25.04.2024

14TH SOPHIA PV-MODULE RELIABILITY WORKSHOP

Comparing humidity-induced stress levels between floating and ground-mounted PV

Nathan Roosloot, François Clayer, Dag Lindholm, Curtis DeGasperi, Ankur R. Desai, Daniel Hornbach, Katy Nugent, Ulrike Obertegger, Blaize Denfeld, Piet Verburg, Huaxia Yao, James Rusak, Kiyoko Yokota, Junhong Wang, Ian D. Jones, Torunn Kjeldstad, Josefine H. Selj, Gaute Otnes

Floating photovoltaics (FPV) at a glance

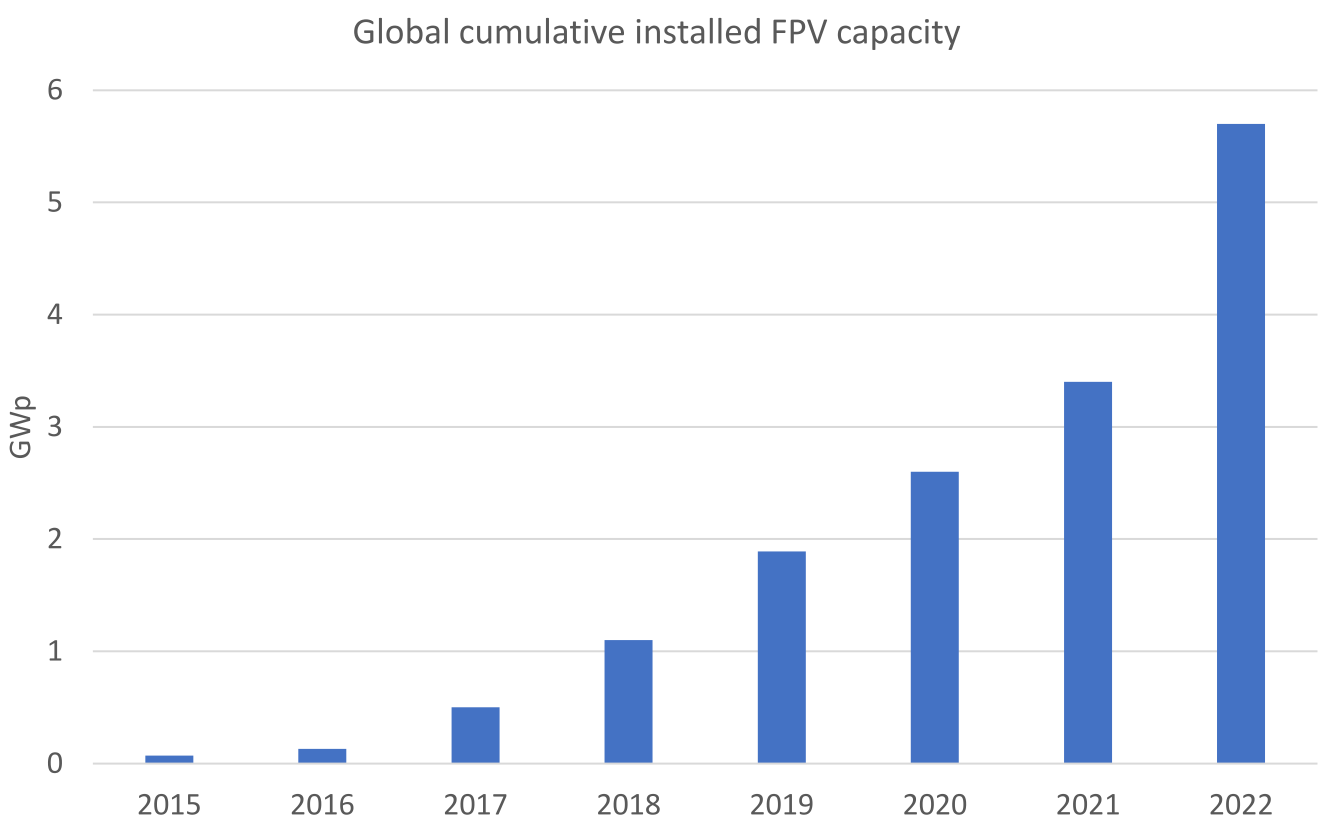
- Can exploit water surfaces for electricity production
- Has *potential* for increased yield due to lower module temperature
- Has *potential* to increase use of existing infrastructure through co-location or hybridization
- Can *likely* reduce evaporation and algae growth

Ciel et Terre[1]

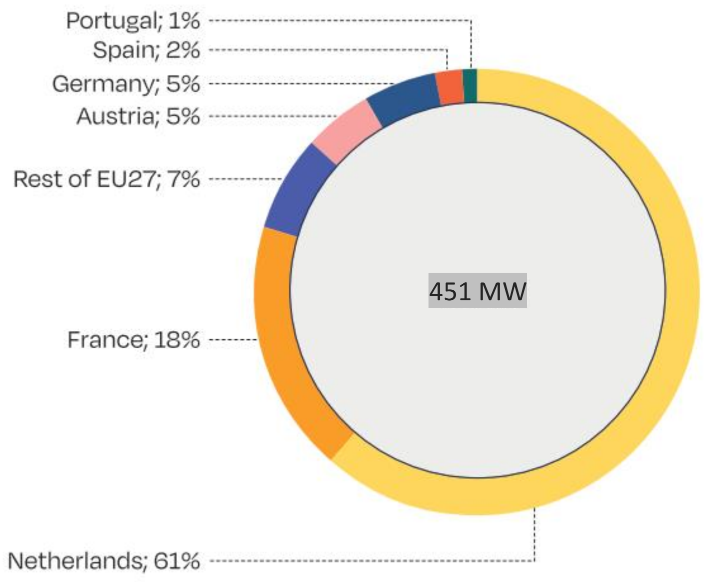
Sungrow[2]

[1]Image adapted from https://www.rechargenews.com/solar/ciel-terre-leads-brazils-10mw-floating-solar-bid/1-1-869221
[2]Image adapted from Sungrow's facebook page

The global FPV market

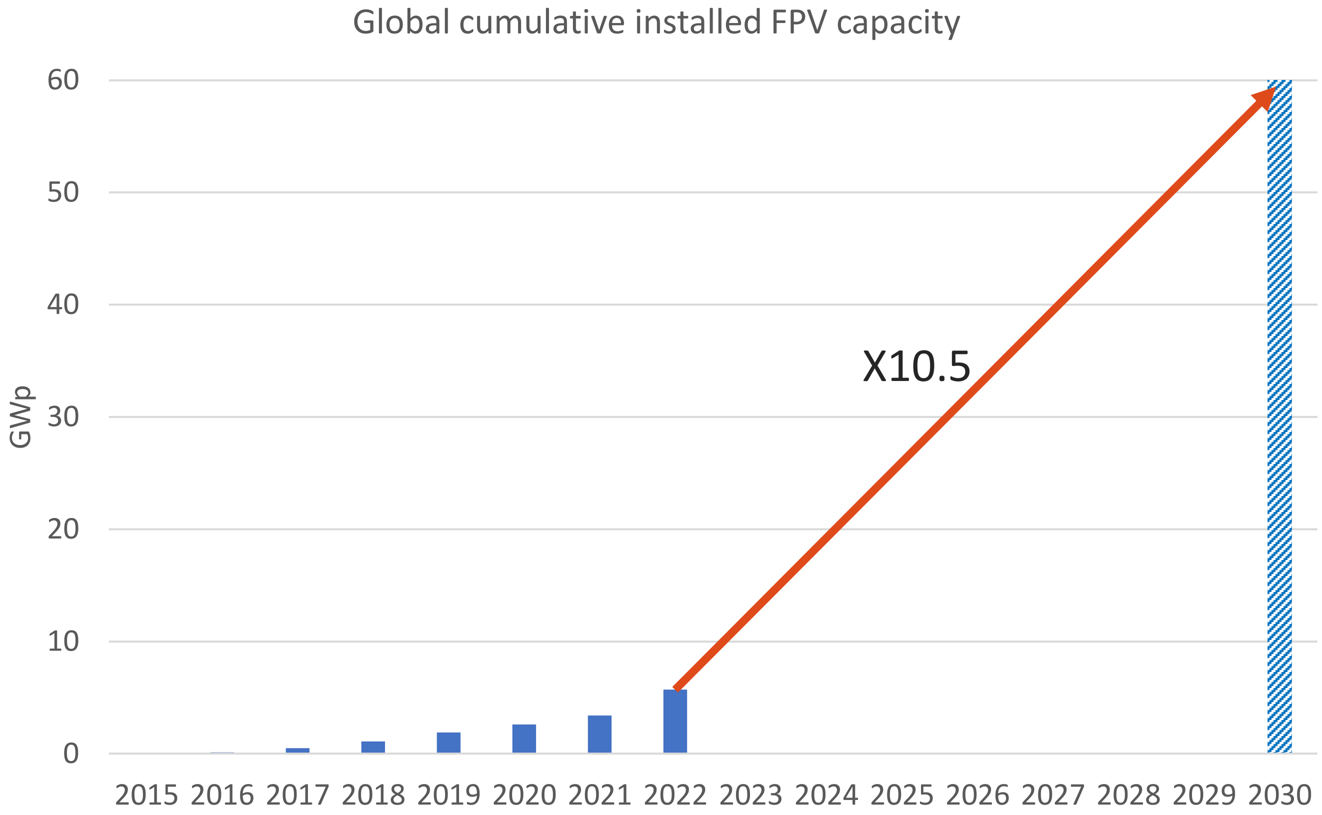


- 70% of total installed capacity in China, 8% in Europe
- Almost all inland: only 20 MW offshore, mostly pilot-scale



Source: SolarPower Europe (2023): *Floating PV Best Practice Guidelines Version 1.0.*

The global FPV market



- 60 GWp projected in 2030[1]
  - 34% YoY growth from 2022-2030, compared to 22% YoY growth for all PV from 2024-2028[2,3]
- 3 to 7.5 TWp potential on hydro dams[4] and 0.4 to 4.0 TWp on man-made reservoirs[5]

[1]IEA PVPS (2023): Trends in photovoltaic applications
2028 PV capacity from [2]IEA: Renewables 2023 - Analysis and forecast to 2028
2023 PV capacity from [3]IEA PVPS (2024): Snapshot of Global PV Markets 2024
[4]10.1016/j.renene.2020.08.080
[5]Where sun meets water, World bank, 2019

The global FPV market

- Despite its growth and potential, the FPV market is
  - Very young
  - Very diverse
- Which leads to
  - Wide range of float technologies, with
    - Large differences in CAPEX and OPEX
  - Lack of standardization
  - Knowledge gaps for FPV reliability
    - Hard to extrapolate learnings to different FPV systems and locations
    - Can be filled by using learnings from GPV

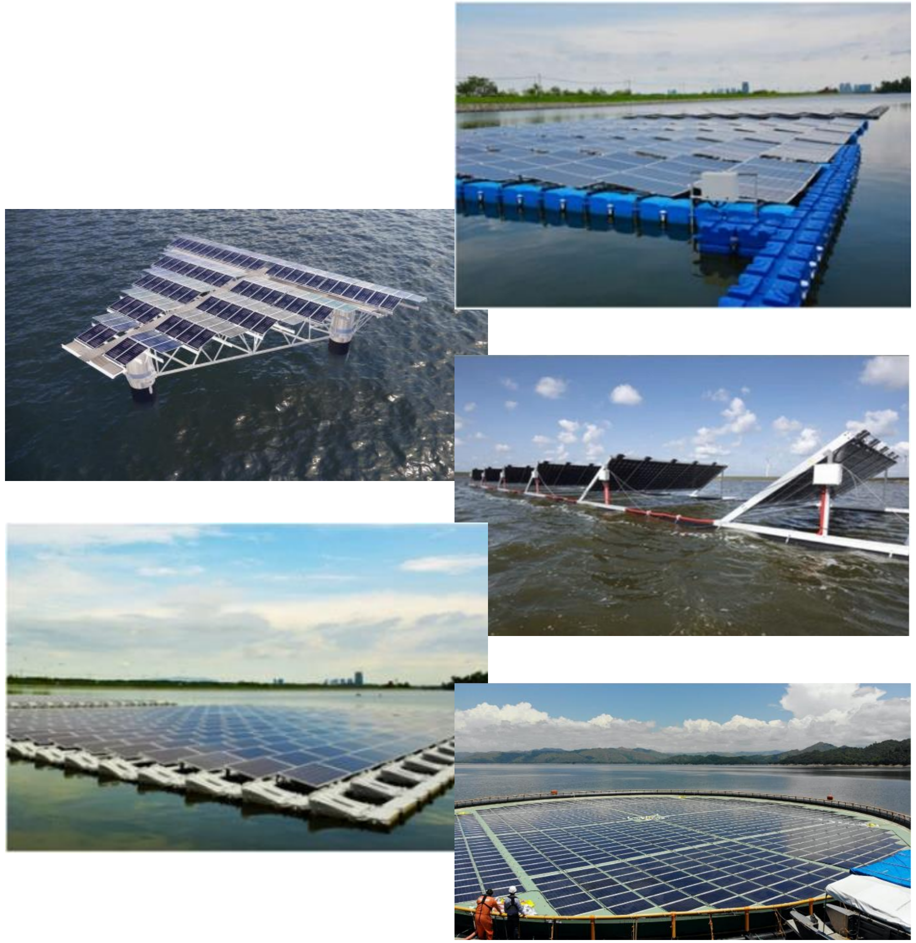
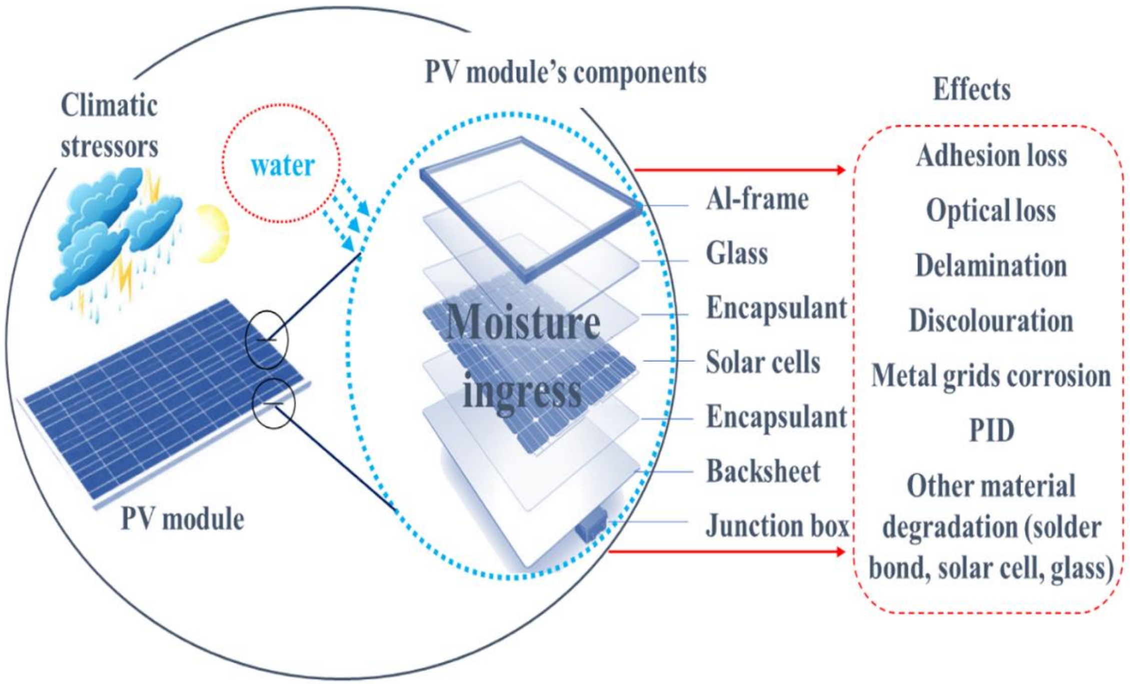
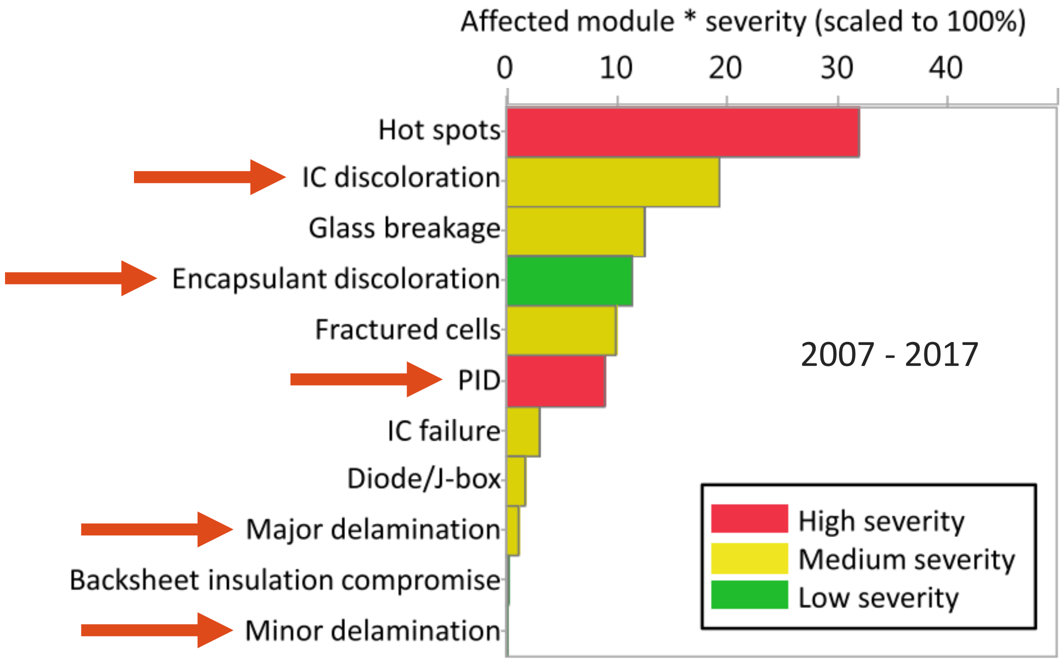


