Building-Integrated PhotoVoltaics
– Project DAPPER and beyond –

Smart Energy Academy

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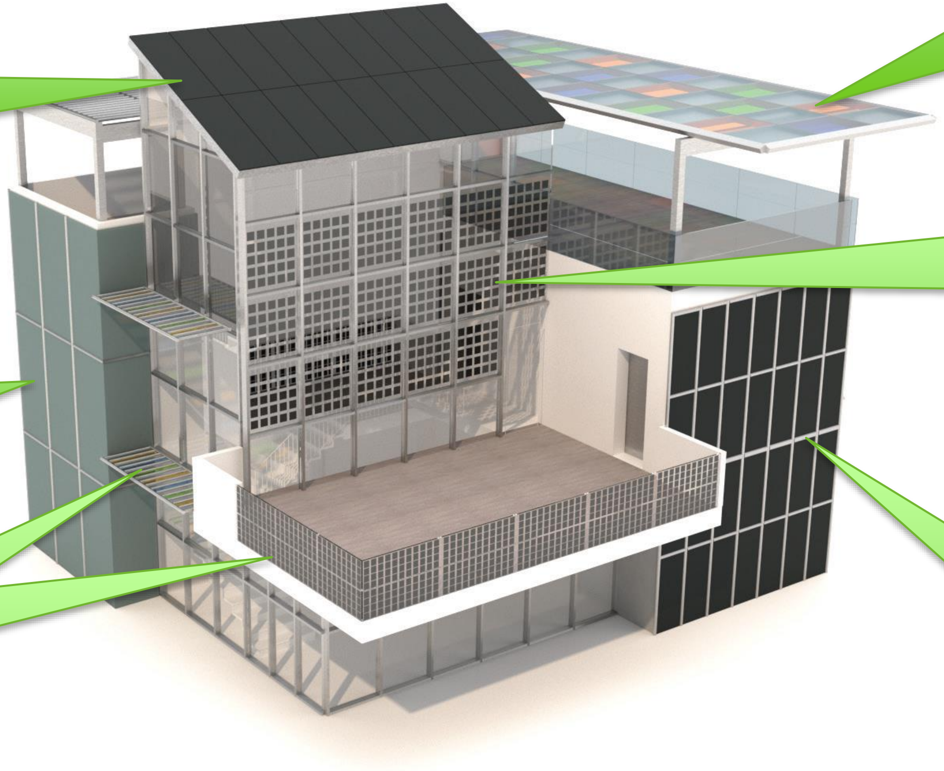
Outline

- BIPV – what is it?
- Complexity - value chain
- What is needed?
- Our approach
- Results of DAPPER
- Way forward
- Related projects

Types of BIPV Elements



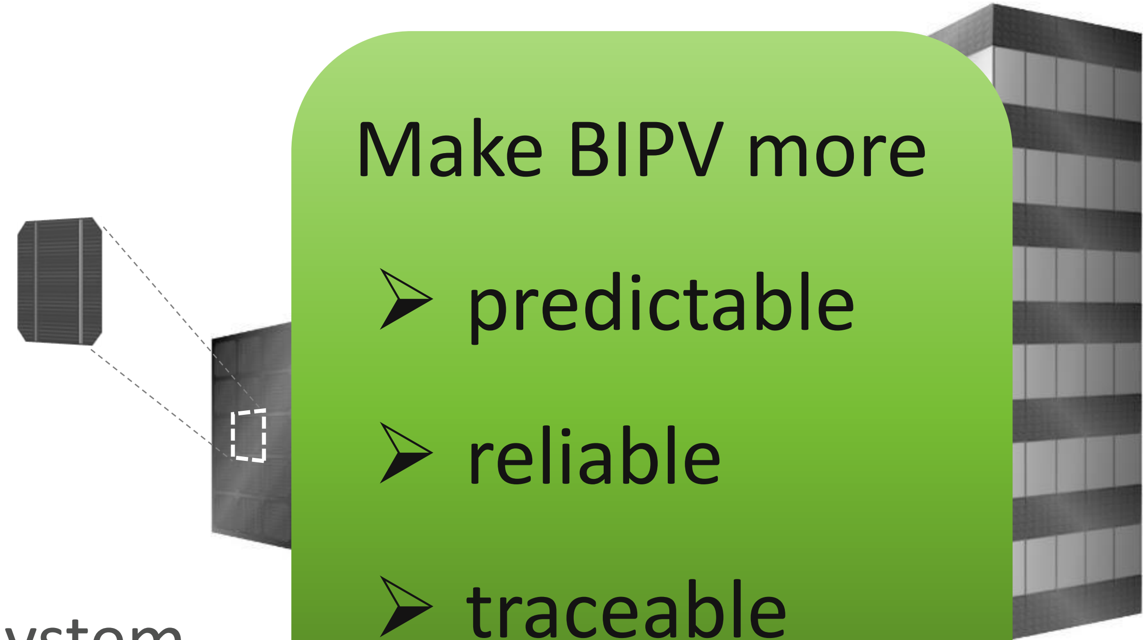
Source: BIPV Status Report 2020, https://solarchitecture.ch/

