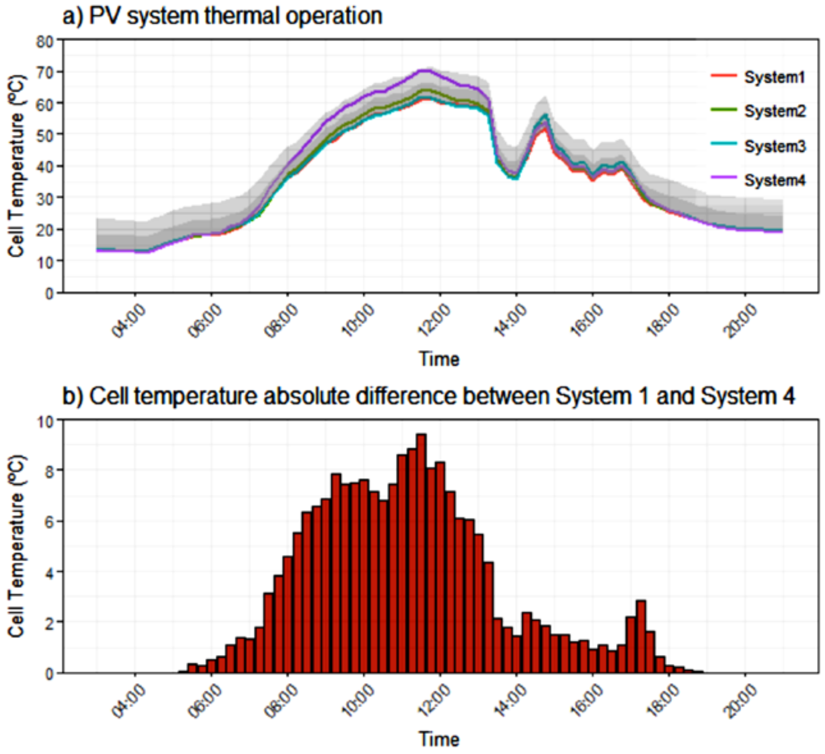
Modelling the effects of PV module polymer thermal and moisture diffusion properties on lifetime energy yield

# Motivation – Module temperature Vs Backsheet properties

- ✓ Effect of Backsheet thermal properties on PV Module/Cell temperature
  - ✓ Literature – Outdoor analysis on five years mono-crystalline modules [1]
    - ✓ Showed in some cases 10°C temperature difference was achieved in same location
    - ✓ After 5 years, No significant difference in degradation




Front- and rear-view images of a PV module from each system: a) System 1 - black thermal management backsheet, b) System 2 - FPE black control backsheet, c) System 3 - FPE white control backsheet and d) System 4 - FPF black control backsheet [1].




Thermal behavior of all systems for a) A typical spring day where System 1 operated in some cases, by up to 10°C lower temperature compared to System 4 and b) [1].

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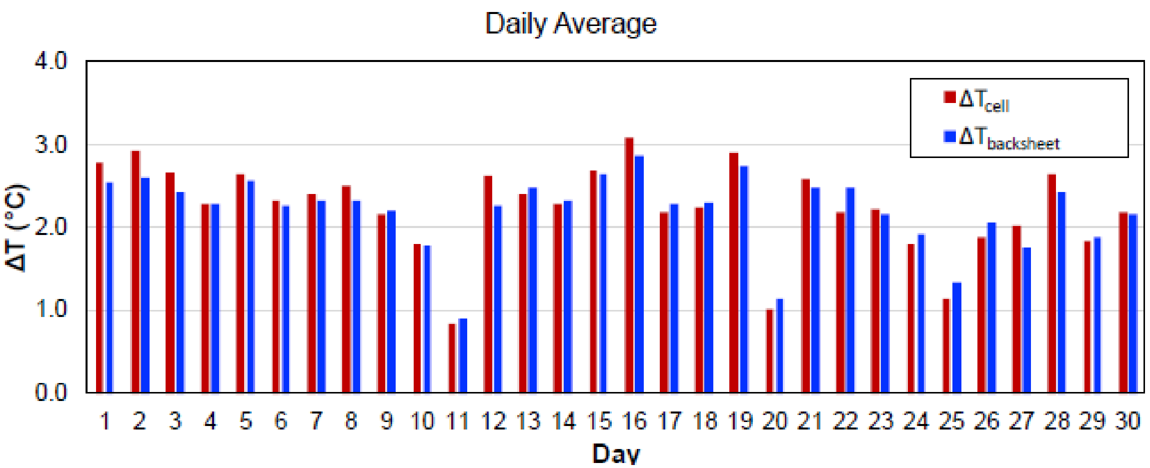
[1]. George Makrides, et al, "Five-year performance and reliability analysis of monocrystalline photovoltaic modules with different backsheet materials", Solar Energy, 2018, https://doi.org/10.1016/j.solener.2018.06.110

# Motivation – Module temperature Vs Backsheet properties

- ✓ Reducing Operating Temperature in Photovoltaic Modules
  - ✓ Literature – Reduction with innovative thermally conductive backsheet (TCB) [2]
    - ✓ Demonstrated that backsheet materials with an increased thermal conductivity contribute to a decrease in the average cell temperature of more than 1 °C in general, and of more than 2 °C on hot sunny days

NOCT test rack and single-cell coupons installed in Mesa, Arizona, USA. (Coupon identification from left to right: TCB-A, TCB-A, TCB-B, TCB-B, TPT, TPT, glass/glass, and glass/glass) [2]




ΔT based on the best performing TCB and worst performing TPT in June 2017, Mesa, Arizona. (a) ΔTcell, (b) daily average ΔT_cell and ΔT_backsheet [2].

THERMAL CONDUCTIVITIES OF THREE DIFFERENT TYPES OF BACKSHEET MATERIAL MEASURED AT 24 °C

| Backsheet Type | Axial Thermal Conductivity (W/m·K) | Radial Thermal Conductivity (W/m·K) |
|---|---|---|
| TPT | 0.153 | 0.486 |
| TCB-A | 0.259 | 0.371 |
| TCB-B | 0.382 | 13.53 |

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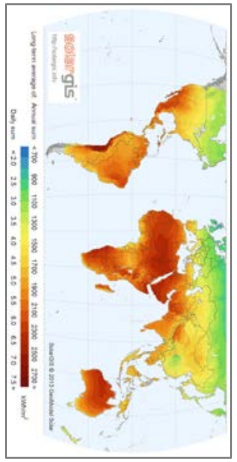
[2]. Jaewon Oh et al. Reduction of PV Module Temperature using Thermally Conductive Backsheets, IEEE JPV, 2018

# 3. Methodology

# Methodology

✓ Focus on thermal and moisture ingress



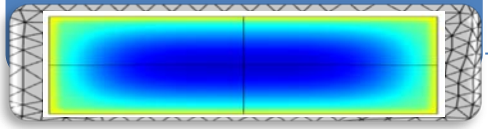
Thermal model

Heat-transfer model

**Thermal model**

*Equivalent Thermal RC network*

Moisture ingress model



Electrical model

**Electrical model**

*I-diode*

UV

Degration models
- Effect of climate
- Effect of BoM

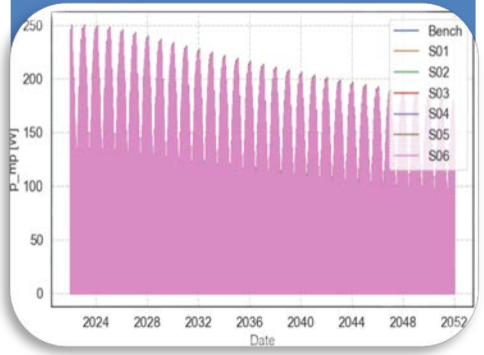
Output

Degradation rate

DC power time series

Energy yield

Other electrical parameters (Impp, Vmpp etc




Varry material properties
- Thickness, Thermal properties, diffusion properties

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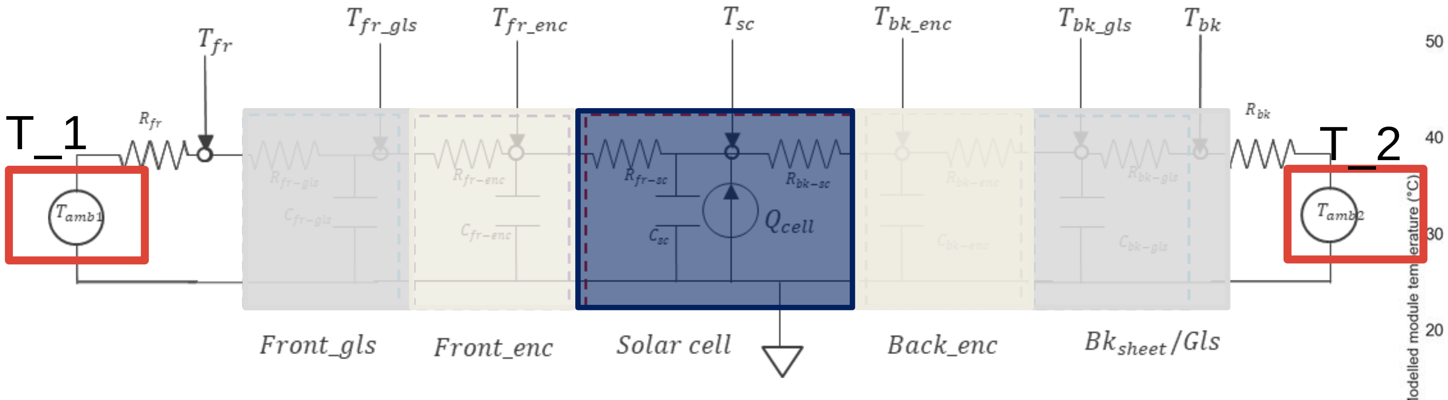
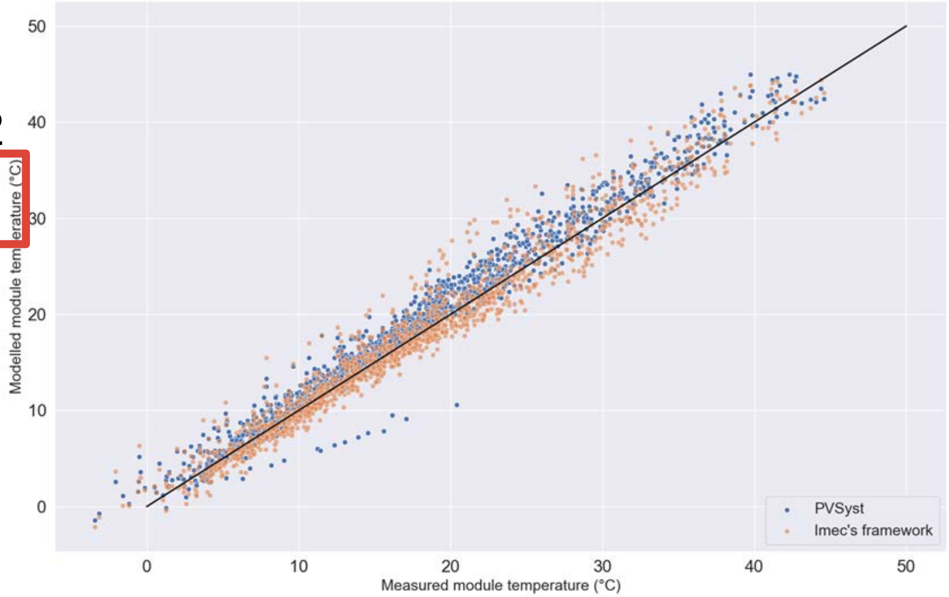
# Methodology – Thermal model