Image credits (top to bottom):
Where sun meets water, World bank, 2019
solarduck.tech
Dörenkämper et al., Solar Energy, 2021
oceansun.no

Humidity-induced stress: moisture ingress in PV modules





Left figure adapted from 10.1016/j.solener.2021.06.055
Right figure adapted from 10.1002/pip.2866

Humidity-induced stress expected for FPV…

- FPV specific modules
  - Glass-glass, POE encapsulant, IP68 junction box rating
- No open data on field degradation/failures of FPV…
- …So we turn to stress levels
  - Temperature and relative humidity

Solar module for floating PV from Hyundai

The bifacial panel has a power output of up to 485 W and an efficiency of up to 21%. It relies on a transparent backsheet and is encapsulated with polyolefin elastomer (POE).

JULY 19, 2021 EMILIANO BELLINI

MODULES & UPSTREAM MANUFACTURING | TECHNOLOGY AND R&D | SOUTH KOREA

The AquaMax module.

Image: Sax Power GmbH

Hanwha Q Cells unveils special panels for floating PV

The South Korean module manufacturer has developed two new products for large-scale floating PV plants. They have power outputs of 415 W and 420 W and efficiencies of 19.4% and 19.6%.

NOVEMBER 19, 2020 EMILIANO BELLINI

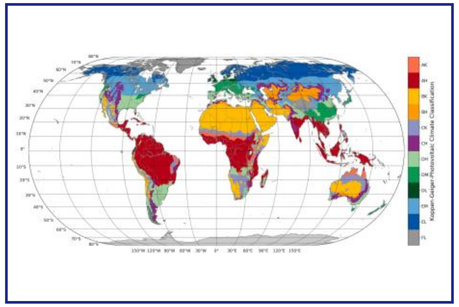
MODULES & UPSTREAM MANUFACTURING | TECHNOLOGY AND R&D | SOUTH KOREA

Shining Blue Ocean, Extraordinary Advancement | JA Solar Technology Releases Offshore PV N-Type Modules, Opening a New "Blue Ocean" of PV in 2024!

Release time: 2024-01-08

Sources:
https://www.pv-magazine.com/2020/11/19/hanwha-q-cells-unveils-special-floating-pv-panels/
https://www.pv-magazine.com/2021/07/19/solar-module-for-floating-pv-from-hyundai/
https://www.jasolar.com/index.php?m=content&c=index&a=show&catid=419&id=557

Module stressors are affected on different levels



Macroclimate

Top image from 10.1016/j.solener.2019.08.072

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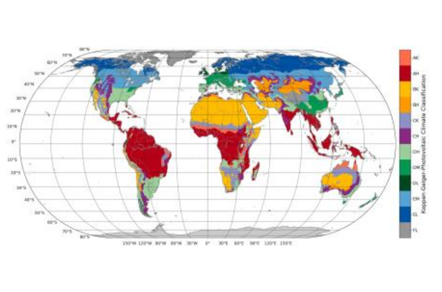

Macroclimate

+Local terrain, vegetation, presence of water, +++

Local climate

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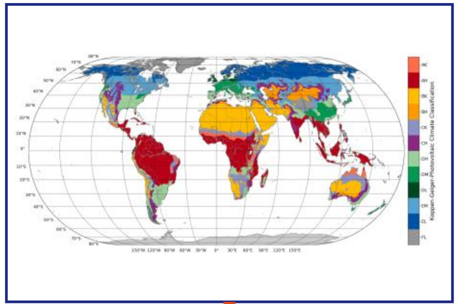

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Local climate

+System design and module mounting

Module-exterior climate / «Microclimate»

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Third from oceansun.no, solarduck.tech, https://ife.no/en/project/smart-naerstrom-2/, https://www.norgesgruppeneiendom.no/prosjekter/dalgaard-byaasen-i-trondheim/

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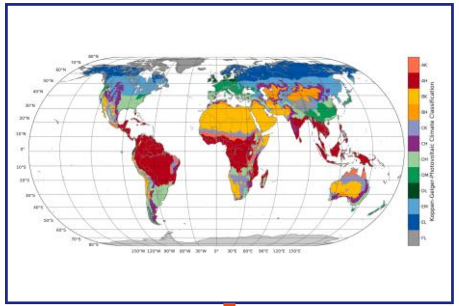

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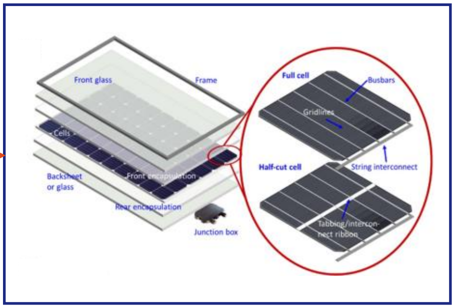
+Module architecture and BOM



Module-interior climate

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Last from 10.1088/2516-1083/ac6111

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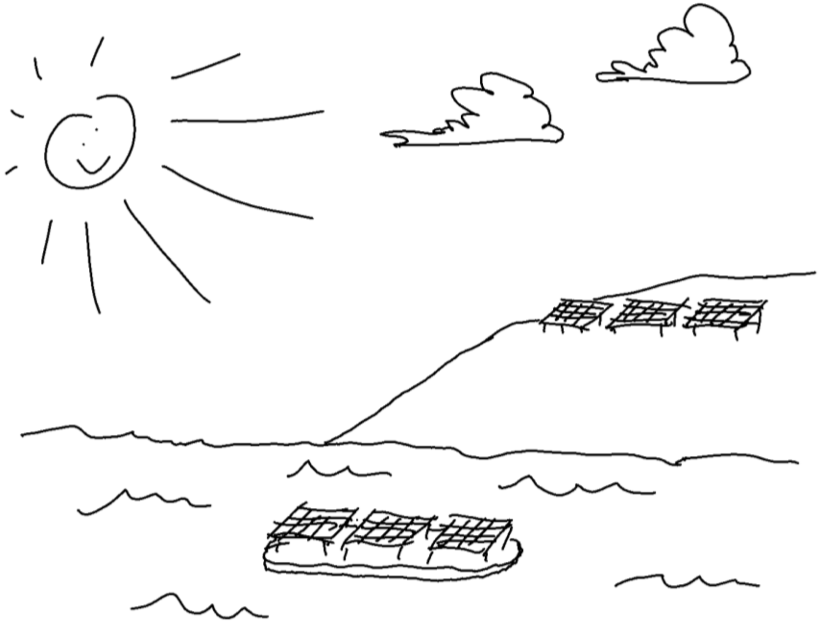

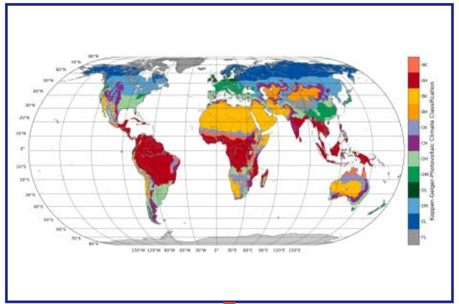

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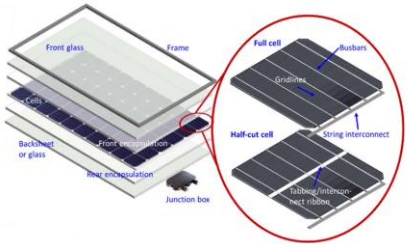

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Drawing made by Marit Ulset

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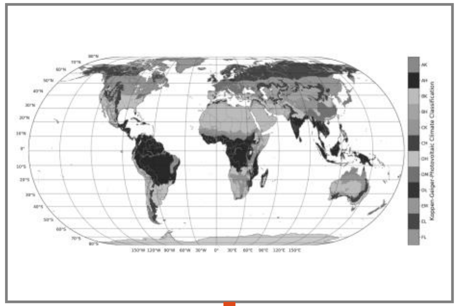

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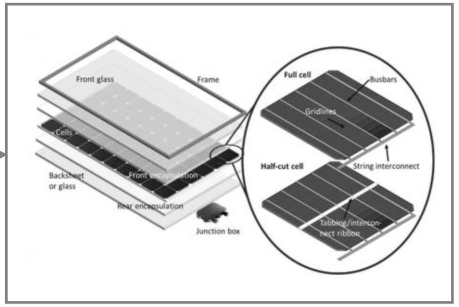

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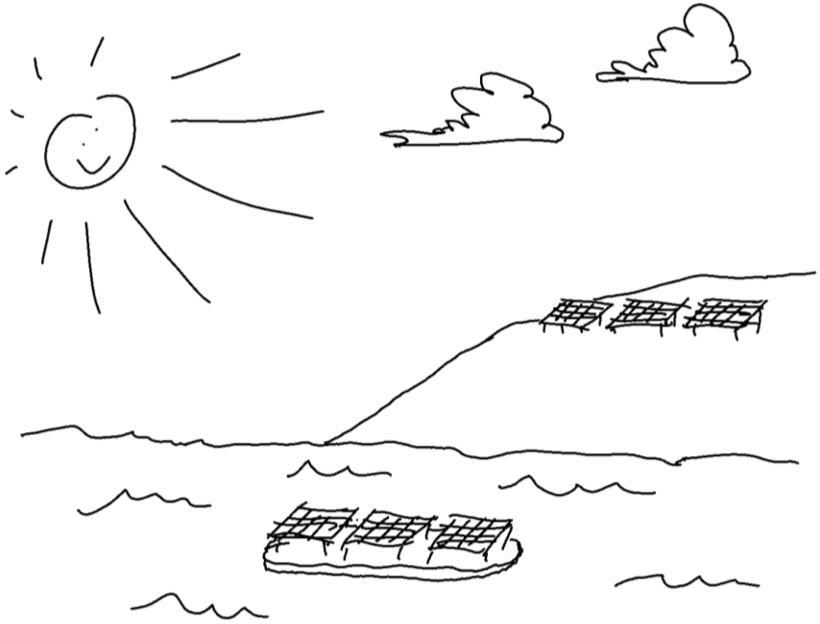

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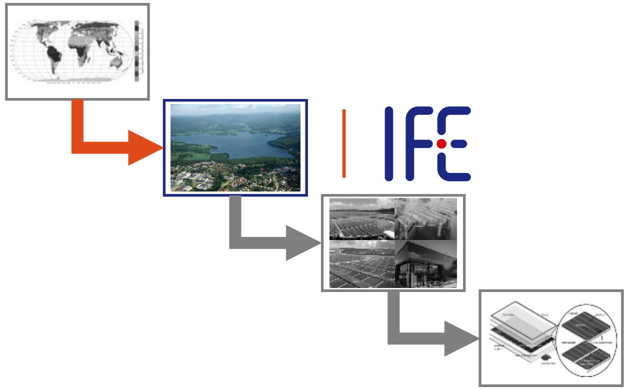
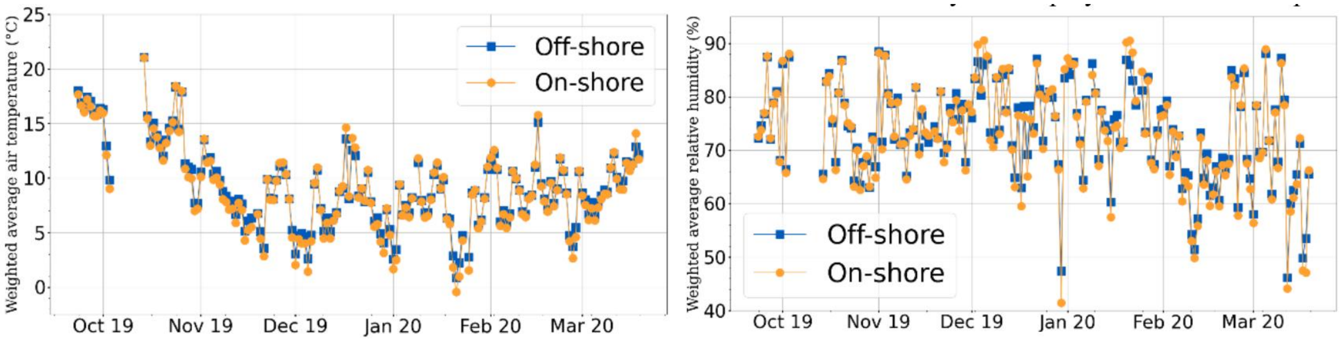
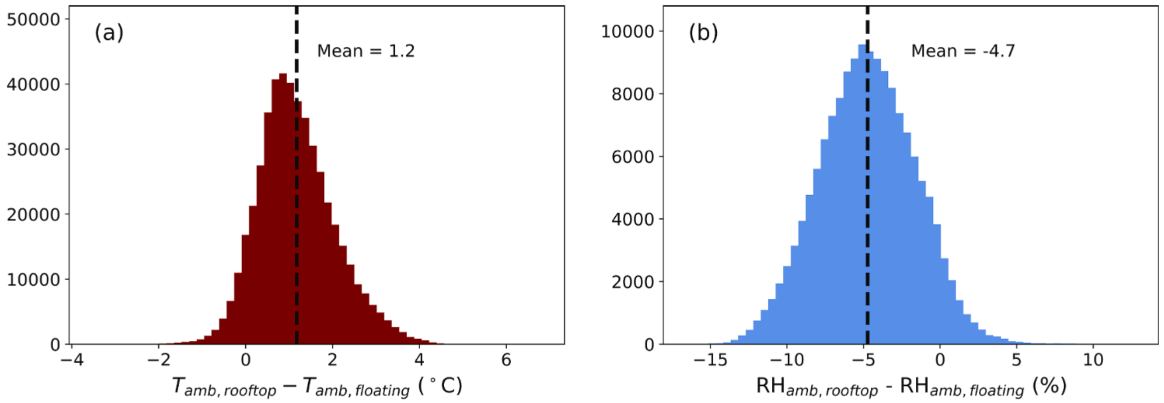
FPV vs GPV at the local climate