Rationale and Context

Building-Integrated Photovoltaics holds great market potential

but:

- **Acceptance** is difficult
- **Performance** not sufficiently clear
  – especially over the entire **lifetime**
- Long lifetimes are required
  – **Reliability** is key
- Integration into Energy Management System requires **Forecasting and Data Monitoring**



Make BIPV more

- predictable
- reliable
- traceable

The project results apply to **Building-Applied** (Rooftop) **PV** as well!

BIPV value chain – barriers and opportunities

	Desire	Plan	Design	Build	Install	Operate
Actor	Owner, Project planner	Architect ⟷	Engineer	Module manufacturer, Façade builder	Construction company, Electrician	Owner O&M contractor
Current status	Showcase projects, performance & reliability critical	Building design with special, engineered components	individual system & component design	Custom manufacturing (PV) Limited choices (electronics)	Individual installation & wiring	No / long-time aggregate monitoring
Impedi-ments		No clear view on options, unknown performance vs. costs, no established sales channels	Custom engineering required	Costs & effort for custom fabrication, limited choice of suitable electronics	Lack of installer training, too much individual installation needed	Difficult monitoring & analysis, lack of operator training, no forecasting
Targets / Oppor-tunities	Proven portfolio NZEB standards	BIM Standardized offering (cf. windows)	Modularization, reduced individual engineering	"Customized mass manufacturing" (semi-automated) dedicated electronics	Prefabricated bus system, standardized components, training	automated monitoring, predictive maintenance, integration into BEMS, generation forecasting

PV roof integration: an interesting case

Ideal goal: replace roof tiles with PV 'tiles'
- Aesthetic adaptation possible
- Seamless integration

BUT:

Sizing challenge:
- small tiles are **expensive** – many interconnections, high fabrication costs;
- large ones are difficult for arbitrary **roof sizes**
- generally **dummies** are needed for full coverage, edges and angles – adapted visual and/or made to size

Solution for flat roofs: thin film PV embedded in polymer roof cover?
- limited area coverage
- lower performance
- shading issues due to other installations
- soiling

Standardization issue:
- building / electrical codes vary
- rafter spacing varies from country to country

Market difficulty:
- needs to be sold like building material, easily installed?
- costs become prohibitive
- e.g. Tesla with discount: 4 \$/Wp before incentives (entire system with installation)

Is there a way ahead?
Predefined tile size sets,
glue-on glassless c-Si
modules for flat roofs?