- ✓ Use thermal – Electrical Analogy to calculate the heat flow in module layers
- ✓ Convection and Radiation are modelled as variable resistor ( i.e Wind speed and ΔT = surface T– ambient T)
- ✓ Fully transient thermal model to capture dynamic thermal behavior






Validated and bechmarked with other thermal models in common simulation frameworks

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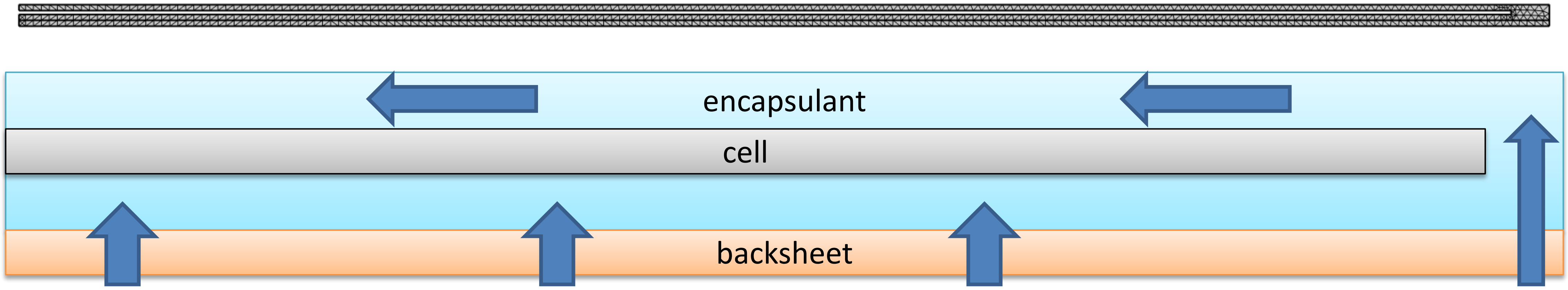
# Methodology – Moisture ingress simulations

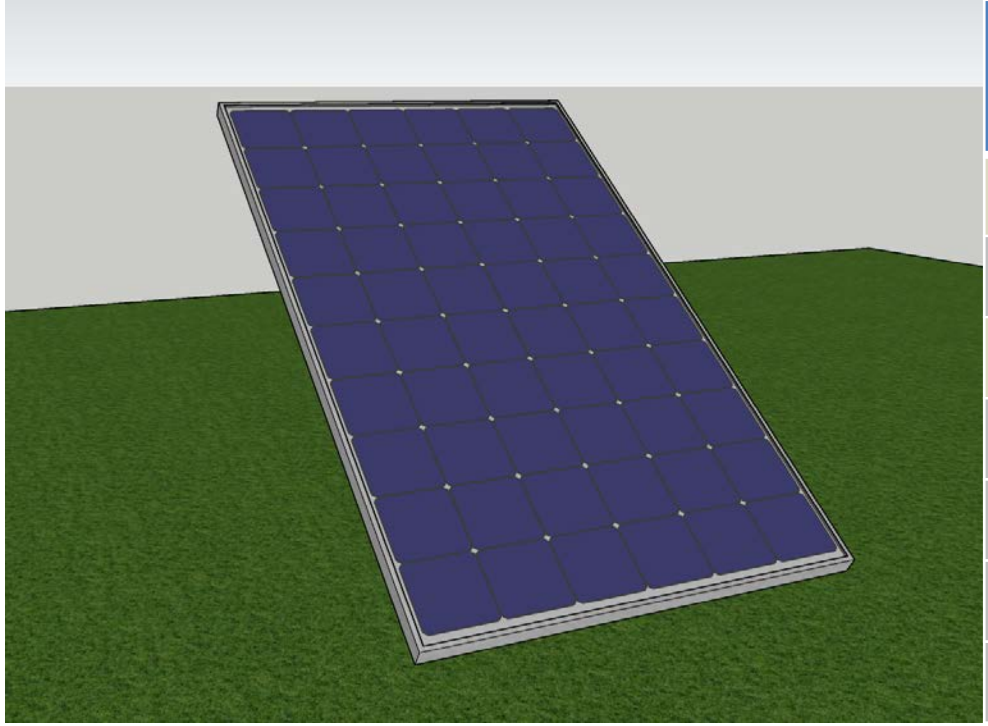
- ✓ Moisture sorption using Fickian diffusion model
  - ✓ $\partial C / \partial t = D \cdot \Delta C$
  - ✓ $D = D_0 \cdot exp\left(\frac{-E_a}{k_B T}\right)$
  - ✓ where C: moisture concentration, D: diffusion coefficient, D0: pre-exponential factor, Ea: activation energ




- ✓ Simulation → Encapsulant and backsheet (BS) around half a cell
- ✓ Boundary condition on air-BS boundary calculated from BS- temperature (T), air T and air RH using Arden-Buck equation and presuming Henry type sorption

# Methodology - Simulated PV module properties

- Glass-backsheet module simulated
  - Varied the thickness and thermal conductivity of the backsheet and encapsulant (based on literature values)



| Scenarios (S) | Backsheet thickness [µm] | Encapsulant thickness [µm] | BS-thermal conductivity [W/m.K] | Enc- thermal conductivity [W/m.K] |
|---|---|---|---|---|
| Benchmark | 300 | 500 | 0.1 | 0.1 |
| S01 | 500 | 500 | 0.1 | 0.1 |
| S02 | 300 | 600 | 0.1 | 0.1 |
| S03 | 300 | 500 | 0.4 | 0.1 |
| S04 | 300 | 500 | 0.1 | 0.4 |
| S05 | 500 | 500 | 0.4 | 0.1 |
| S06 | 300 | 600 | 0.1 | 0.4 |

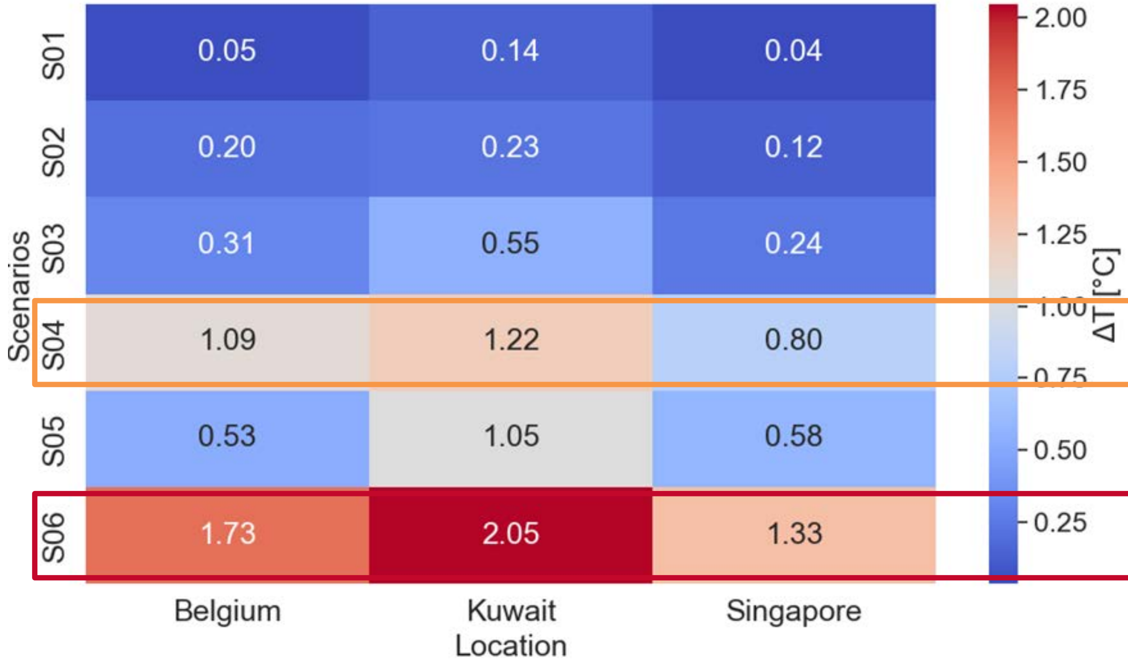
| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

# 4. Results

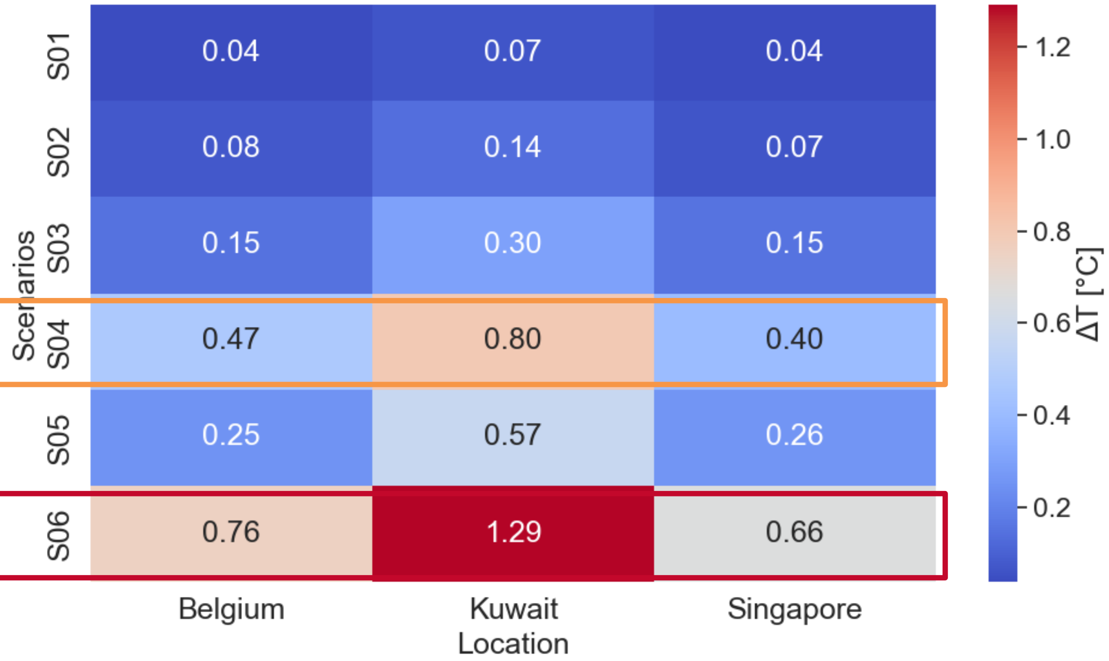
# Results – Thermal properties

✓ Estimate the delta T in different locations

Absolute change in annual maximum temperature [%]