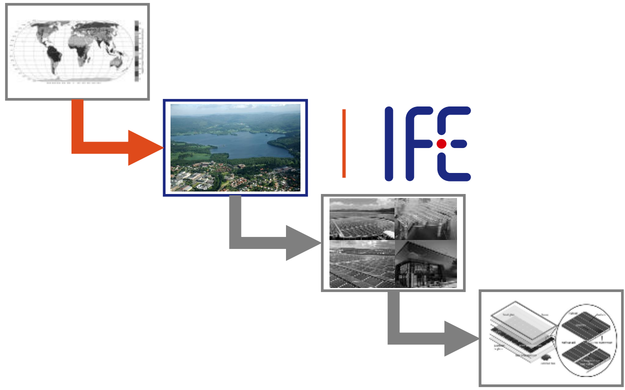
- Some existing comparisons of FPV and GPV
- Measurements of air T and RH at an FPV site and on land
  - Temperate climate[1]:
    - No significant differences
  - Tropical climate[2]:
    - Lower air T, higher RH on water
- However:
  - Only two sites, so hard to draw general conclusions
  - Studies only use daytime RH & T
  - Limited insight into coupling of RH & T and dynamics on shorter timescales



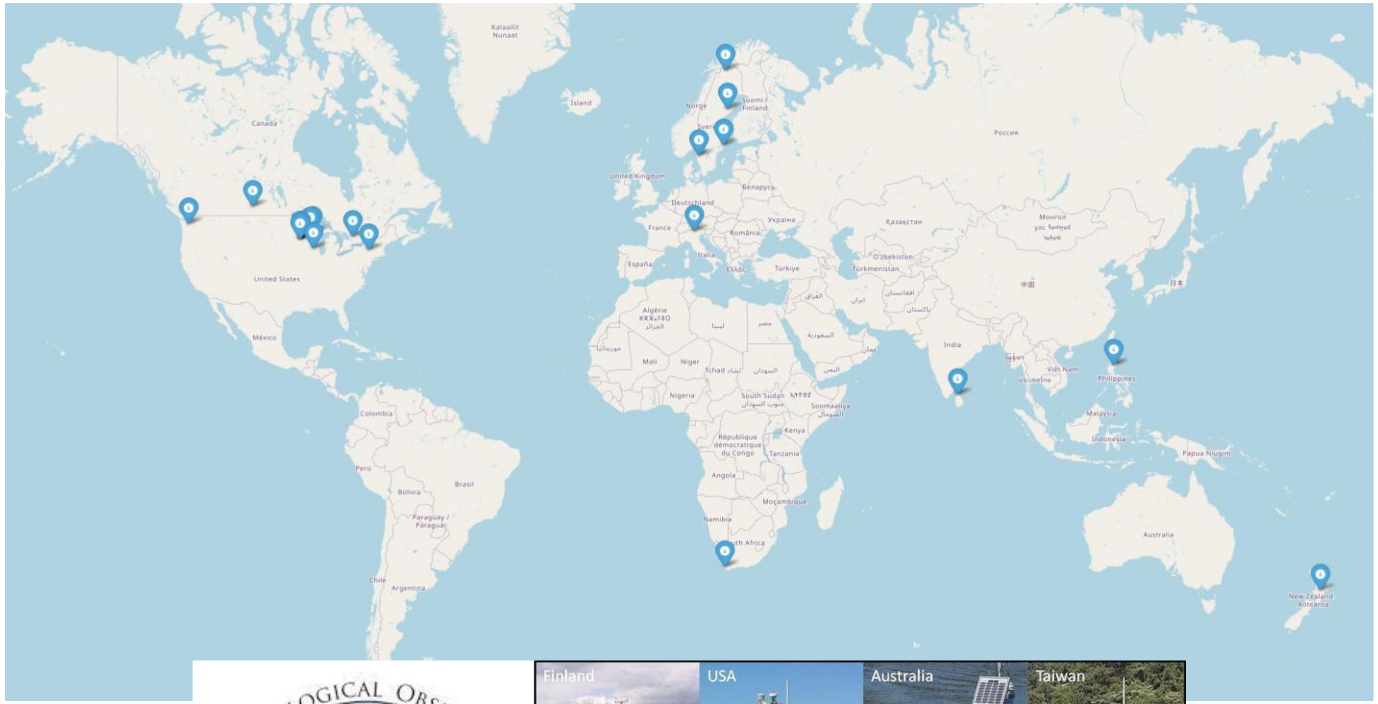


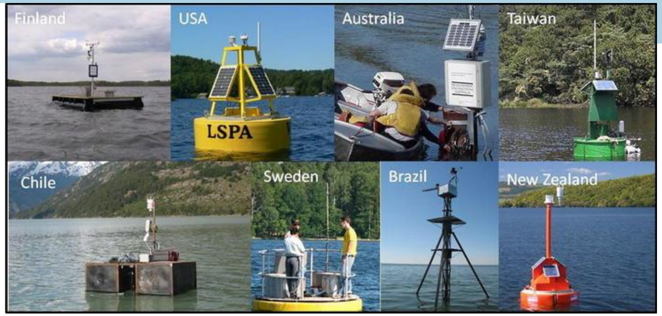
1 adapted from 10.4229/EUPVSEC20202020-6DO.15.2
2 adapted from 10.1016/j.solener.2020.12.019

FPV vs GPV at the local climate – our work



- Collected environmental data from 21 in-land water bodies and nearby locations on land through GLEON
  - 8 different countries, 7 different KG climate zones
  - Lake sizes: $2.1*10^{-3}$ km^2 – 620 km^2
  - Time series duration: 3 months – 14y
  - Resolution: 1 – 60 min





GLEON images from 10.1007/s10021-016-0075-y & GLEON Facebook page

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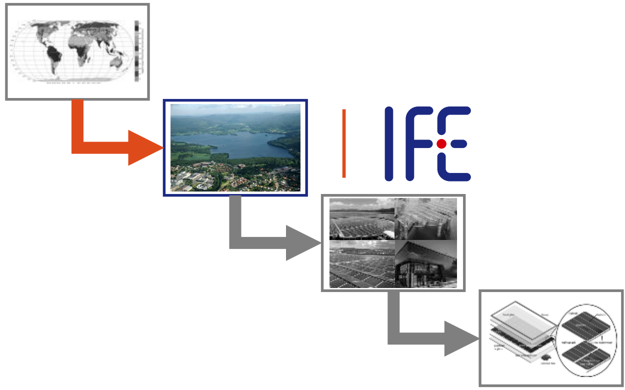

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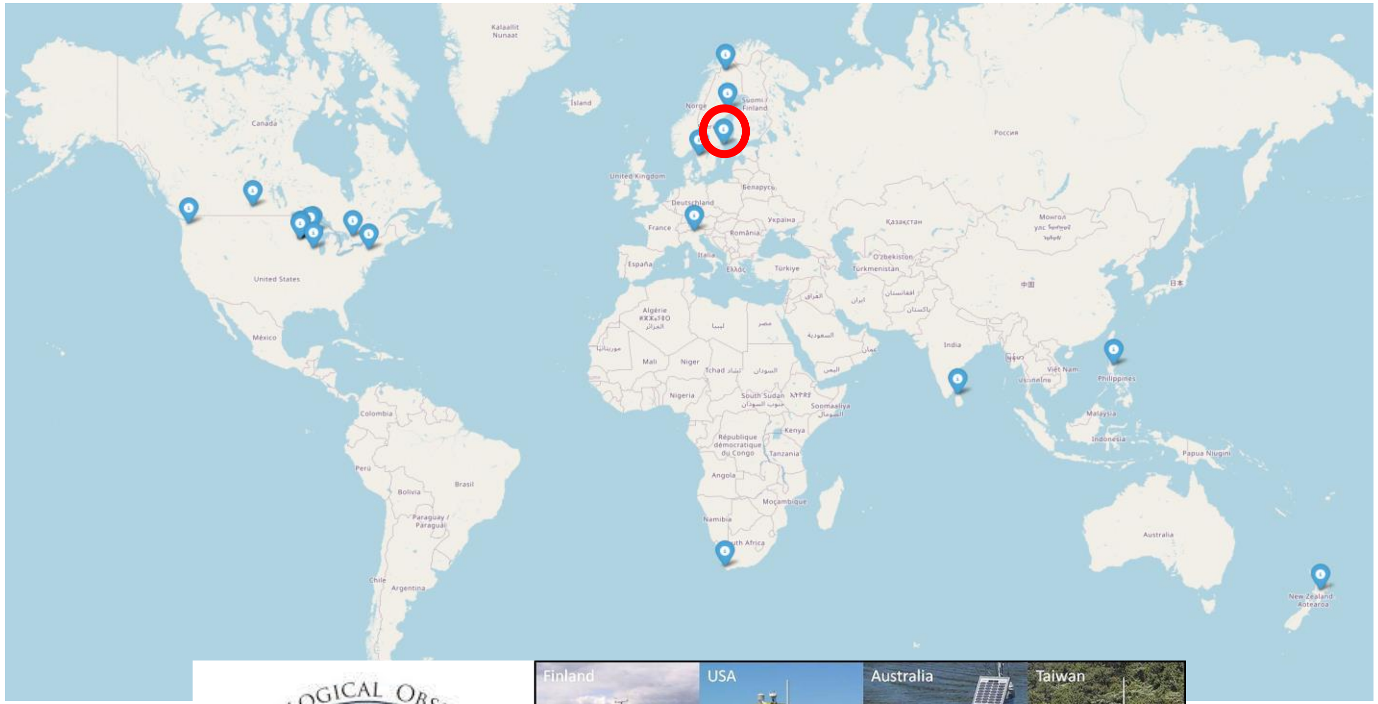

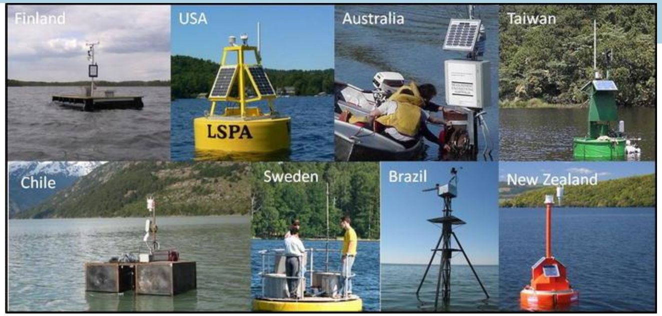

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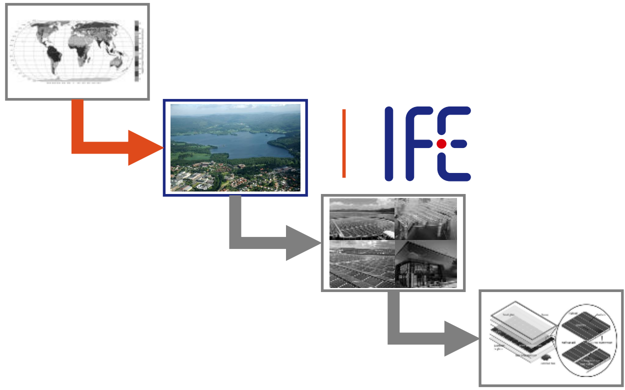
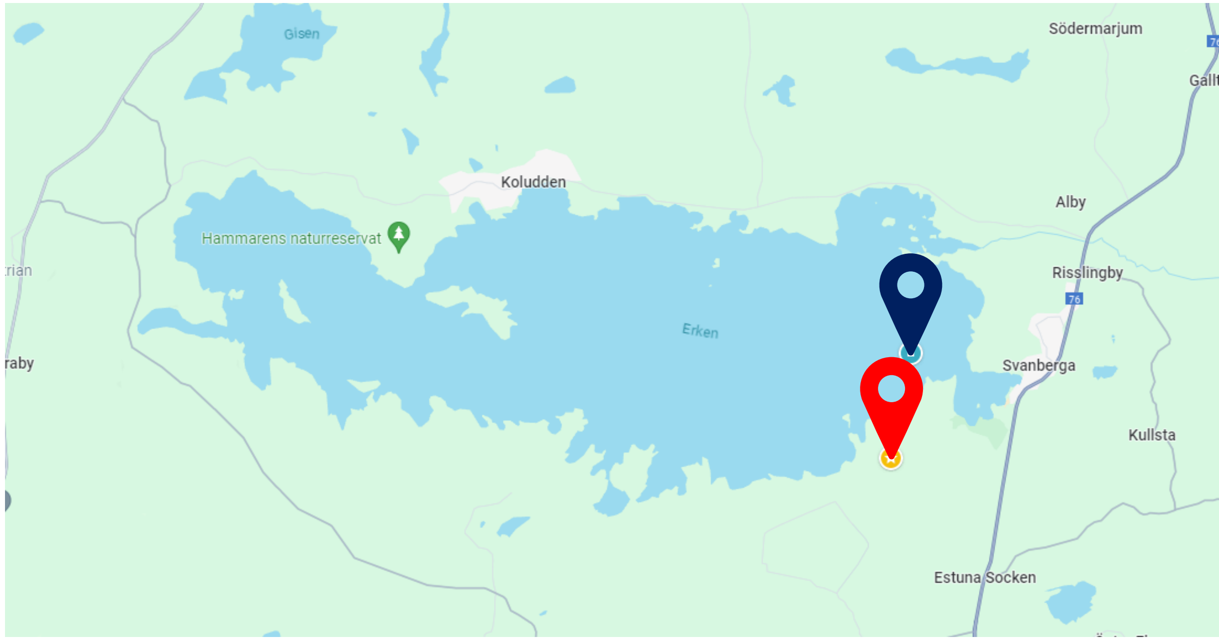
FPV vs GPV at the local climate - Lake Erken



- Lake of 26 km^2 in Sweden (59˚ N, 18˚ E)
- Dfb KG climate zone (Continental with no dry season and warm summer)
- Measurements:
  - Lake bouy and land station ~1.3km from the bouy (350m from closest shore)
  - Data from 2016-06 to 2022-12 at 1h resolution
    - Air & water T, RH, WS



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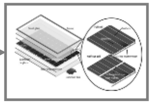
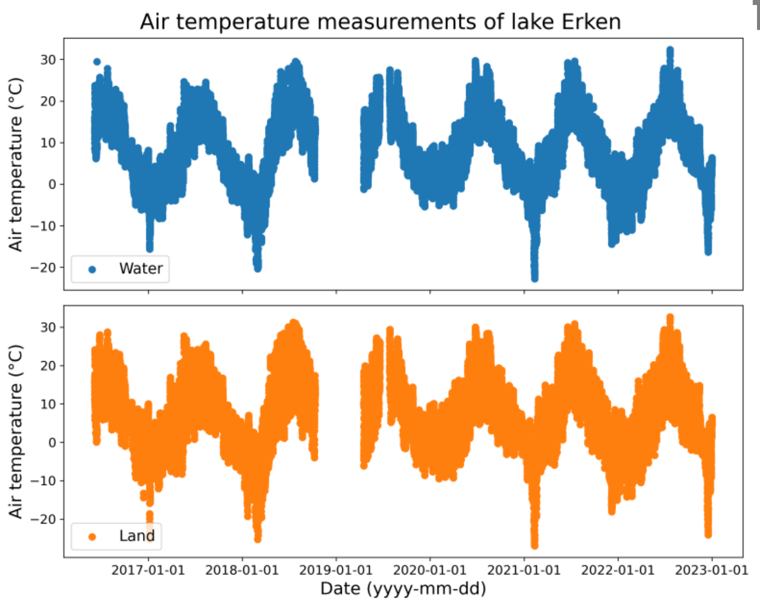