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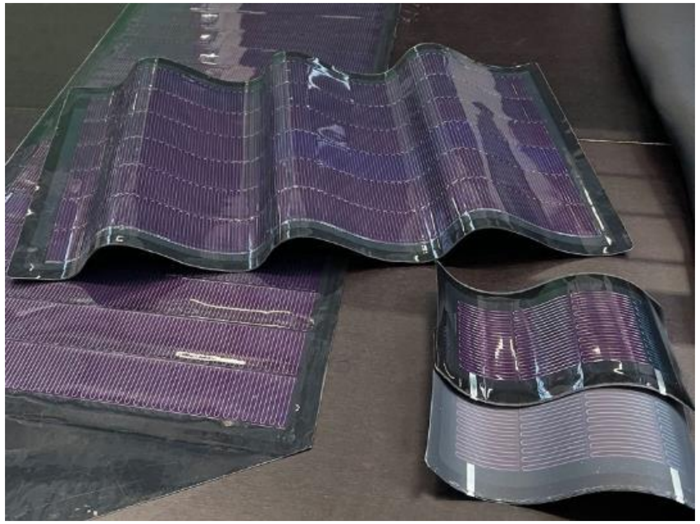
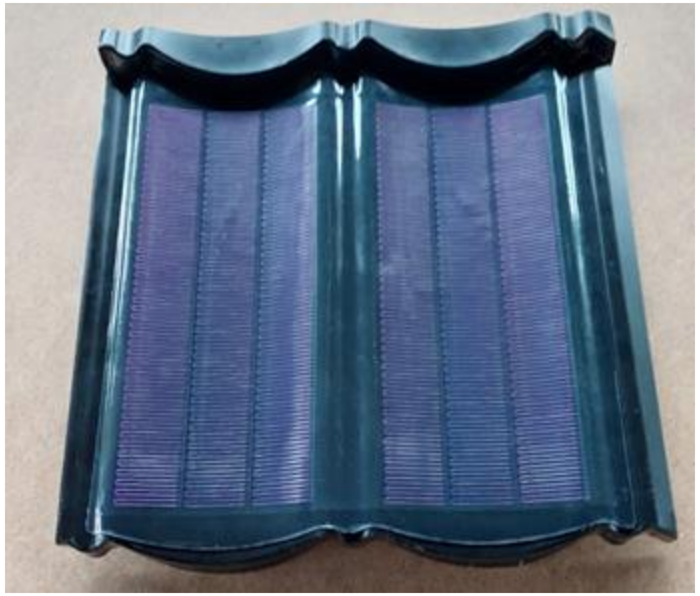
Example: Enfoil