Absolute change in annual mean temperature [%]




| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

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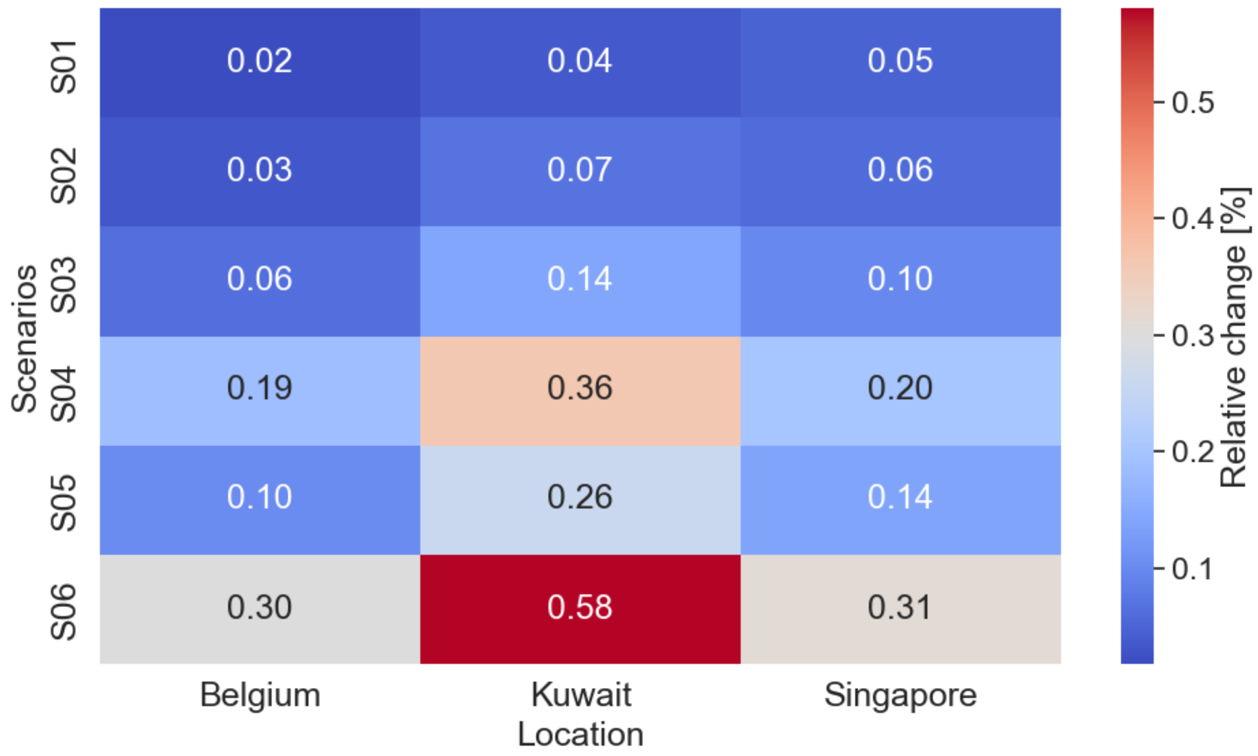
# Results – Thermal properties

✓ Effect of delta T on the first year energy yield




No significant change

| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

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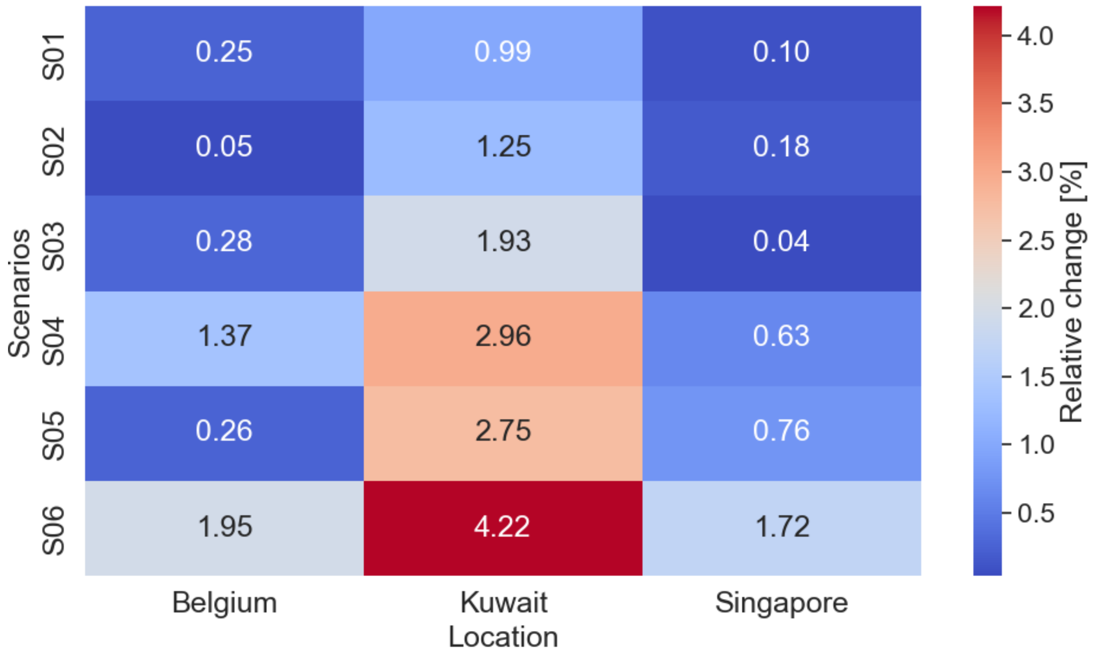
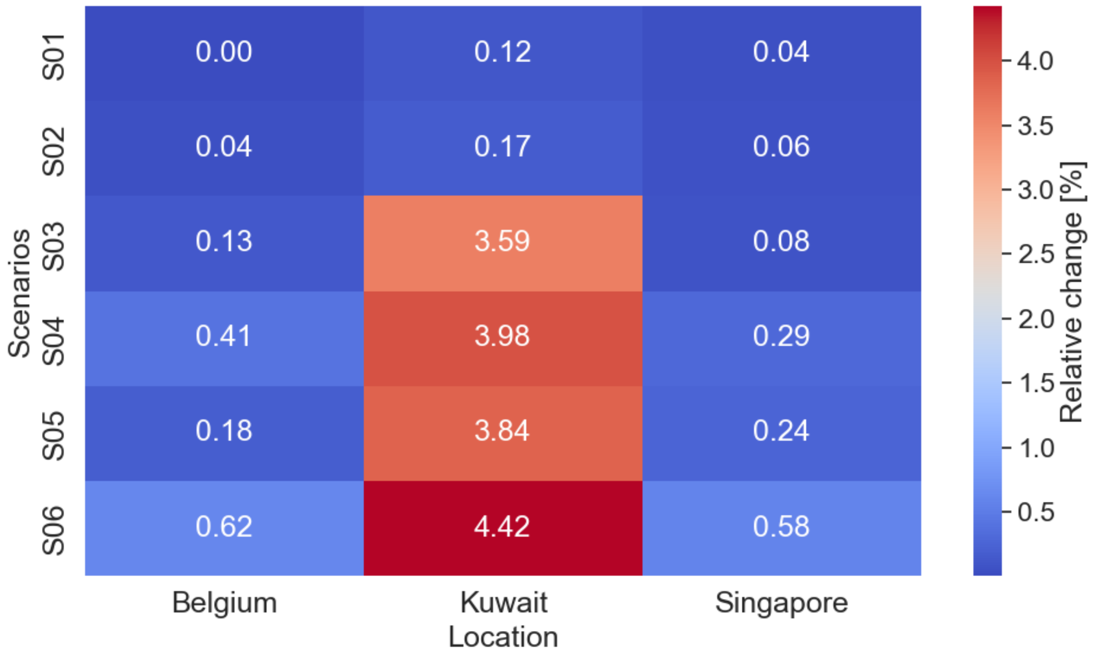
# Results – Thermal and diffusion properties

✓ Change backsheet $D_0$ by 90% $\left[\partial C/\partial t = D \cdot \Delta C \quad \rightarrow D = D_0 \cdot exp\left(\frac{-E_a}{k_B T}\right)\right]$

Relative change in degradation rate [%]




Relative change in lifetime yield [%]