- General trends
  - Air temperature
    - Land and water similar profiles
    - Clear seasonality



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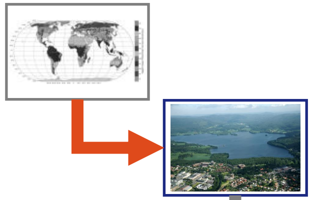
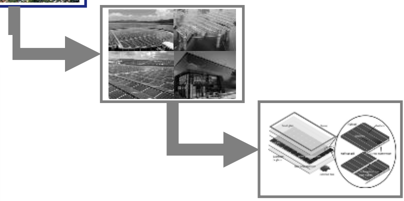
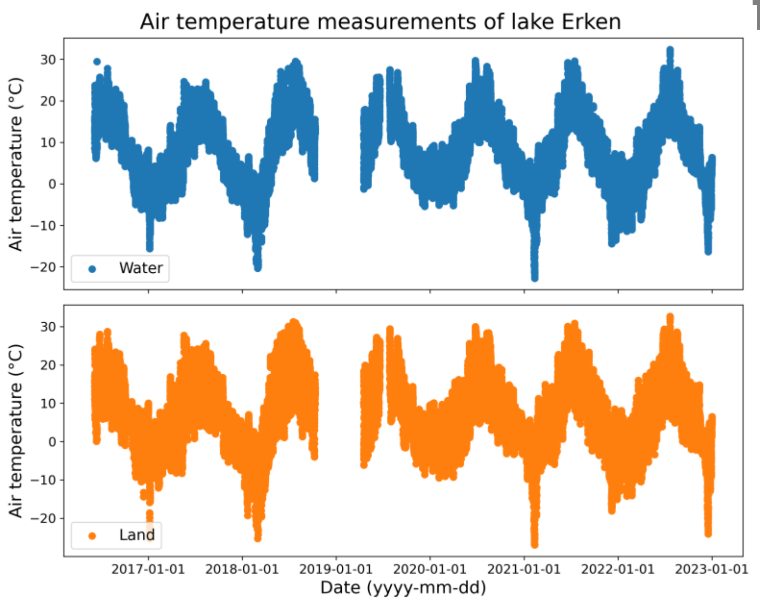
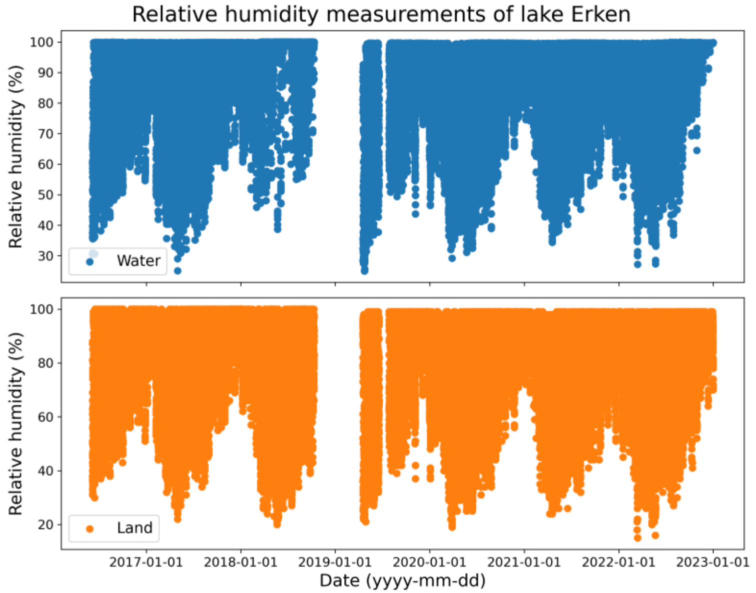




- General trends
  - Air temperature
    - Land and water similar profiles
    - Clear seasonality
  - Relative humidity
    - Again, similar profiles
    - Lower humidities in spring/summer, but also high humidities year round





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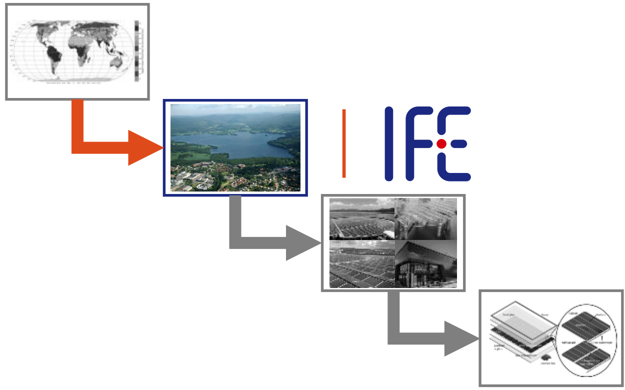
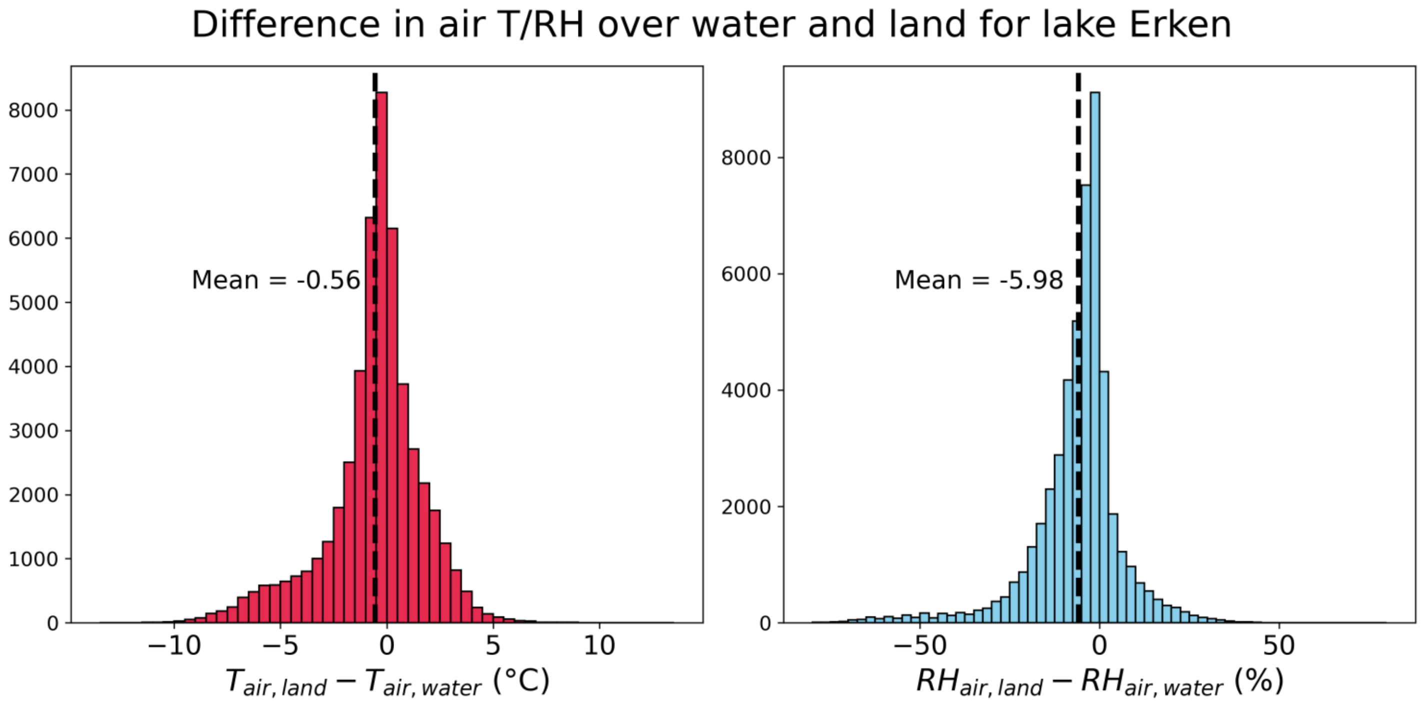
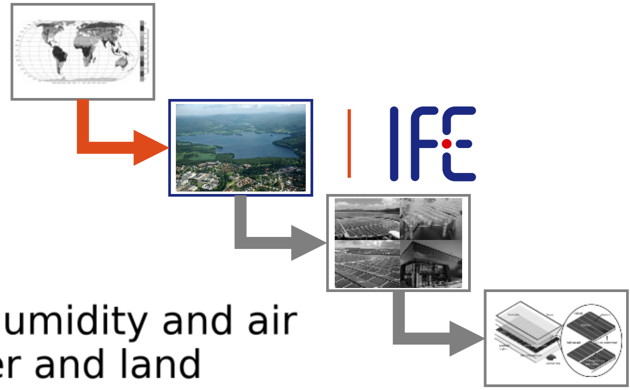


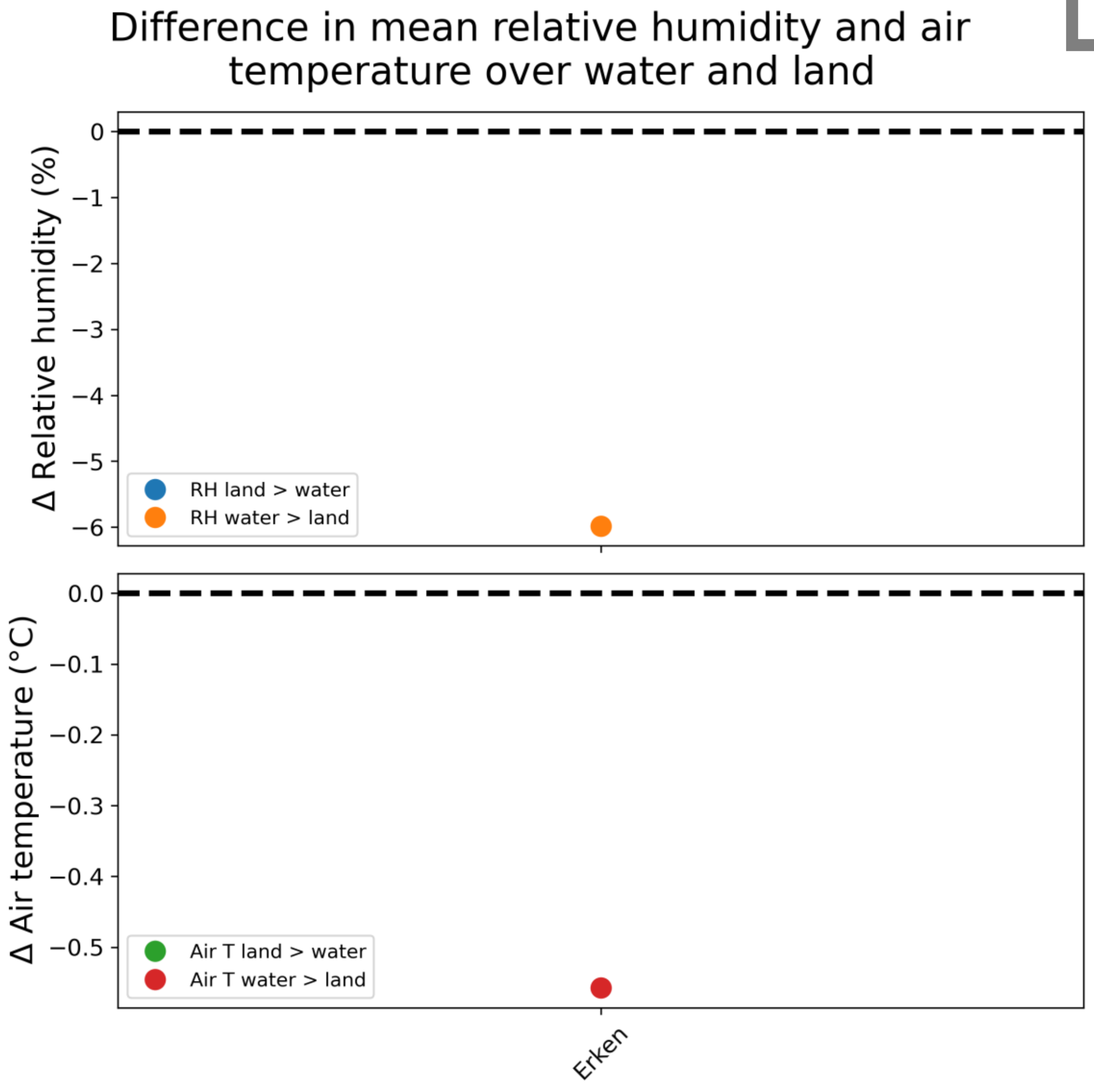
- Difference land and water:
  - Similar air temperatures – water somewhat higher
  - RH over water higher than on land



FPV vs GPV at the local climate – full dataset



- Comparing mean RH and air T over water and air on other sites shows:



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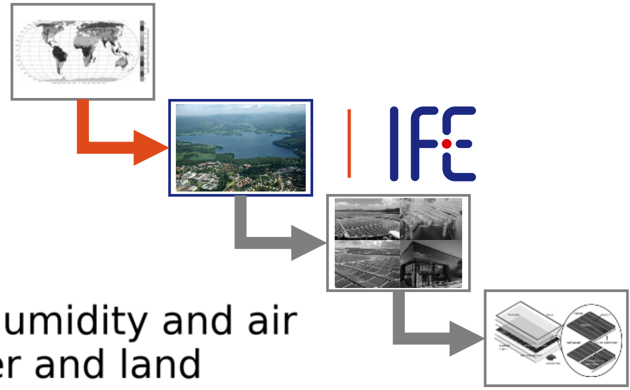
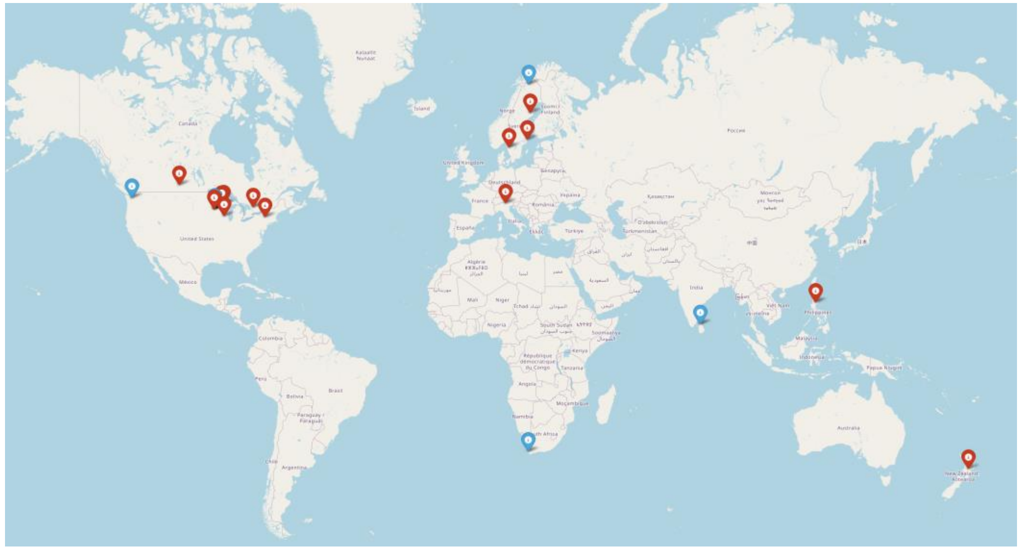
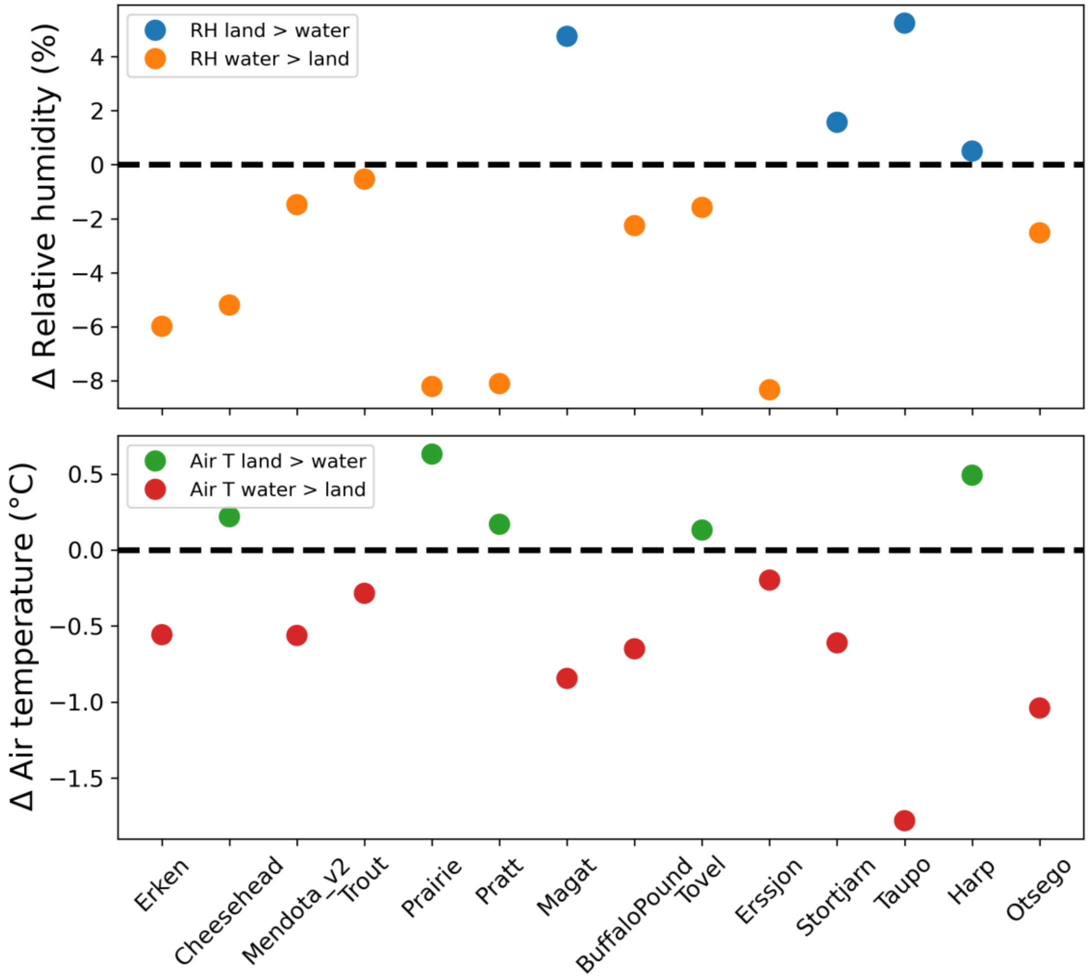


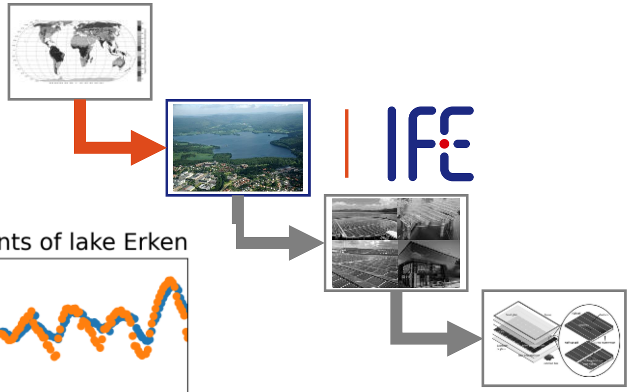
- Comparing mean RH and air T over water and air on other sites (red pins) shows:
  - RH over water mostly higher than over land, but opposite can also happen!
  - Air T over water and land often similar (within 2 ˚C), either can be higher
  - Note that different lake sizes, climates, timeseries duration, distance between measurements etc. influence results



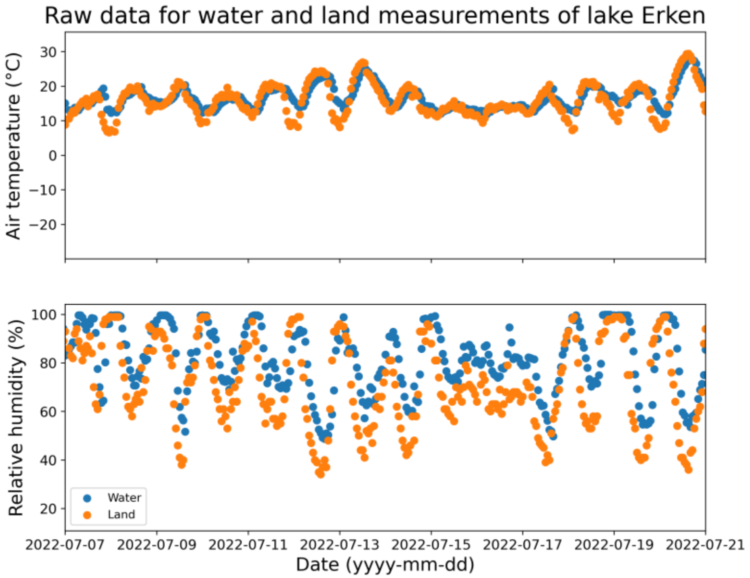
Difference in mean relative humidity and air temperature over water and land



FPV vs GPV at the local climate - Lake Erken



- Short term dynamics
  - Summer
    - RH follows daily air T: up to 100% at night (low T), lower values at during day (high T)
    - RH over water consistently higher than over land



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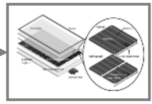
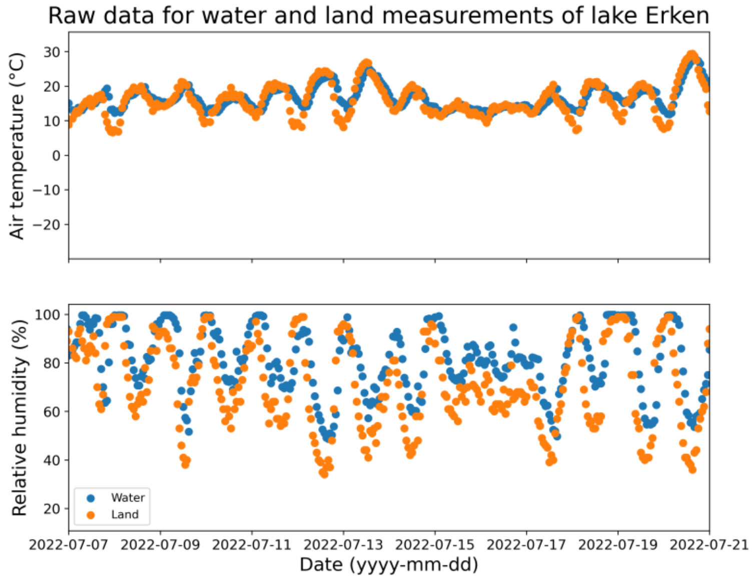
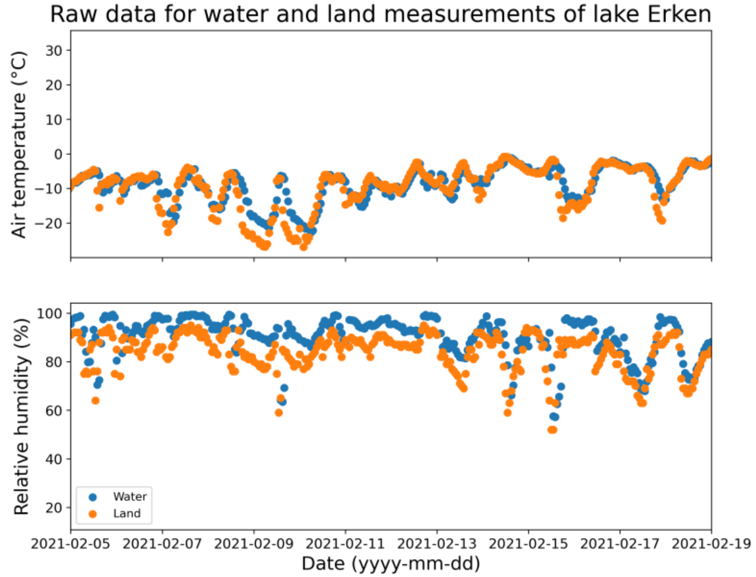


- Short term dynamics
  - Summer
    - RH follows daily air T: up to 100% at night (low T), lower values at during day (high T)
    - RH over water consistently higher than over land
  - Winter
    - Similar fluctuations in winter, although daily profile somewhat less clear
    - Again, RH over water consistently higher than over land





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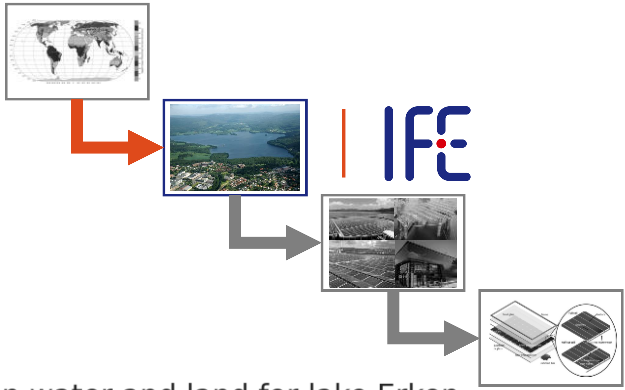
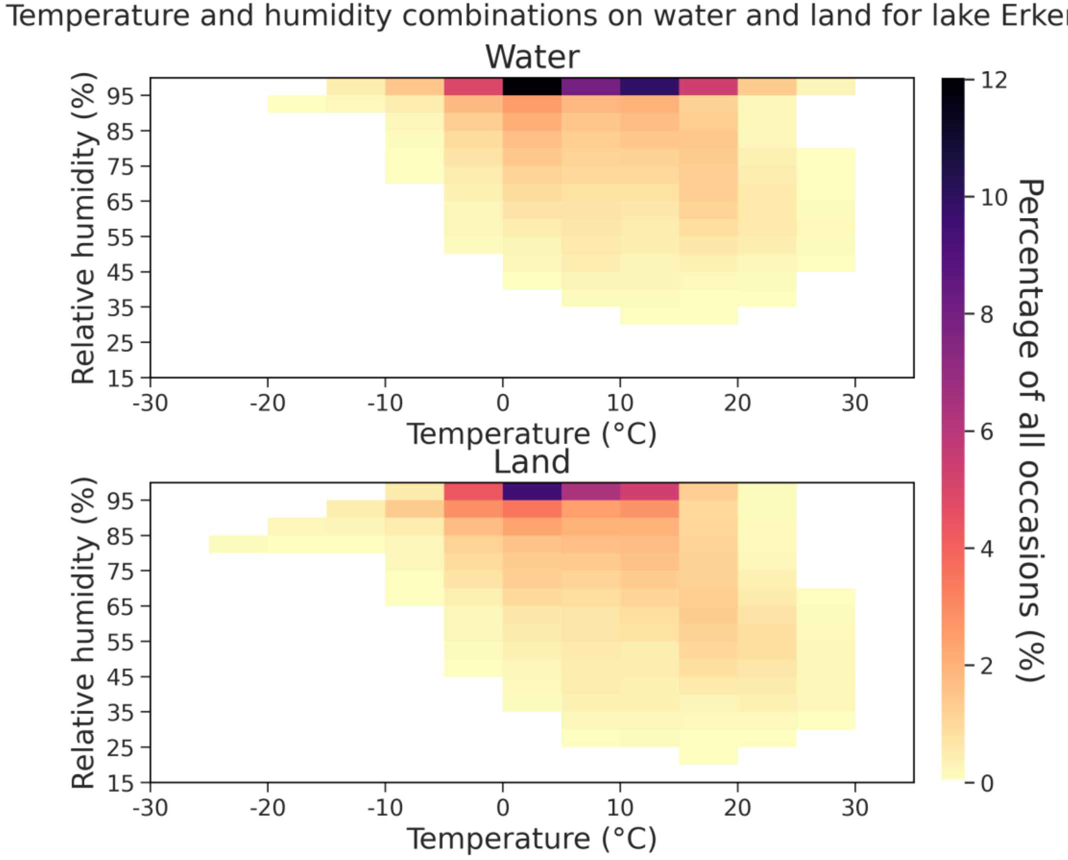
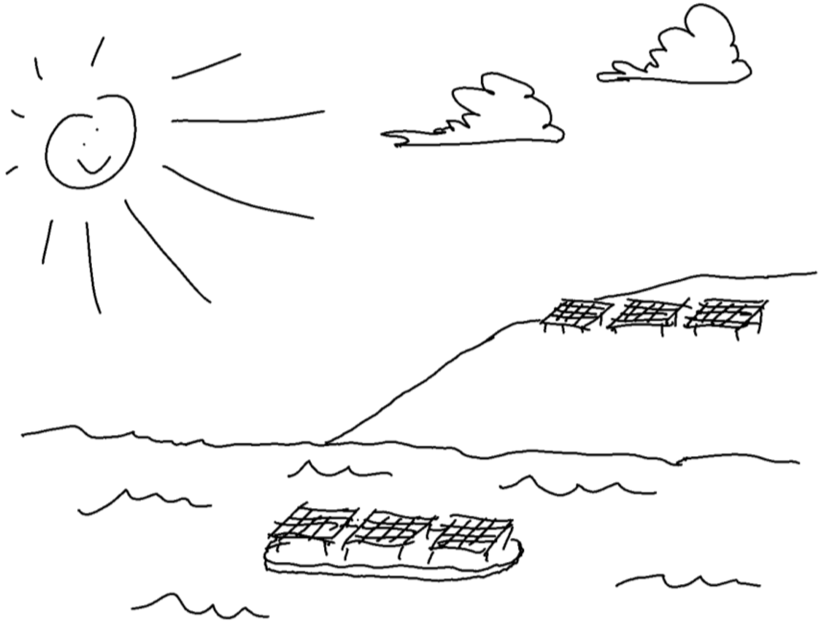
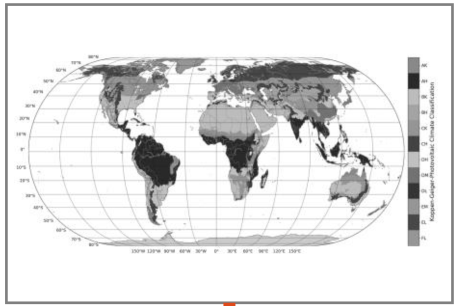


- RH&T combined determine moisture ingress:
  - Above water
    - RH bin of 95-100% is the most frequent at 9/10 T bins
    - 44% of all data has RH 95-100%
  - Above land
    - RH bin of 95-100% is the most frequent at 4/11 T bins
    - 28% of all data has RH 95-100%
    - Higher temperatures linked to lower RH



Module stressors are affected on different levels





Macroclimate

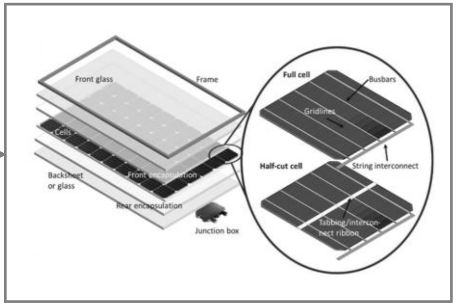
+Local terrain, vegetation, presence of water, +++

Local climate

+System design and module mounting

Module-exterior climate / «Microclimate»