- Thin-film CIGS on steel foil
- Polymer embedment





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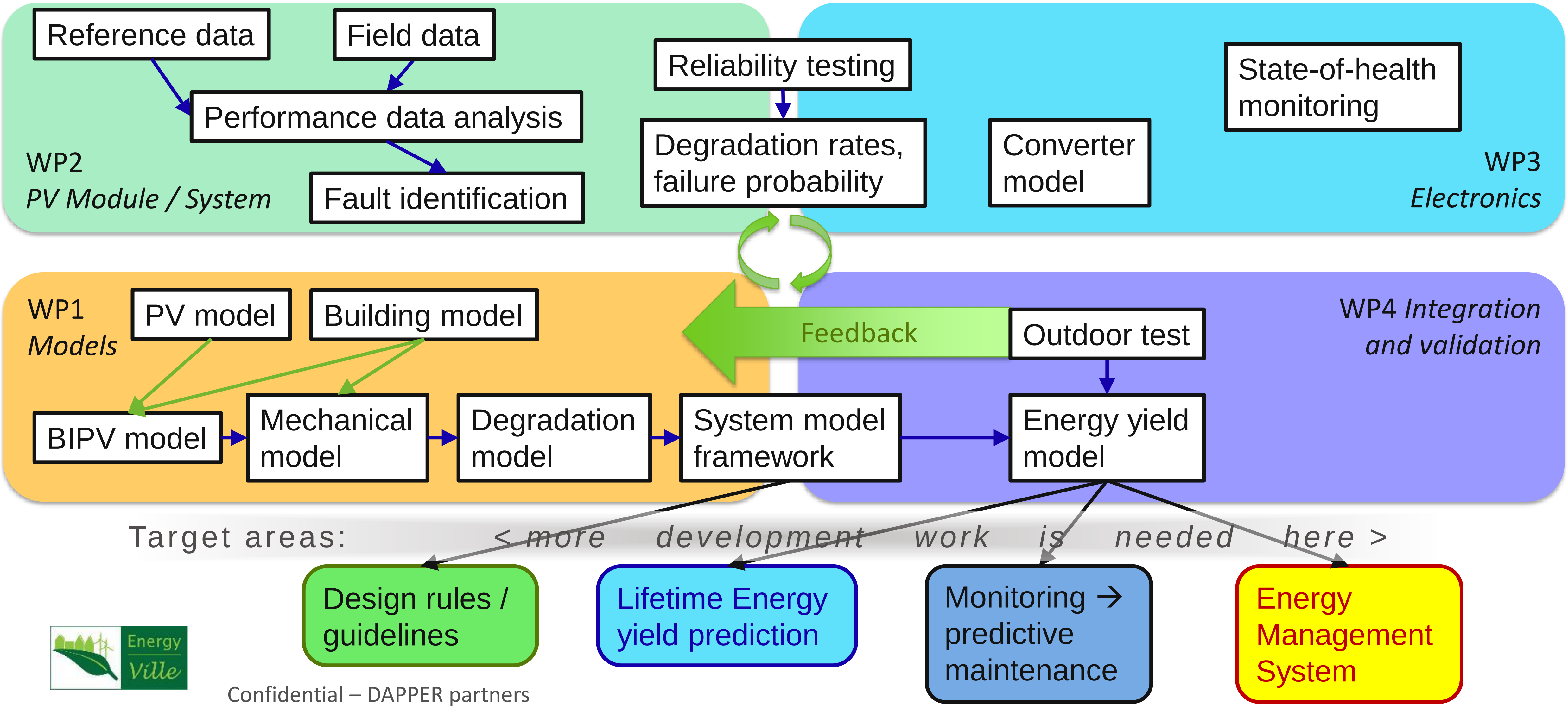
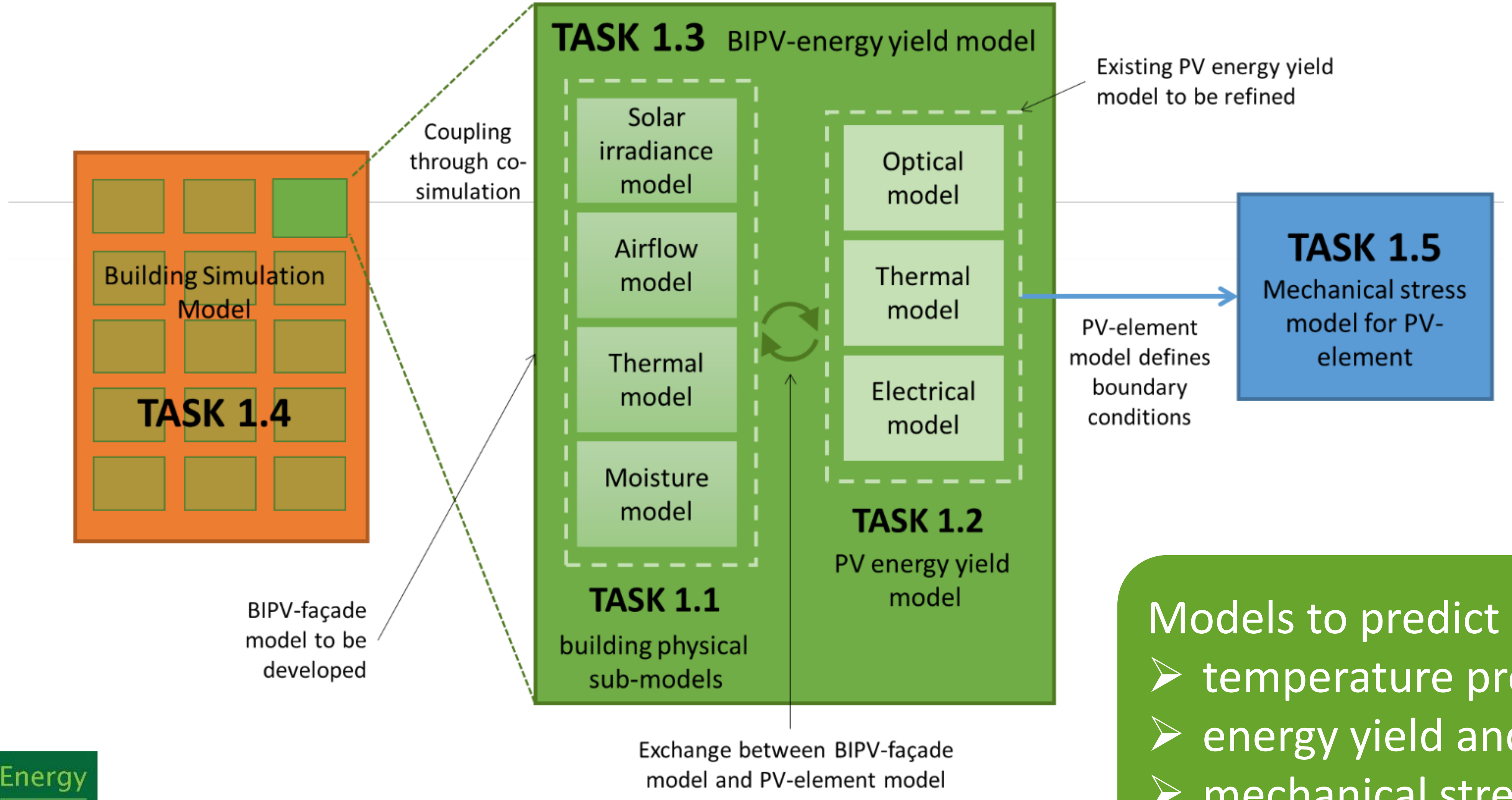
Pictures © Enfoil, www.enfoil.com