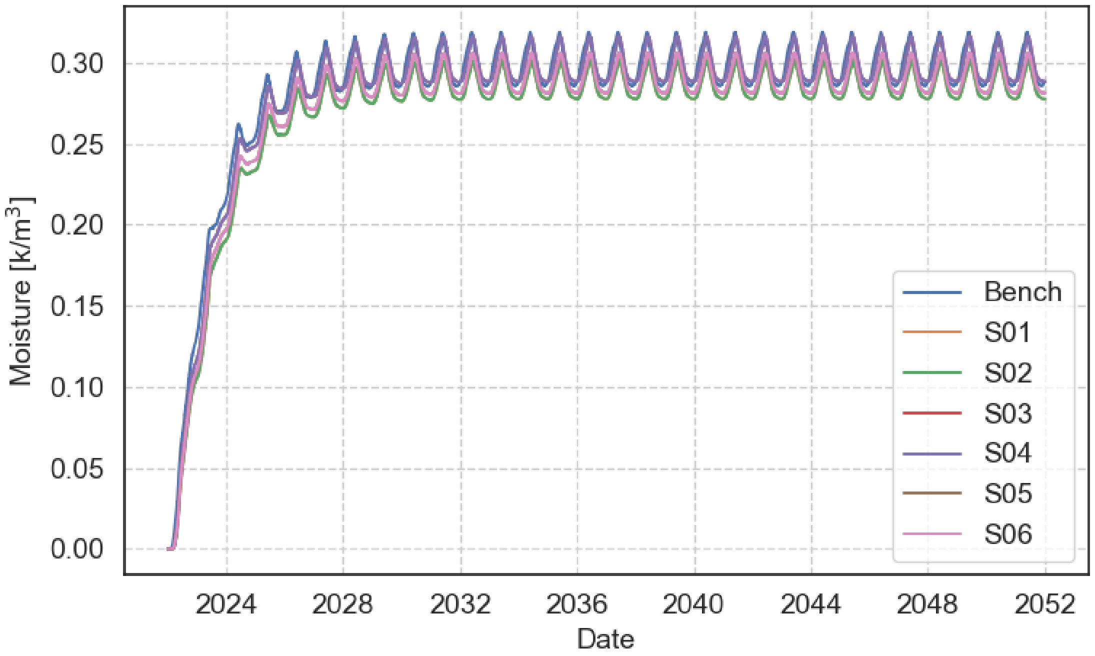



| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

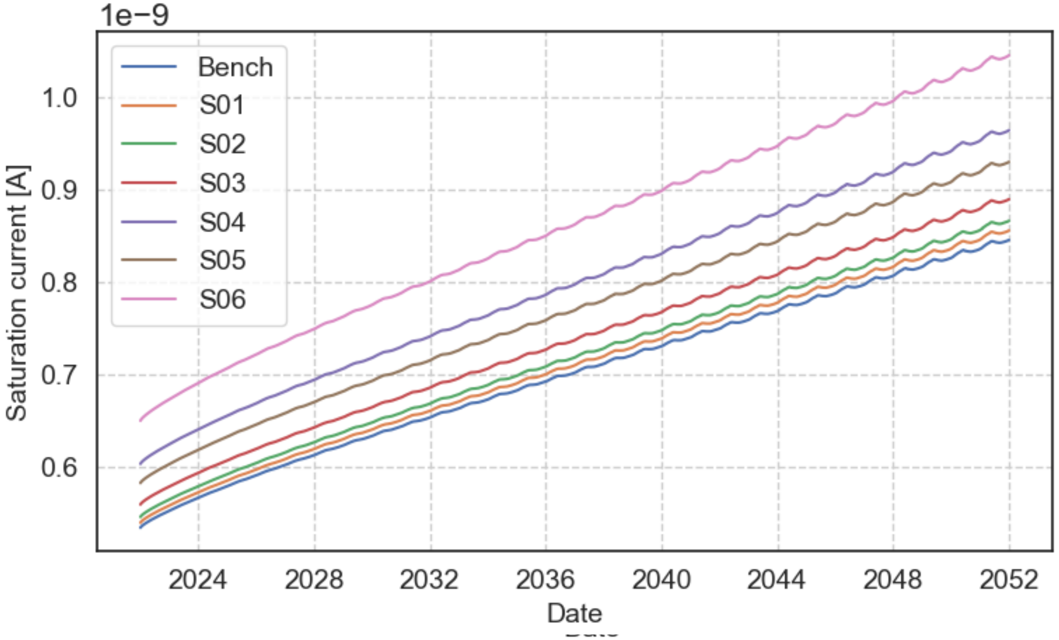
# Results – Thermal and diffusion properties

- ✓ Change backsheet $D_0$ by 90% $\left[\partial C / \partial t = D \cdot \Delta C \quad \rightarrow \quad D = \mathbf{D_0} \cdot exp\left(\frac{-E_a}{k_B T}\right)\right]$

## Moisture levels




## Electrical parameters




| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

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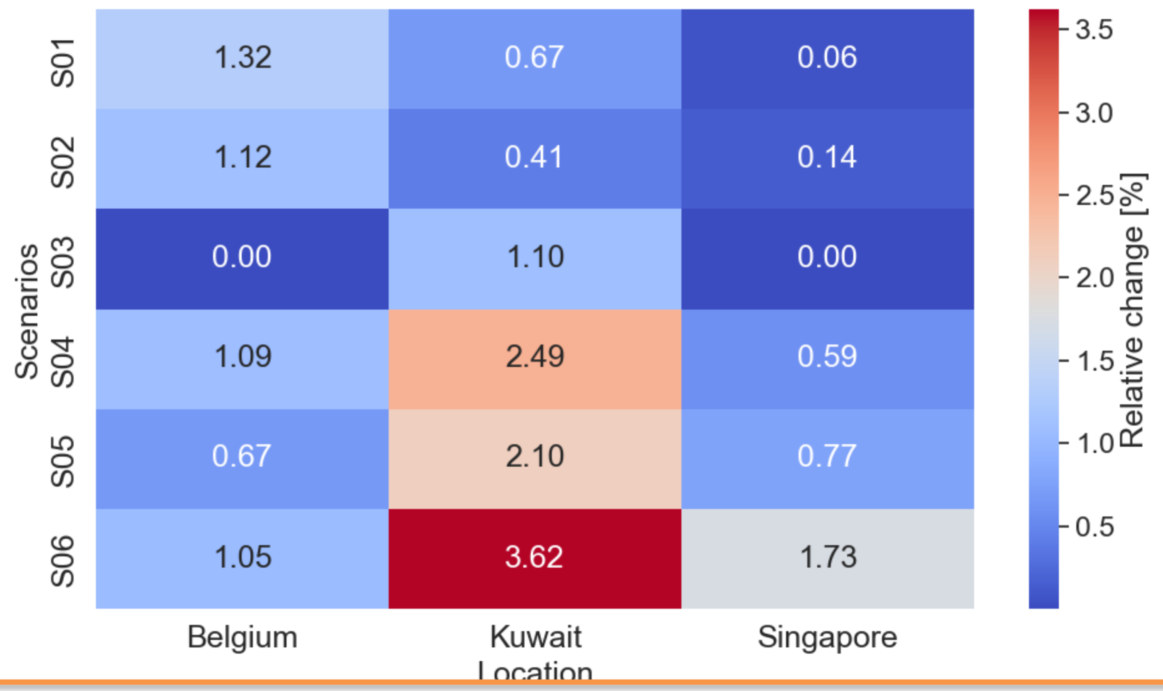
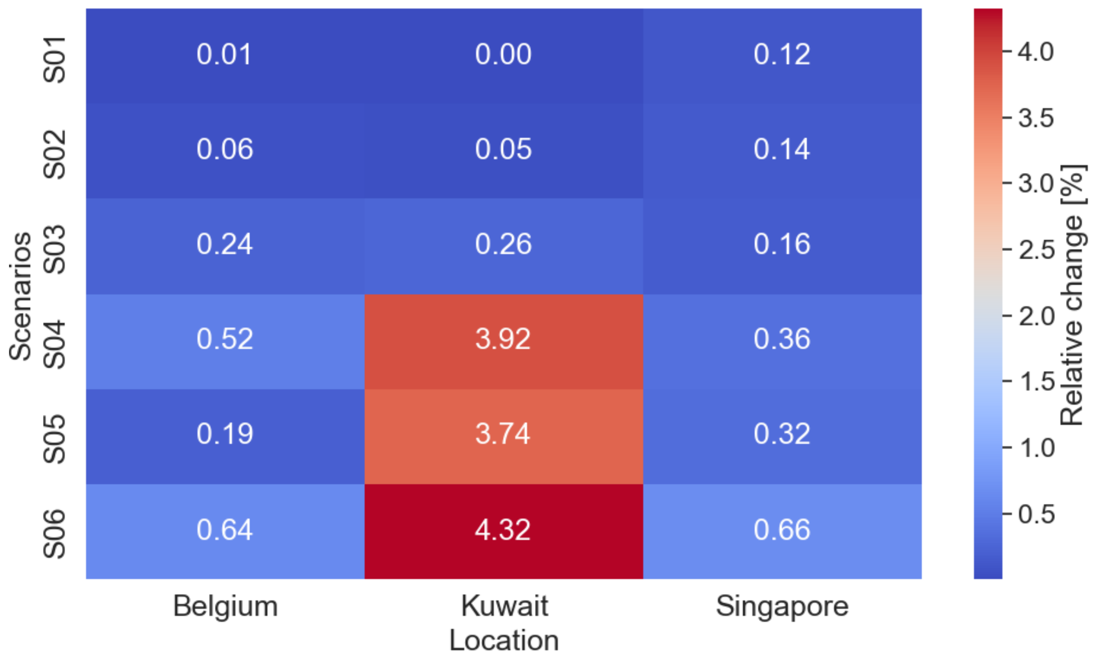
# Results – Thermal and diffusion properties

✓ Change Encapsulant $D_0$ by 25% $\left[\partial C/\partial t = D \cdot \Delta C \quad \rightarrow D = \boldsymbol{D_0} \cdot exp\left(\frac{-E_a}{k_B T}\right)\right]$

Relative change in degradation rate [%]




Relative change in lifetime yield [%]




| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

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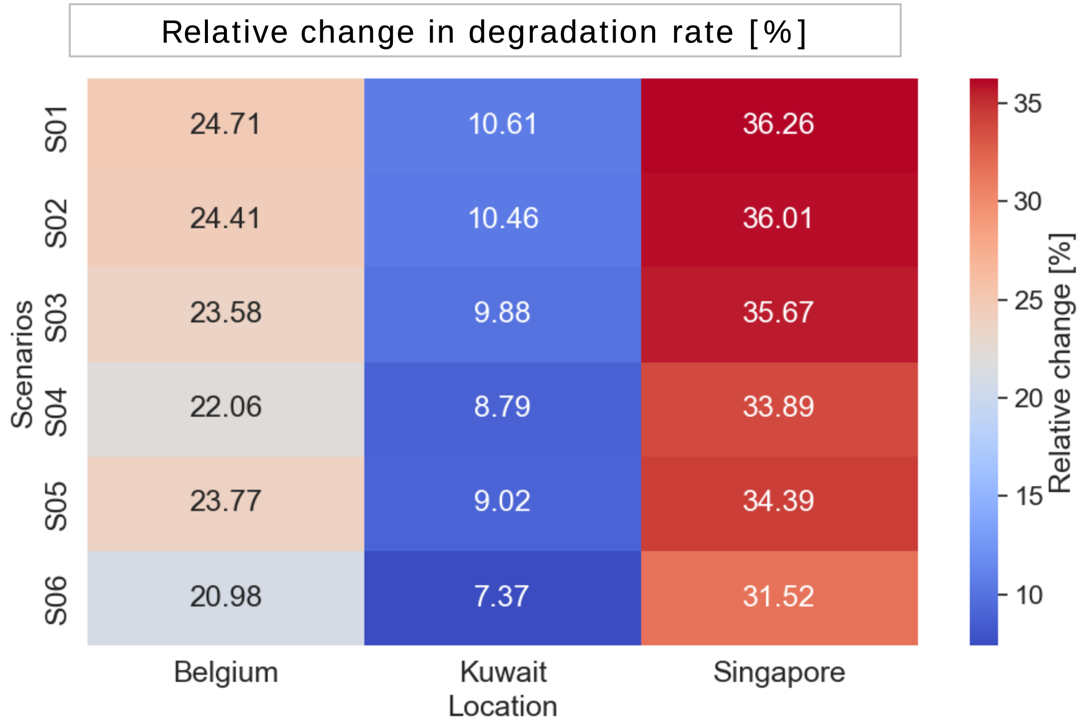
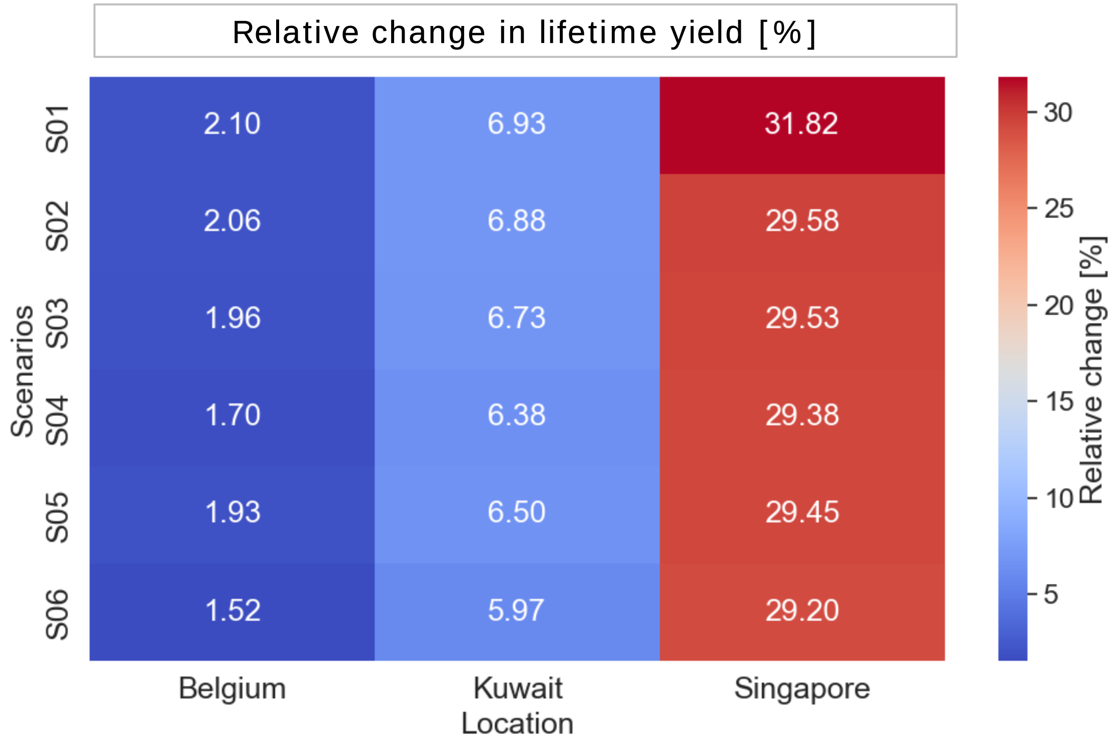
# Results – Thermal and diffusion properties

✓ Change Encapsulant $S_0$ by 40% $\left[S = S_0 \cdot exp\left(\frac{-E_a}{k_B T}\right)\right]$




| S01 | S02 | S03 | S04 | S05 | S06 |
|---|---|---|---|---|---|
| Change BS-thickness by 40% | Change Enca-thickness by 40% | Change BS-thermal conductivity by 75% | Change Enca-thermal conductivity by 75% | BS-thickness 40% and BS condctivity by 75% | Enc-thickness 40% and Enc-conductivity 75% |

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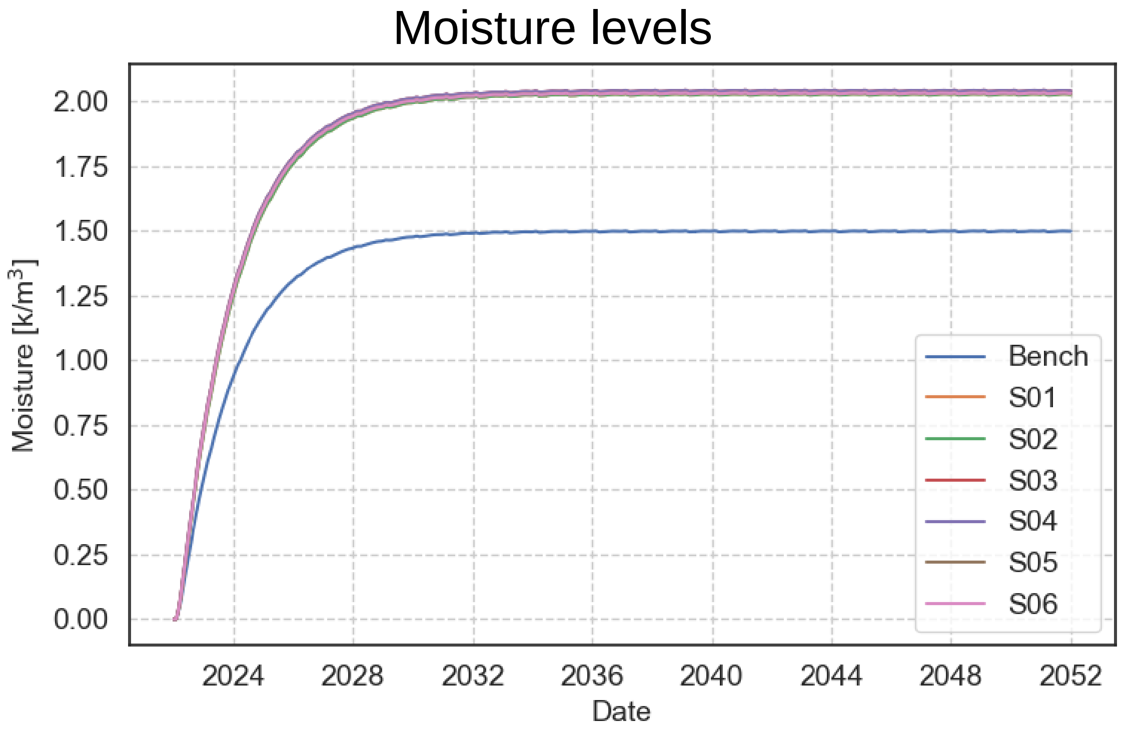