+Module architecture and BOM



Module-interior climate

Top image from 10.1016/j.solener.2019.08.072
Second from https://upload.wikimedia.org/wikipedia/commons/c/c3/Maridalsvannet_aerial.jpg
Third from oceansun.no, solarduck.tech, https://ife.no/en/project/smart-naerstrom-2/, https://www.norgesgruppeneiendom.no/prosjekter/dalgaard-byaasen-i-trondheim/
Last from 10.1088/2516-1083/ac6111
Drawing made by Marit Ulset

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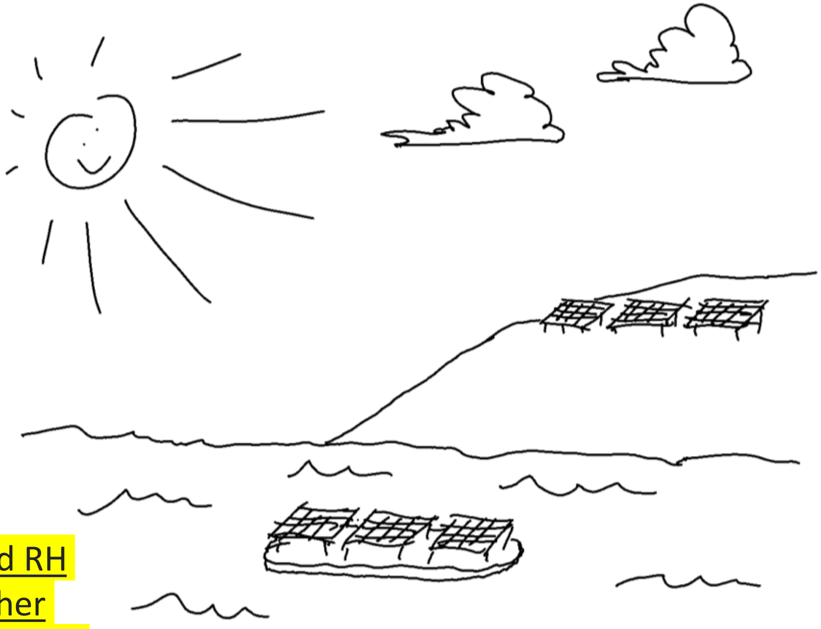

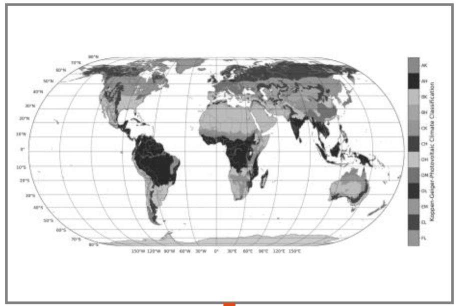

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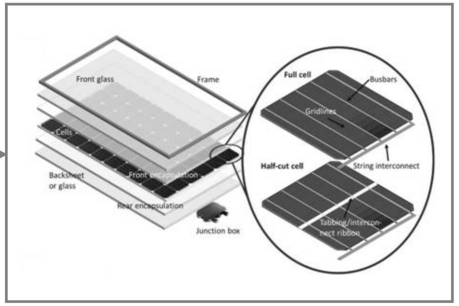

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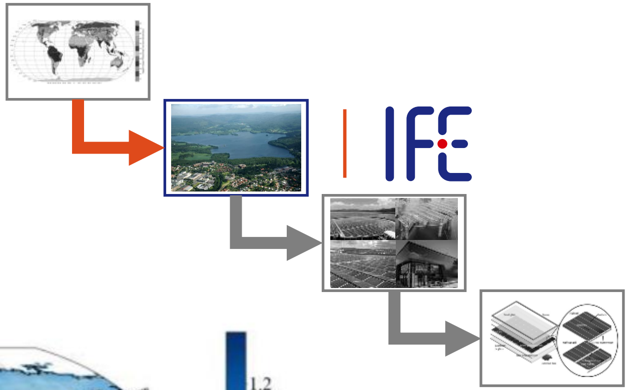
FPV vs GPV at the local climate



- Ambient data alone has a moderate correlation with moisture content inside a module[1]

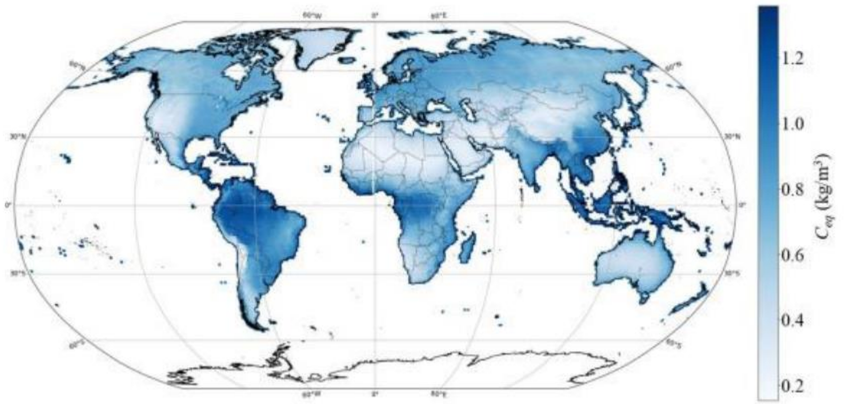
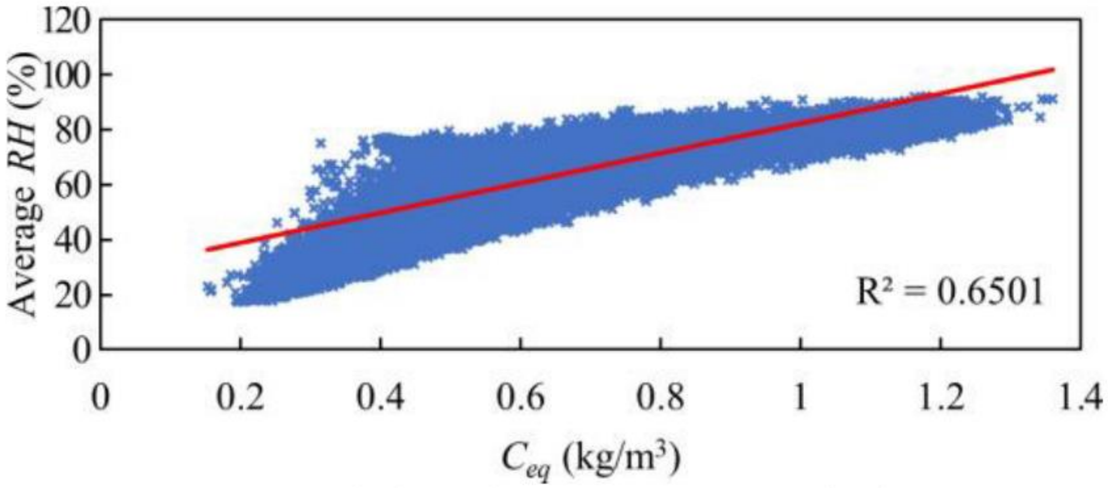
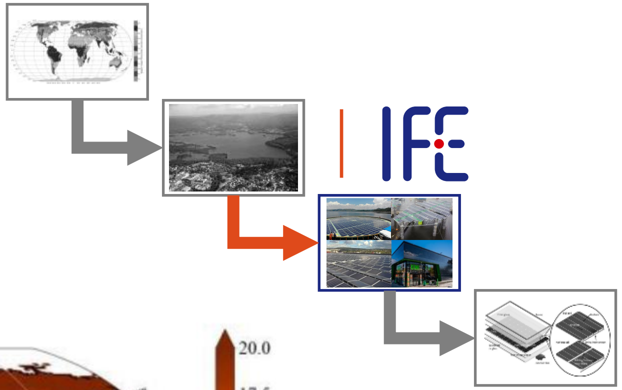


Figure 5: Worldwide mapping of C_{eq} in kg/m^3.



[1] 10.4229/WCPEC-82022-3EO.1.3

FPV vs GPV at the local climate



- Ambient data alone has a moderate correlation with moisture content inside a module[1]
- T and RH at module determine moisture ingress

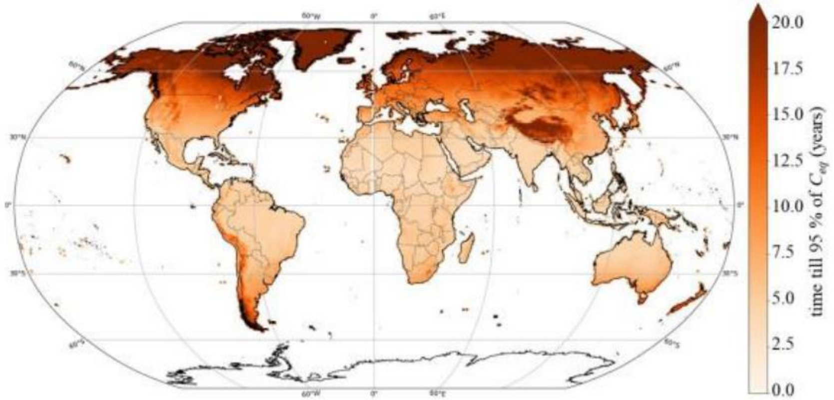
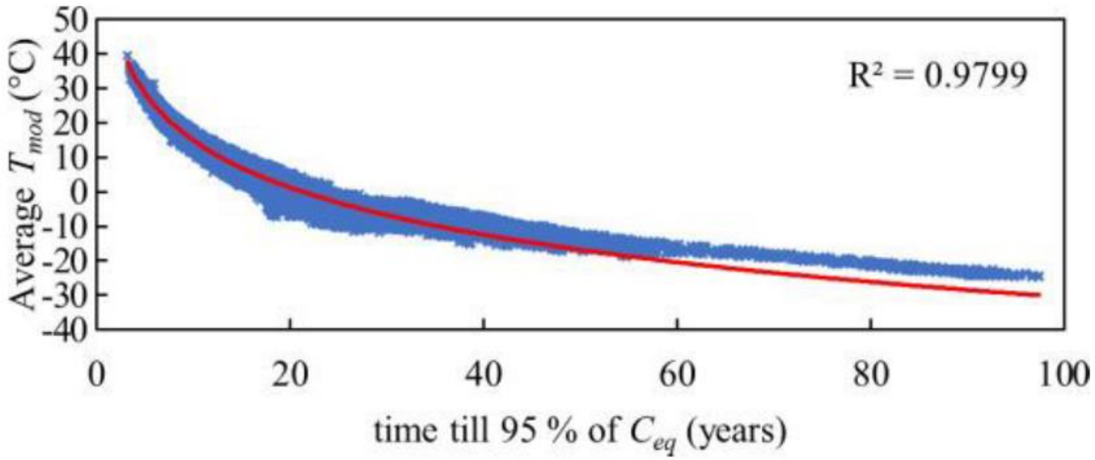
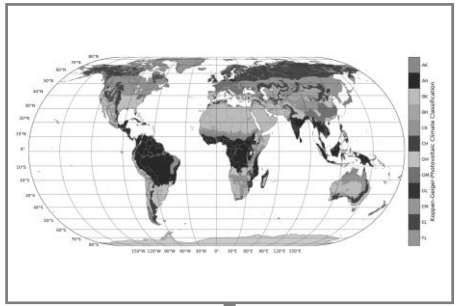


Figure 9: Worldwide mapping for the time in years till 95 % of C_{eq} is reached.



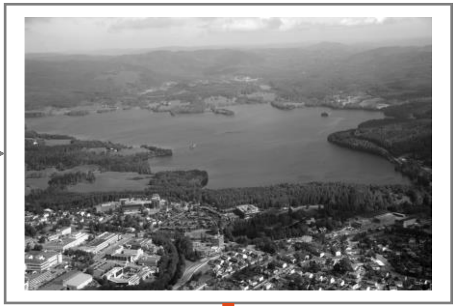
[1] 10.4229/WCPEC-82022-3EO.1.3

Module stressors are affected on different levels



Macroclimate

+Local terrain, vegetation, presence of water, +++



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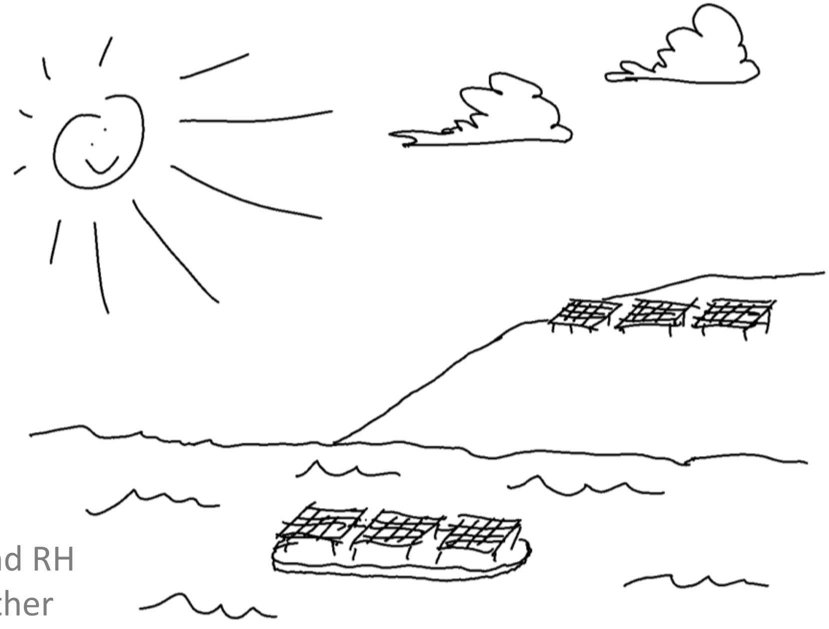
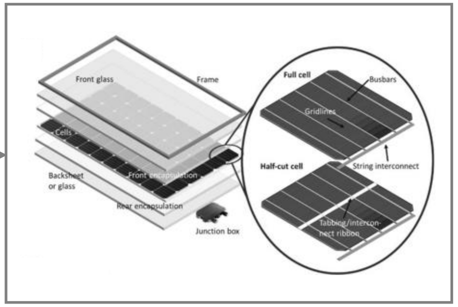
Average ambient T and RH can be higher over either water or air, RH&T coupling and short term dynamics of relevance



+System design and module mounting

Module-exterior climate / «Microclimate»

+Module architecture and BOM



Module-interior climate

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Last from 10.1088/2516-1083/ac6111
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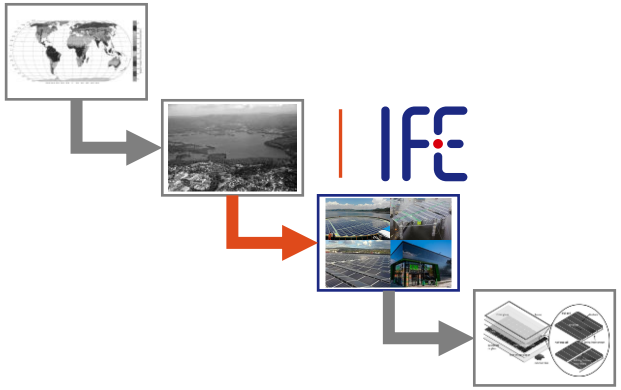
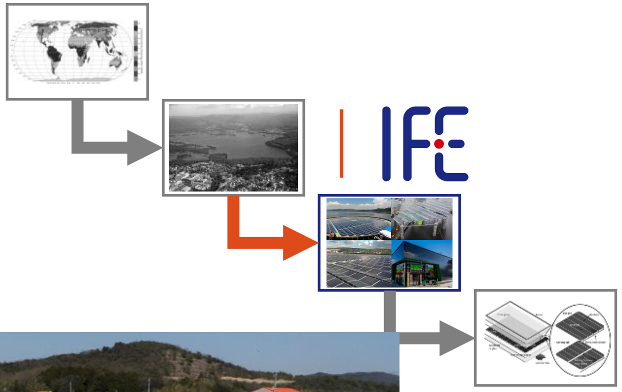
FPV vs GPV at the module-exterior climate