Project content and targets



Co-Simulation of Building and PV



Models to predict

- temperature profiles,
- energy yield and
- mechanical stress

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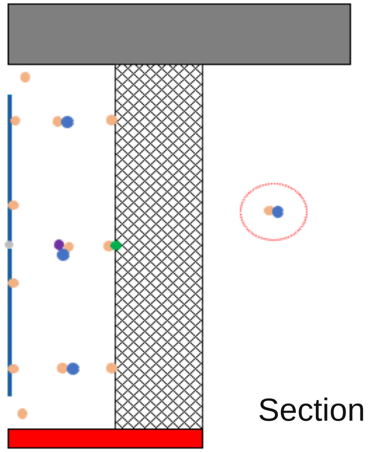
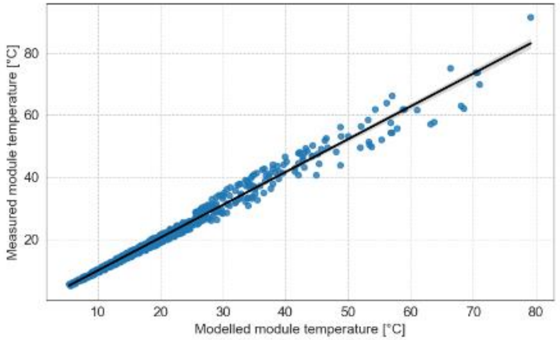
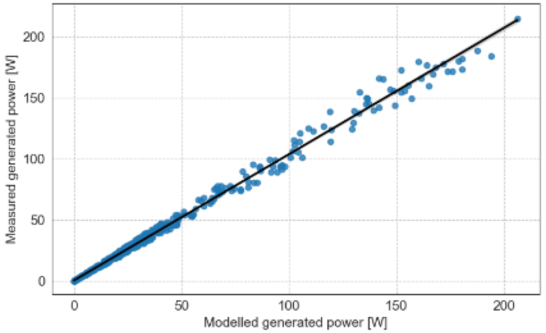
Validation