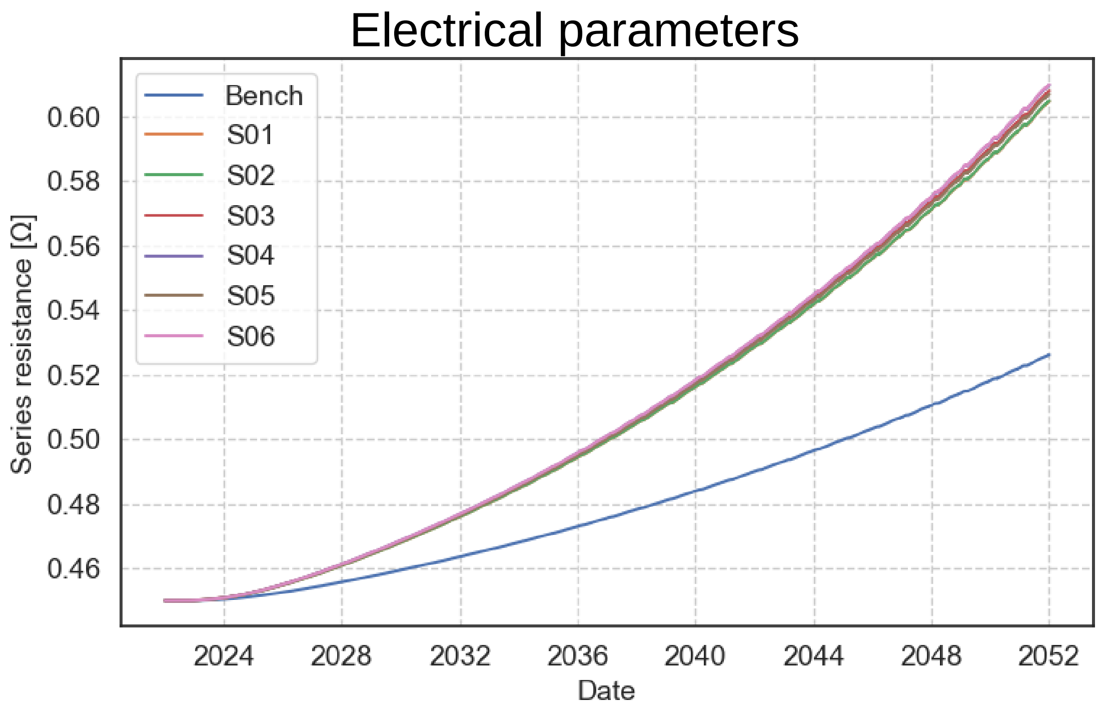


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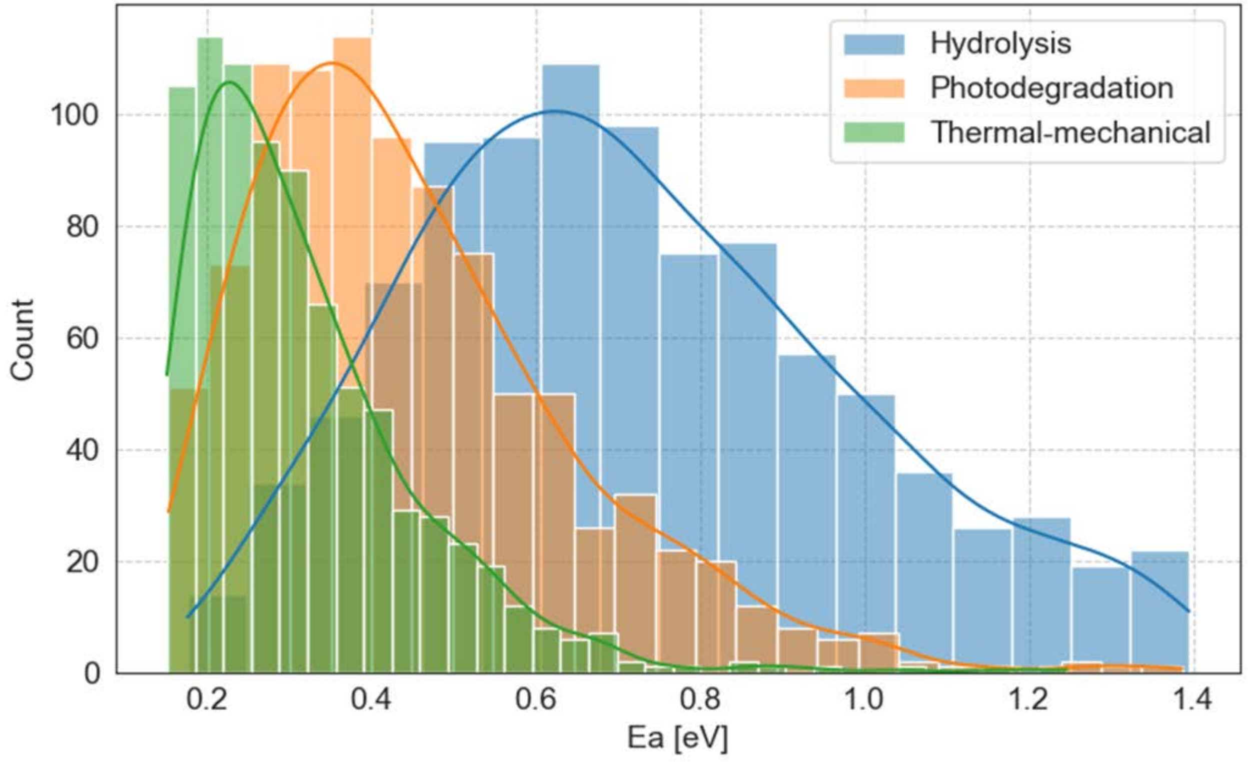
# Results – WHAT IF the material is resistant to moisture

- ✓ Parameterising the degradation rate models
  - ✓ Applied a non-central F distribution continuous random variable (1000 samples).
  - ✓ Degradation rates are evaluated for each sample

| Degradation mechanism/ process | Degradation rate models $f(RH, UV, T_{max}, T, \Delta T)$ |
|---|---|
| Hydrolysis | $k_H(T, RH) = A \times RH^n \times \exp\left(\frac{-E_a}{k_B \cdot T}\right)$ |
| Photodegradation | $k_p(UV, T, RH)$ $= A \times UV^X \times (1 + RH^n) \times \exp\left(\frac{-E_a}{k_B \cdot T}\right)$ Ea = activation energy |
| Thermal-mechanical | $k_{Tm}(\Delta T, T_{max})$ $= A \times (\Delta T + 273)^{\theta} \times C_r \times \exp\left(-\frac{E_a}{k_B . T_{max}}\right)$ |

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# Results – WHAT IF the material is resistant to moisture

- ✓ Parameterising the degradation rate models
  - ✓ Degradation rates are evaluated for each sample for each hour (resolution can be adjusted)
  - ✓ Scan through the degradation rates for optimization

| Degradation mechanism/ process | Degradation rate models $f(RH, UV, T_{max}, T, \Delta T)$ |
|---|---|
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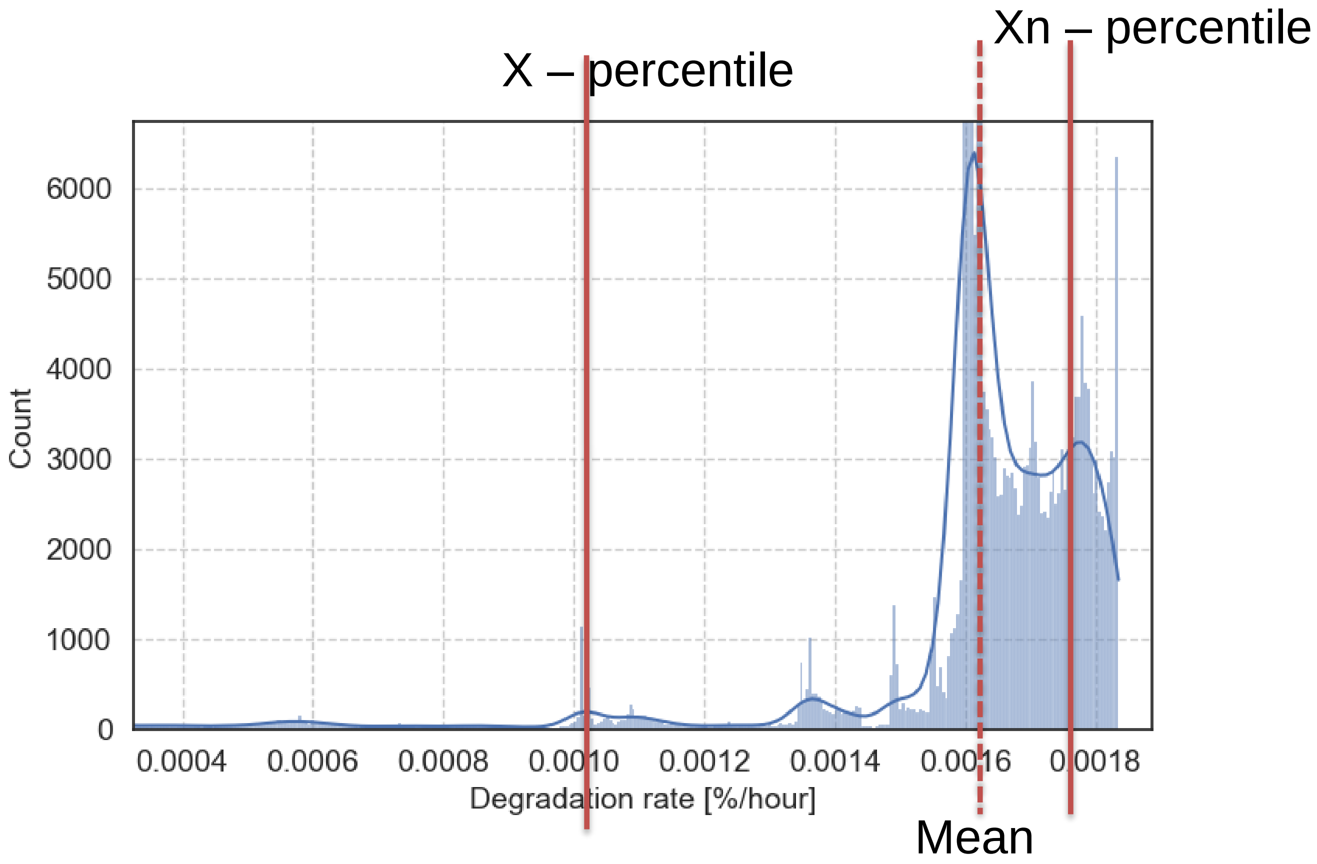


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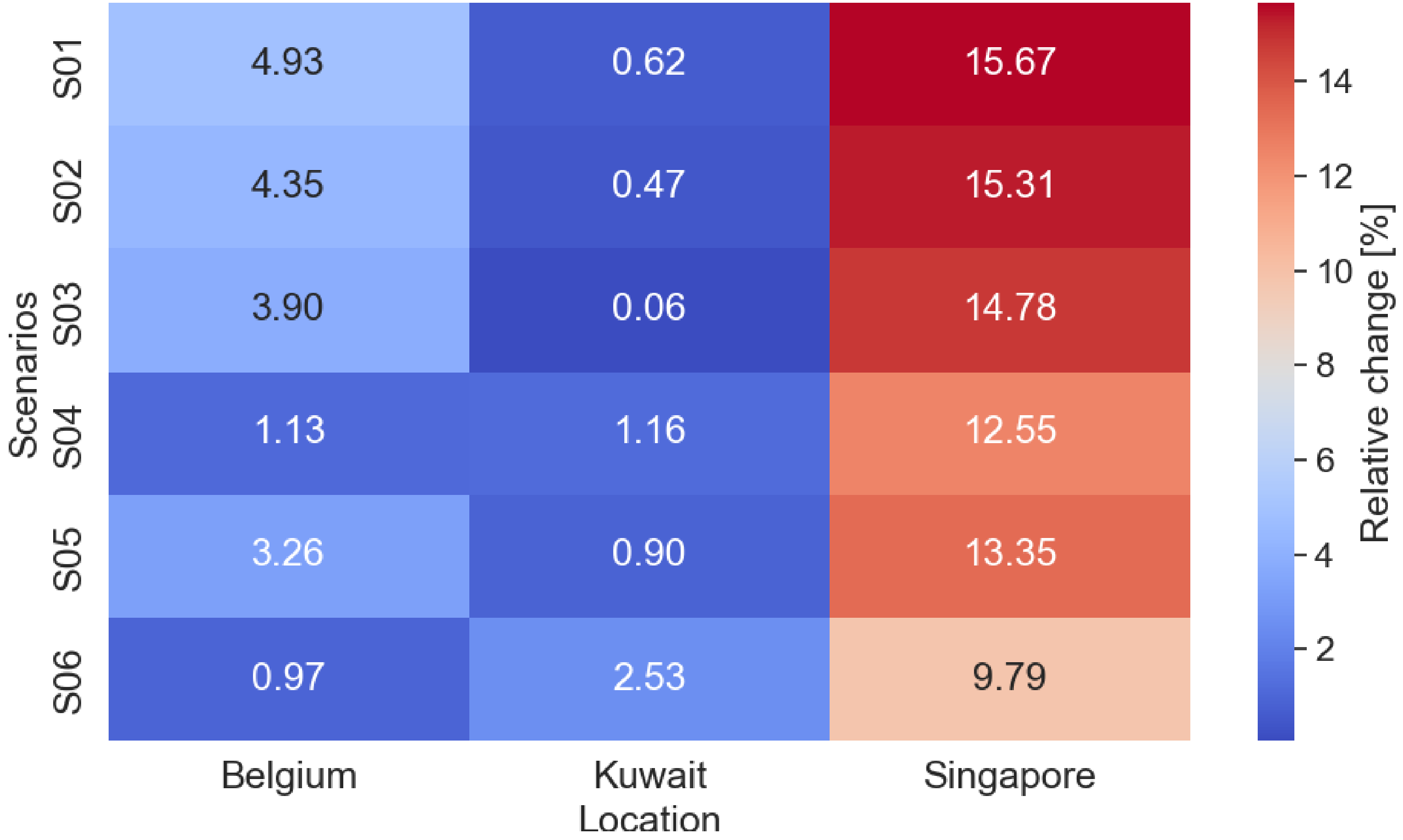
# Results – WHAT IF the material is resistant to moisture