- T and RH at module determine moisture ingress
  - $T_{mod} = T_{amb} + \frac{G_{POA}}{U_0 + U_1 \times WS}$ [1]
  - $RH(T_{mod}) = RH(T_{air}) \times \frac{p_{sat}(T_{air})}{p_{sat}(T_{mod})}$

[1] 10.1002/pip.813



FPV vs GPV at the module-exterior climate

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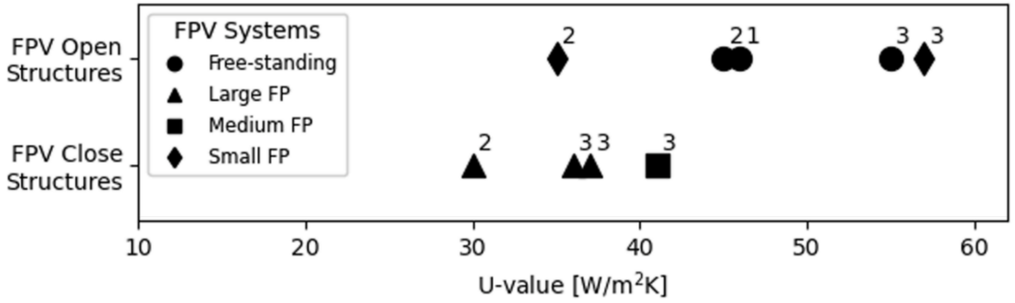
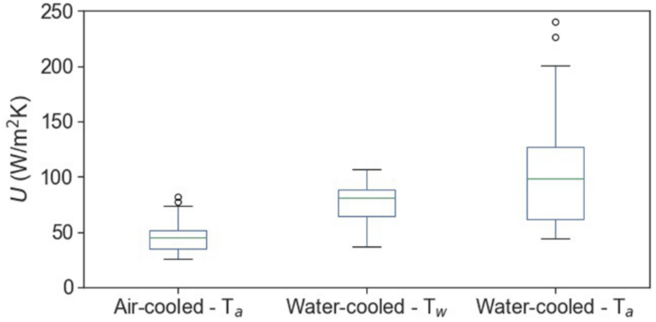
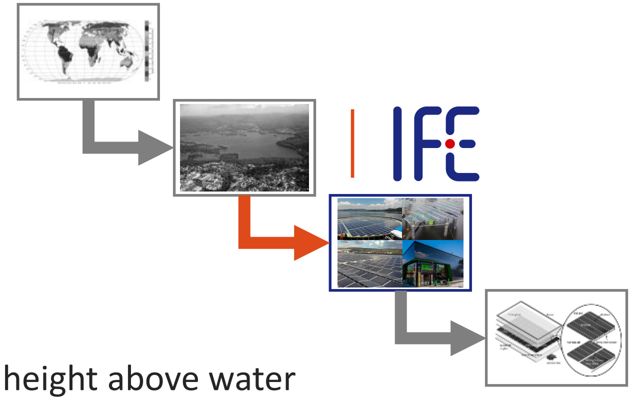
– Different (F)PV systems can have different G_{POA} and U values





[1] 10.1002/pip.813
Images from oceansun.no, https://www.rechargenews.com/solar/ciel-terre-leads-brazils-10mw-floating-solar-bid/1-1-869221
Middle figure from
Bottom figure from 10.1016/j.solener.2021.03.022

FPV vs GPV at the module-exterior climate



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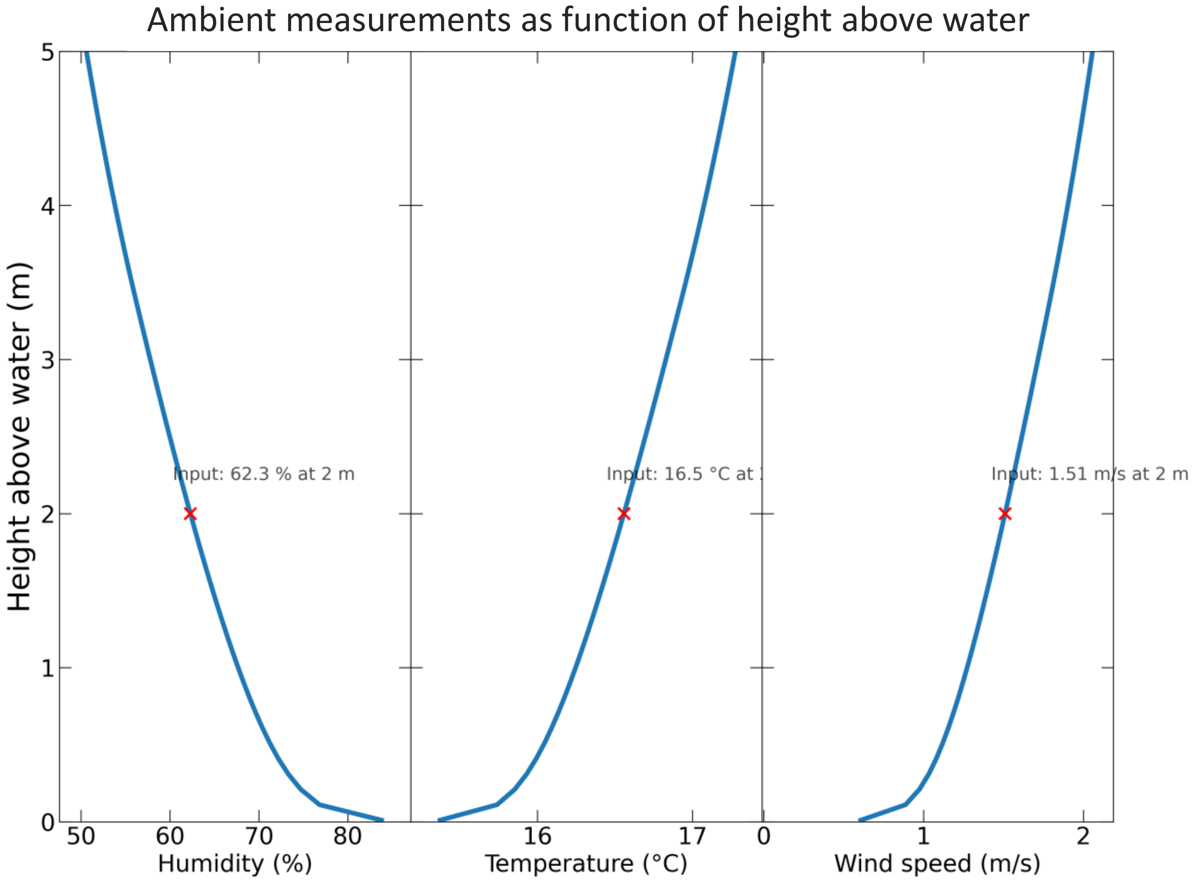
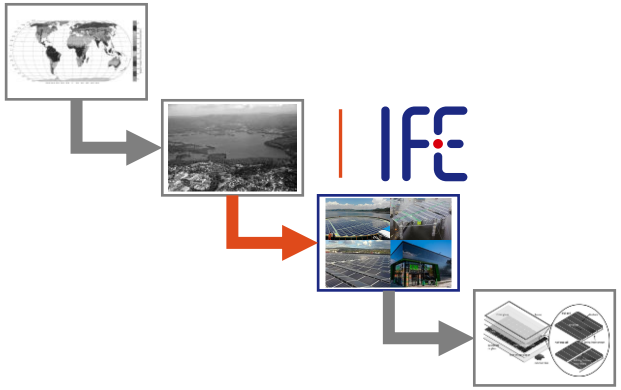
- Different (F)PV systems can have different G_{POA} and U values
- Different FPV systems have different *ambient* parameters based on height above water
  - Can be calculated via the Lake Heat Flux Analyzer (LHFA)[2]
    - Does not take effect of FPV system on ambient parameters into account



[2] 10.1002/pip.813
[3] 10.1016/j.envsoft.2015.04.013



FPV vs GPV at the module-exterior climate – our approach

1. Consider one GPV and two FPV systems
   - Water-cooled with FPV modules on water
   - Air-cooled with FPV certain height above water

Images from oceansun.no, https://www.rechargenews.com/solar/ciel-terre-leads-brazils-10mw-floating-solar-bid/1-1-869221

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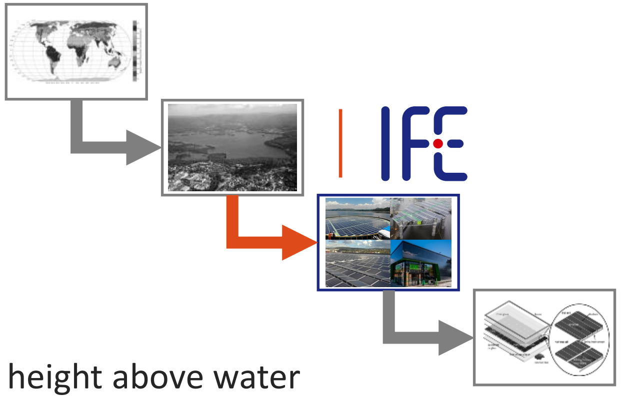
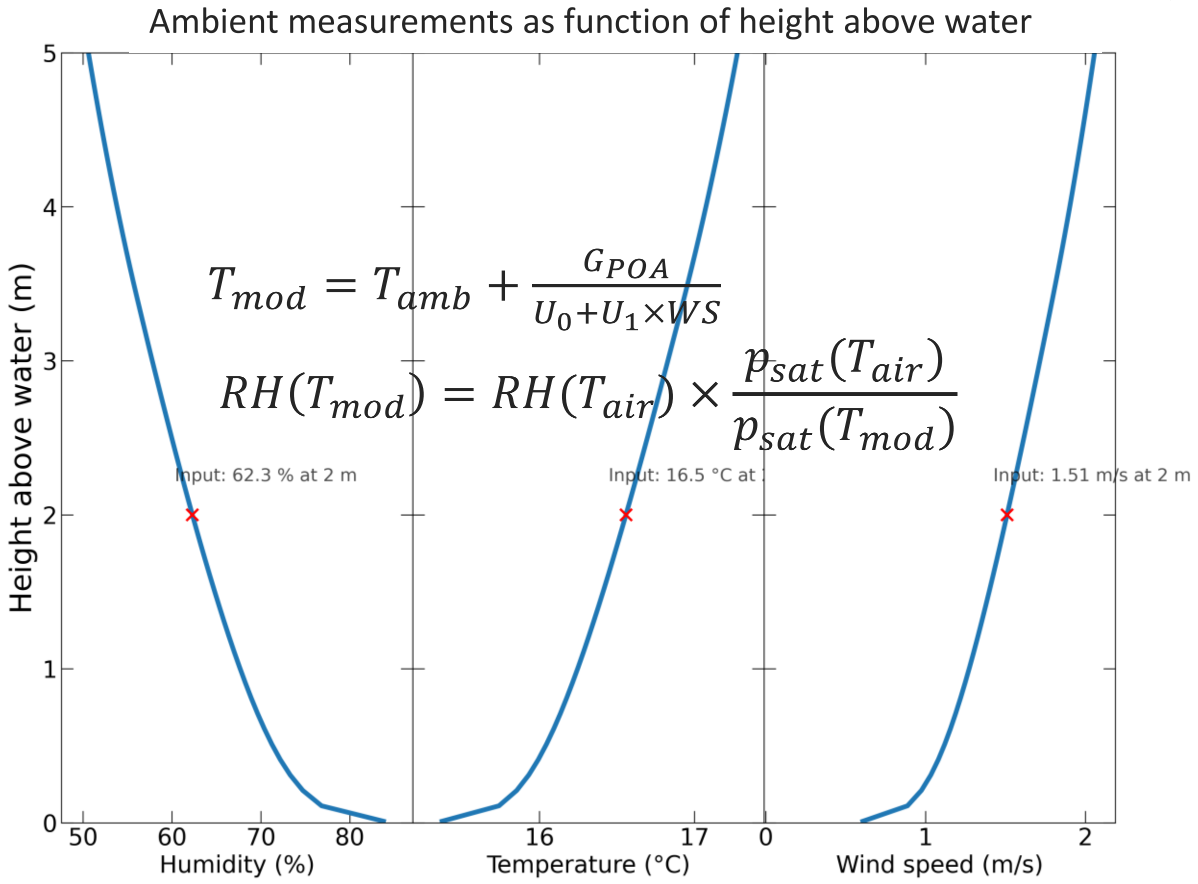


1. Consider one GPV and two FPV systems
   - Water-cooled with FPV modules on water
   - Air-cooled with FPV certain height above water
2. Calculate ambient parameters at module height using LHFA
3. Ambient to module parameters
   1. Get G_{POA} via satellite data
   2. Calculate the module T and RH using appropriate U-values

– Work in progress..



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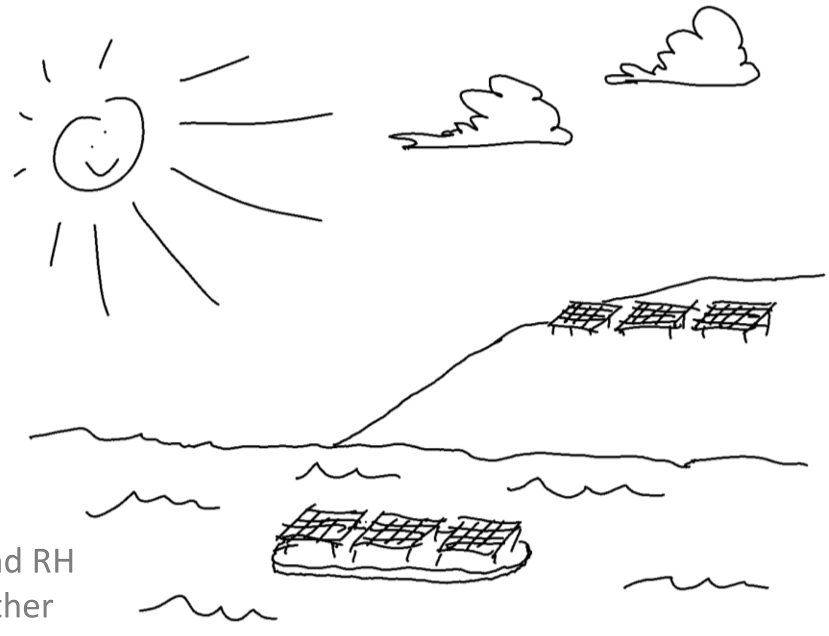
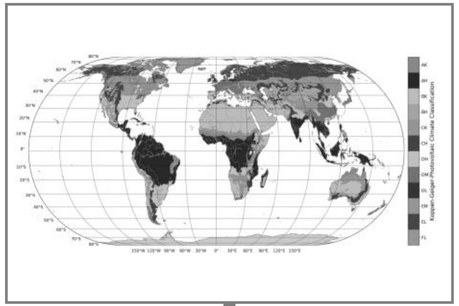
Module stressors are affected on different levels





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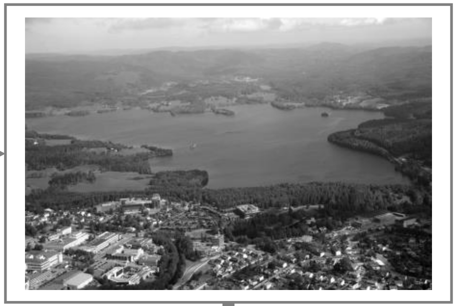

Local climate

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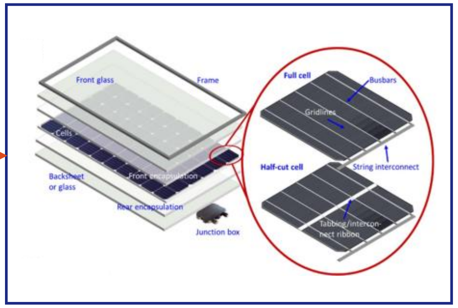
Module-exterior climate / «Microclimate»