- ✓ Repeating the solubility simulation taking the 60th percentile of the degradation rates influenced by moisture

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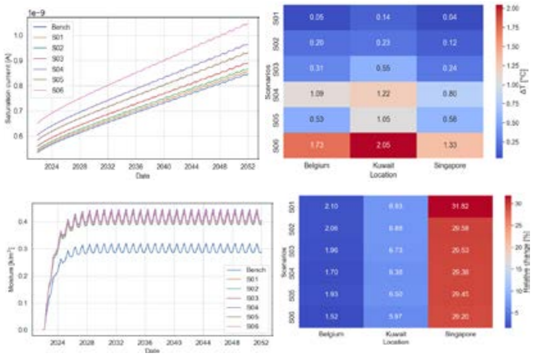
# 5. Conclusion

# Conclusion

- ✓ A simulation approach to study the effects of PV polymer thermal and diffusion properties on lifetime energy yield is presented

  - ✓ Effect of Backsheet and encapsulant <u>thickness</u> is negligible
  - ✓ Combination of <u>thickness</u> and <u>thermal conductivity</u> can lead to over <u>2°C</u> increase of cell temperature
  - ✓ Most moisture parameters showed negligible effect on lifetime energy except for the <u>solubility</u> which showed a significant change of up to 31 %
  - ✓ Effects are <u>location</u> dependent – More visible in <u>hotter</u> environment
  - ✓ Further validation with monitored modules in different locations is underway





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# Thank you

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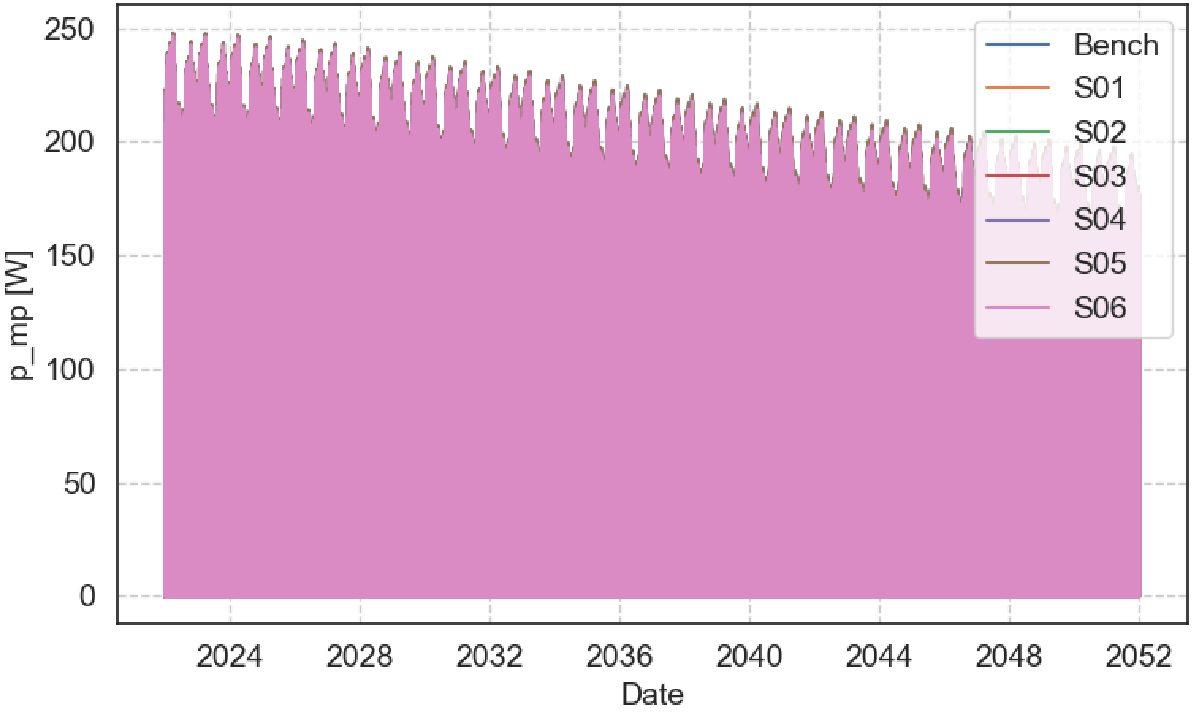
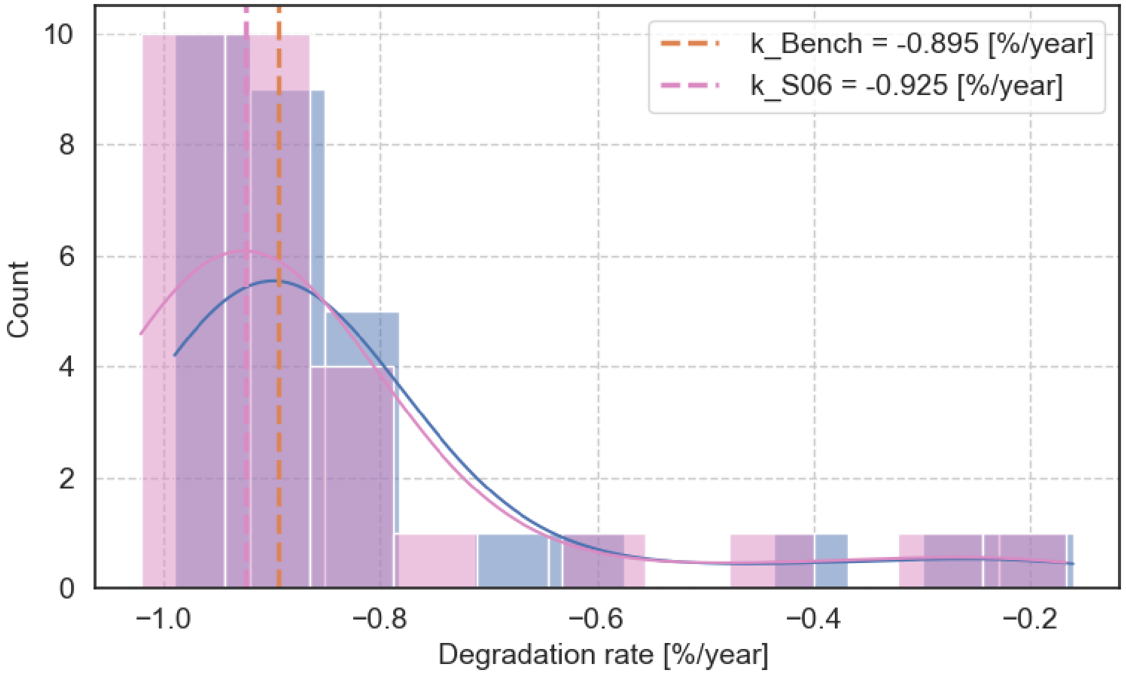
# Results – Thermal and diffusion properties

- ✓ Change backsheet $D_0$ by 90% $\left[D = D_0 \cdot exp\left(\frac{-E_a}{k_B T}\right)\right]$
  - ✓ Simulated power degradation (Kuwait)

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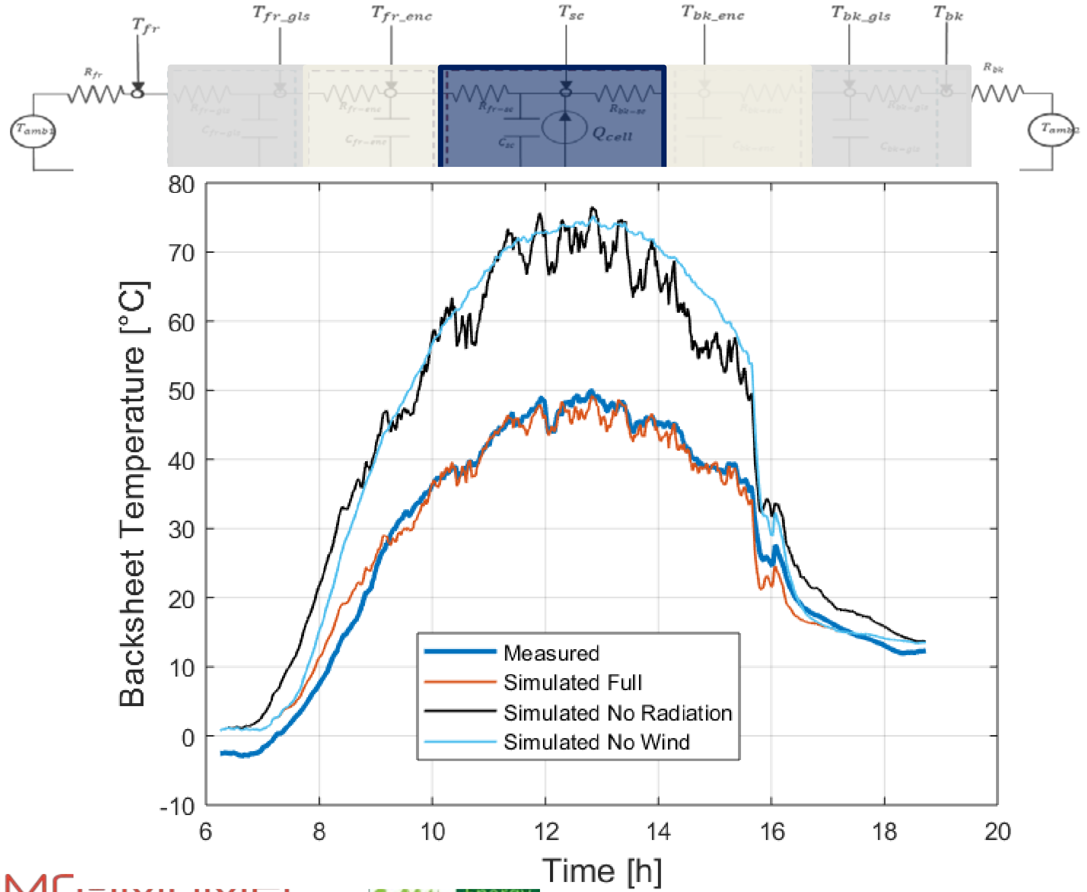
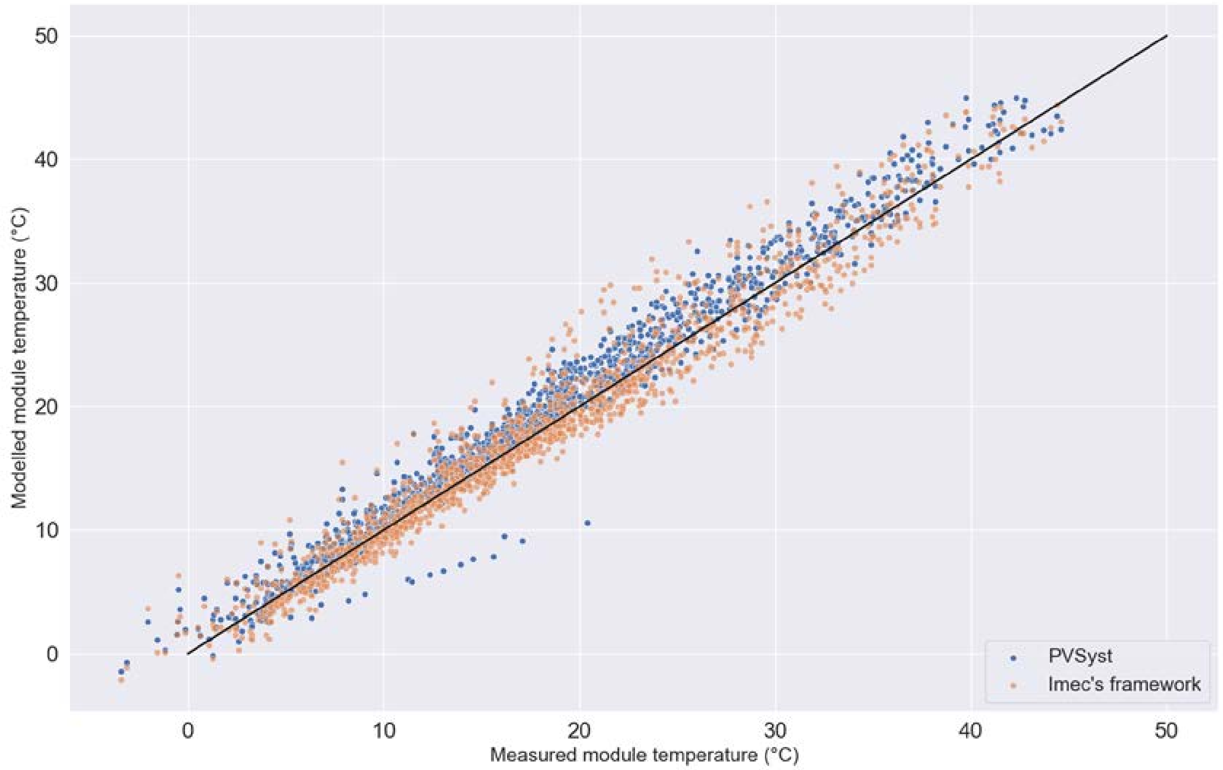
restricted

# Methodology – Thermal simulation

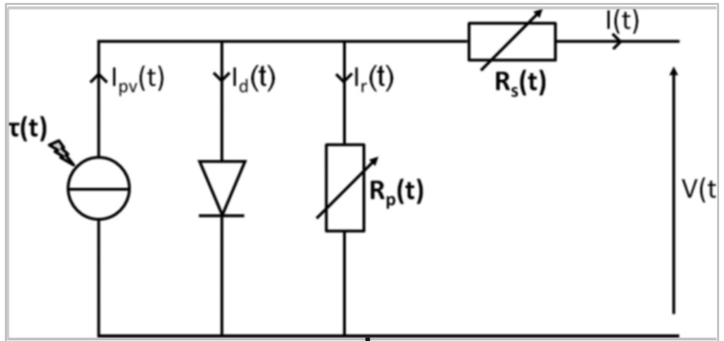
- ✓ Thermal model
  - ✓ Use thermal – Electrical Analogy to calculate the heat flow in module layers
  - ✓ Convection and Radiation are modelled as variable resistor ( i.e Wind speed and ΔT = surface T– ambient T)
  - ✓ Fully transient thermal model to capture dynamic thermal behavior.



# Methodology – Circuit based degradation model

- ✓ Degradation models
  - ✓ Based on I-V circuit model
  - ✓ Consider the impact of different climate variables




$$I(t) = I_{pv}(t) - I_0\left[\exp\left(\frac{V + R_S(t)\cdot I}{V_t\cdot a}\right) - 1\right] - \frac{V + R_S(t)\cdot I}{R_P(t)}$$

$$I_{pv}(t) = (I_{pv,n} + K_I\Delta T)\frac{G(t)}{G_n}$$

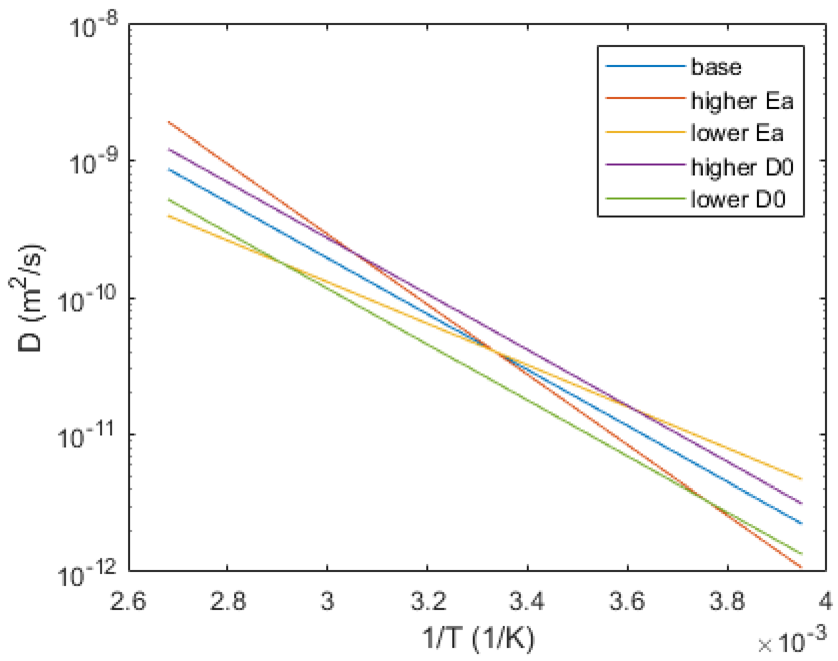
$$I_0 = \frac{I_{sc,n} + K_I\cdot\Delta T}{\exp\left(\frac{V_{oc,n} + K_V\cdot\Delta T}{a\cdot V_t}\right) - 1}$$

$$G(t) = \tau(t)\cdot G_0$$

| Indicator | Reliability model | Degradation rate models $f(RH, UV, T_{max}, T, \Delta T)$ |
|---|---|---|
| Series resistance | $R_S(t) = R_{S_{ref}}\cdot\exp\left[\left(k_{R_S}\cdot t\right)^{\theta}\right]$ | $k_{R_S}(T, RH) = A\times RH^n\times\exp\left(\frac{-E_a}{k_B\cdot T}\right)$<br>RH = relative humidity/moisture |
| Shunt resistance | $R_{Sh}(t) = R_{Sh_{ref}}\cdot\exp\left[-\left(k_{R_{Sh}}\cdot t\right)^{\gamma}\right]$ | $k_{R_{Sh}}(T, RH) = A\times RH^n\times\exp\left(\frac{-E_a}{k_B\cdot T}\right)$<br>Ea = activation energy |
| Transmitance | $\tau(t) = \tau_{ref} - \tau_{ref}\cdot\exp\left[-\left(\frac{1}{k_\tau\cdot t}\right)^{\mu}\right]$<br>_ref = reference value<br>k = degradation rate<br>μ = model parameter<br>(applies for all models) | $k_\tau = \delta\cdot\left(1 + k_p(UV, T, RH) + k_{Tm}(\Delta T, T_{max})\right) - 1$<br>$k_p(UV, T, RH) = A\times UV^X\times(1 + RH^n)\times\exp\left(\frac{-E_a}{k_B\cdot T}\right)$<br>$k_{Tm}(\Delta T, T_{max}) = A\times(\Delta T + 273)^{\theta}\times C_r\times\exp\left(-\frac{E_a}{k_B.T_{max}}\right)$ |
| Saturation current | $I_o(t) = I_{o_{ref}}\cdot\exp\left[\left(k_{I_o}\cdot t\right)^{\beta}\right]$ | $k_{I_o} = \delta\cdot\left(1 + k_p(UV, T, RH) + k_{Tm}(\Delta T, T_{max})\right) - 1$ |

# Variation of moisture sorption parameters

- Simulations varying: $D_0$, $E_a$ of D, and $S_0$ of encapsulant, as well as $D_0$ of backsheet
  - Variation of $E_a$: $D_0$ varied accordingly, to keep D constant at 300 K
- Each set of parameters simulated for different values of T from T simulations + from Faiman model
- Base values from literature for an EVA encapsulant and TPT backsheet (rounded) [1]
- Parameter varied based on realistic values for EVA and backsheets with PET core layer




| encapsulant | Ea_D (kJ/mol) | D0 ($*10^{-4}$ $m^2/s$) | S0 ($kg/m^3$) | Ea_S (kJ/mol) |
|---|---|---|---|---|
| base | 39 | 2.5 | 280 | 12.5 |
| Vary D0 | | 1.5 / 3.5 | | |
| Vary Ea | 29 / 49 | 4.54e-2 / 138 | | |
| Vary S0 | | | 180 / 380 | |

| backsheet | Ea_D (kJ/mol) | D0 ($*10^{-4}$ $m^2/s$) | S0 ($kg/m^3$) | Ea_S (kJ/mol) |
|---|---|---|---|---|
| base | 42.2 | 0.06 | 1048 | 12.26 |
| Vary D0 | | 0.6 / 0.006 / 0.0006 | | |

[1] Mitterhofer, PhD thesis, Ljubljana 2021

# Motivation – Material properties

✓ Different sizes of backsheet – encapsulant materials

*Table 2: Overview of layer thickness in µm and structures found on the tested solar field*

| BS class | NF | SF | SF | SF | SF | SF | SF |
|---|---|---|---|---|---|---|---|
| Layer thickness | PA | Primer/ PET/ PP | PVDF/ PET/ PE-1 | PVDF/ PET/ PE-2 | PVDF/ PET/ PE-3 | PVF/ PET/ PE-1 | PVF/ PET/ PE-2 |
| air-side layer (µm) | - | 5-10 | 30 | 30 | 50 | 30 | 40 |
| intermediate layer (µm) | - | 160 | 260 | 330 | 380 | 160 | 260 |
| inner layer (µm) | - | 140 | 120 | 80 | 100 | 110 | 50 |
| Total (µm) | 340 - 390 | 305-310 | 410 | 440 | 530 | 300 | 350 |

[4]. Claudia Buerhop Lutz*, Oleksandr Stroyuk, PV Modules and Their Backsheets A Case Study of a Multi-MW PV Power Station