Comparison of GPV with two FPV cases, results TBD

+Module architecture and BOM



Module-interior climate

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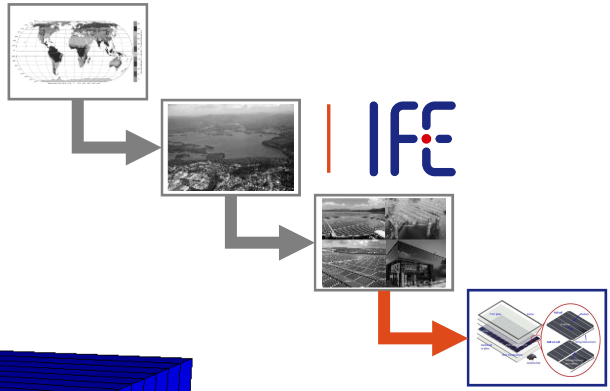
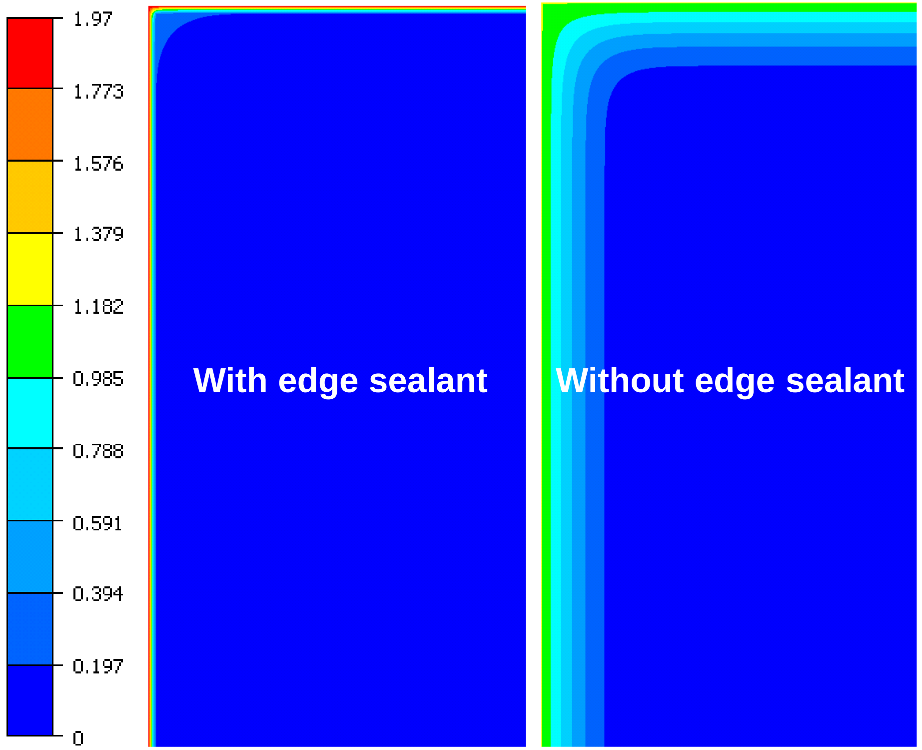
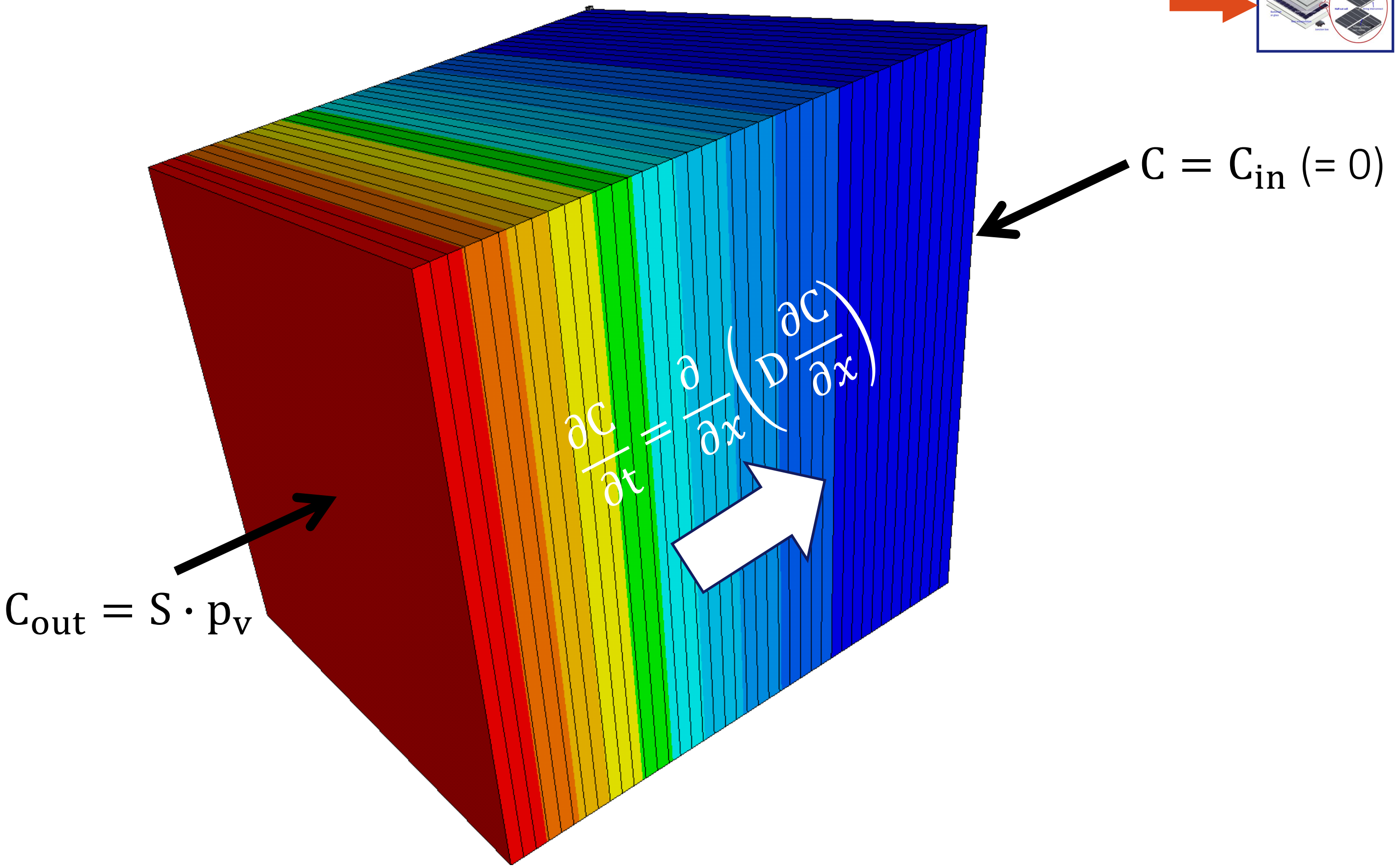


FPV vs GPV at the module-interior climate – our approach

- Module-exterior climate as input into Finite Element Modelling to compare moisture ingress between FPV and GPV on selected sites and BOMs



One year of exposure



Summary

- FPV is a market with great promise
- To unlock this promise, more knowledge on FPV reliability is crucial
- This work aims to compare humidity-induced stress of FPV and GPV at
  1. The local climate
     - Air T and RH can be higher above either land or water
     - Short term dynamics and coupling of RH & T can give relevant insights
  2. The module-exterior climate
     - Use local climate data and Lake Heat Flux Analyzer to compute ambient parameters at different heights above water
     - Translation from ambient to module parameters for different FPV systems
  3. The module-interior climate
     - Use module-exterior parameters as input for FEM of moisture ingress

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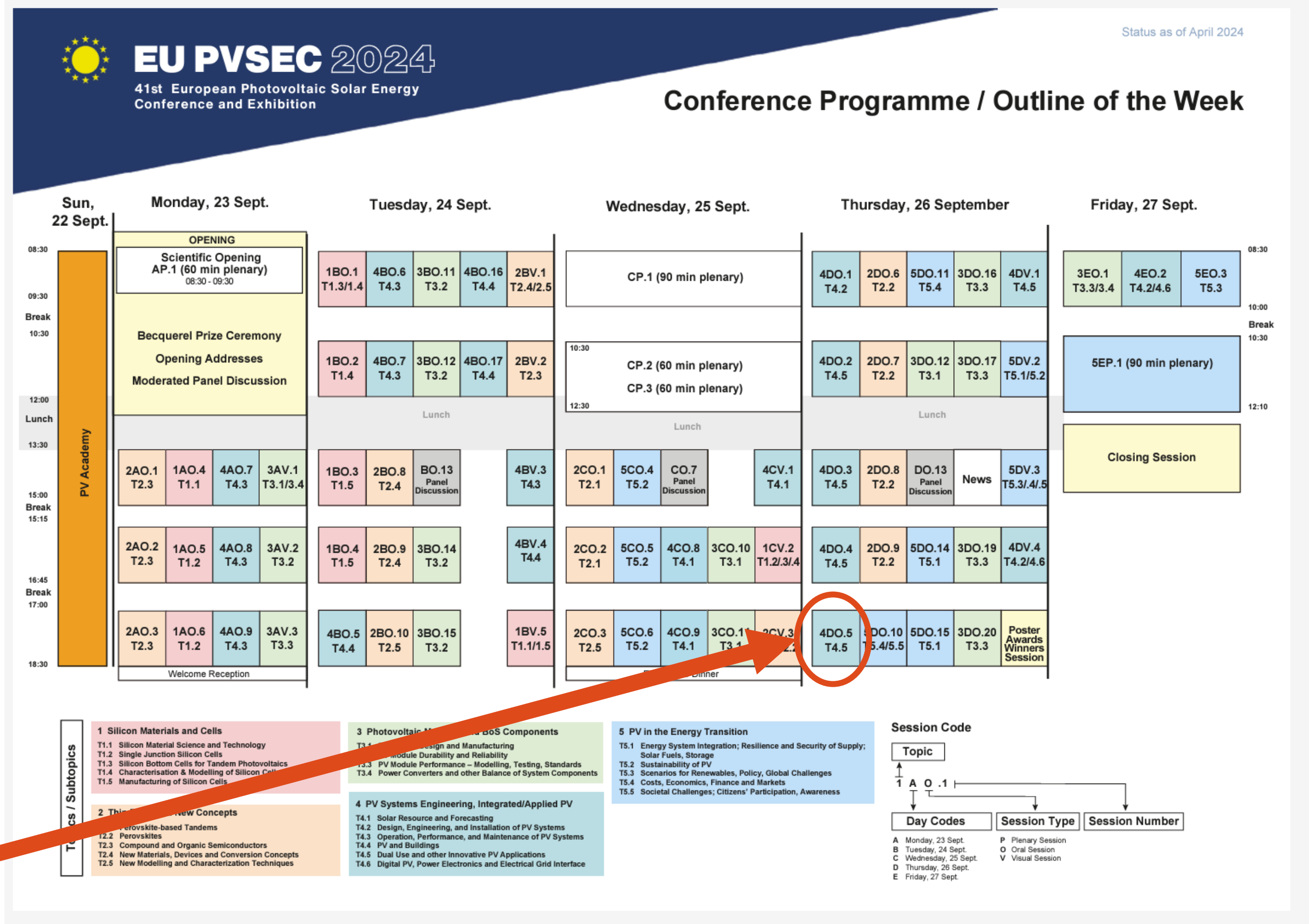
- More results coming at 2024 EU PVSEC (4DO.5.3)



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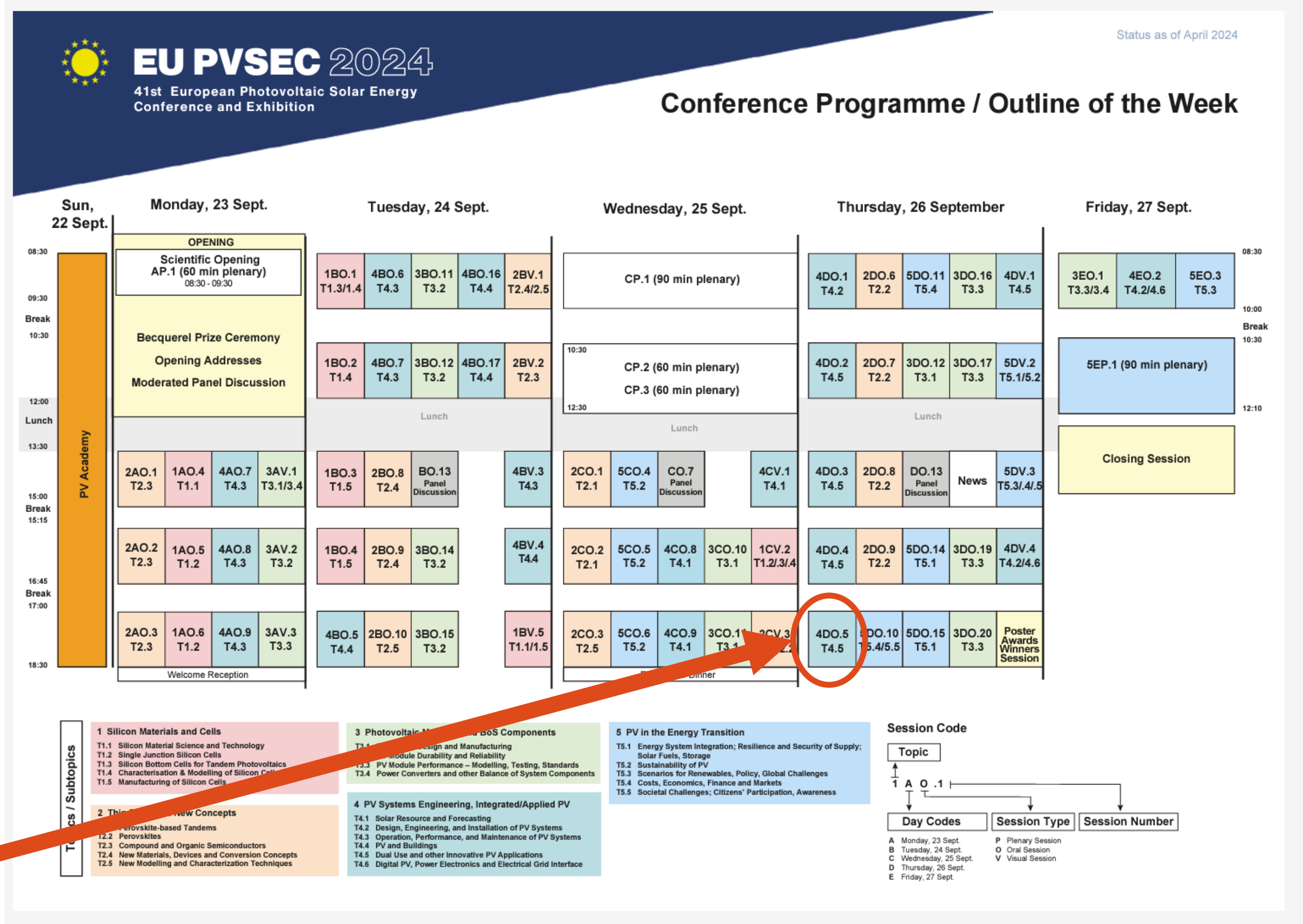

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- Thank you for your attention!

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Nathan Roosloot
PhD Candidate

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Lake Erken: large differences in RH over water and land

- Both summer and winter contain periods where RH over water is constant at 100%, while that over land follows daily fluctuations
  - Not sure if physical or not, following up with site owner
- Without these data, mean difference between RH on land and water likely lower, but would still be negative