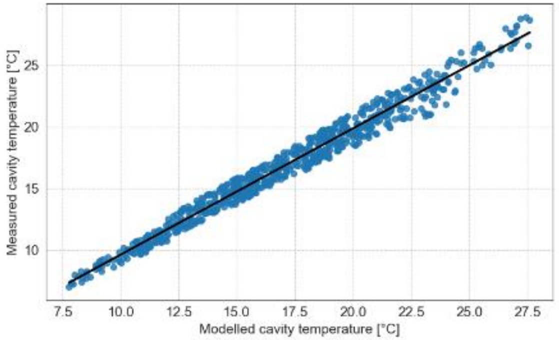


Section with indication of sensors

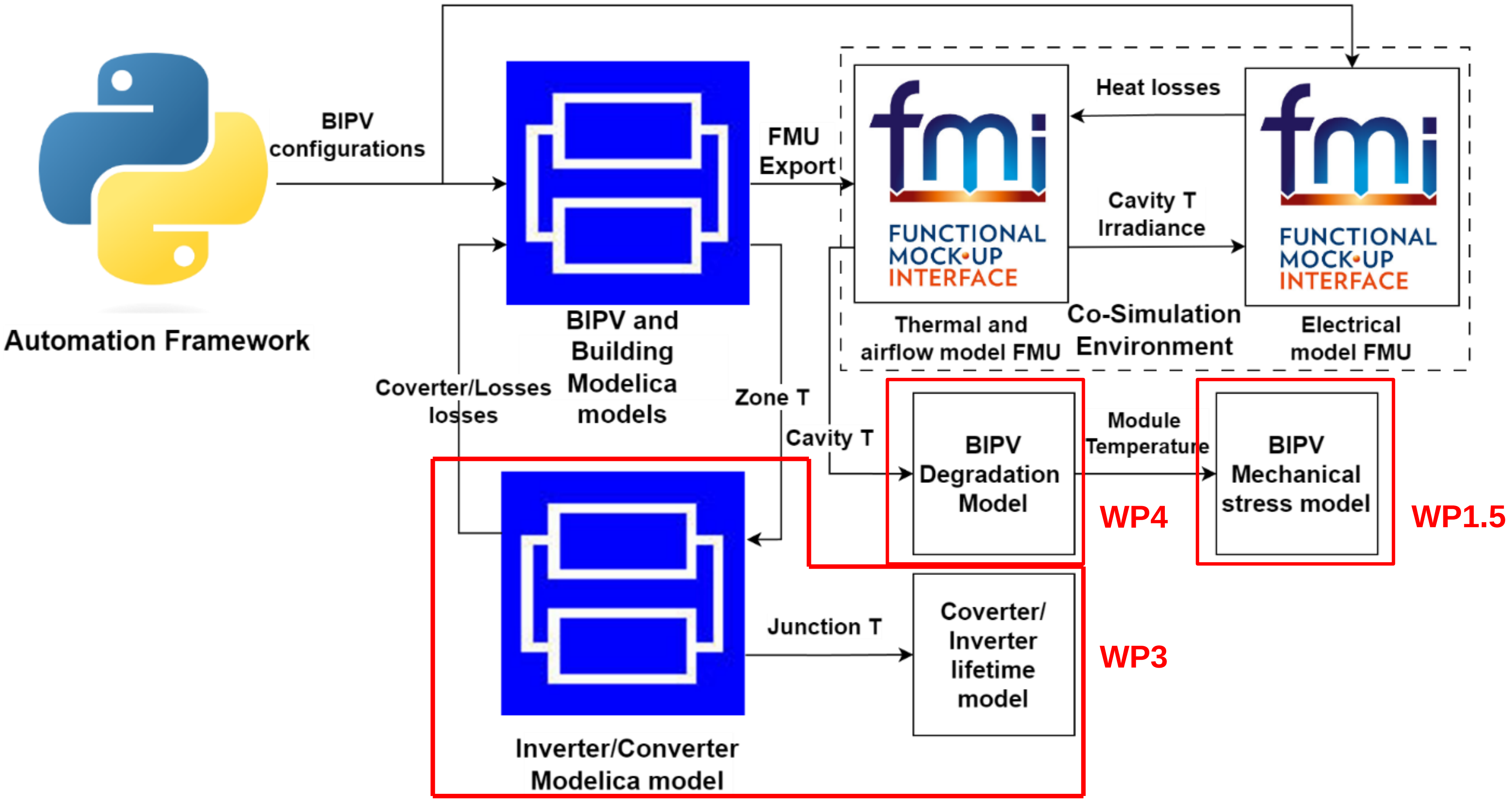
Vliet module		
	RMSE/NRMSE	MAE/MAPE
Module temperature (Average)	1.94 °C/7.32%	1.19 °C/4.63%
Cavity temperature (Average)	0.96 °C/6.82%	0.73 °C/4.02%
Power output	4.17 W/7.14%	1.92 W/5.52%
EnergyVille		
	RMSE/NRMSE	MAE/MAPE
Module temperature (Average)	1.86 °C/7.94%	1.07 °C/6.43%
Cavity temperature (Average)	0.84 °C/9.01%	0.69 °C/6.89%
Power output	3.22 W/7.62%	1.51 W/6.32%





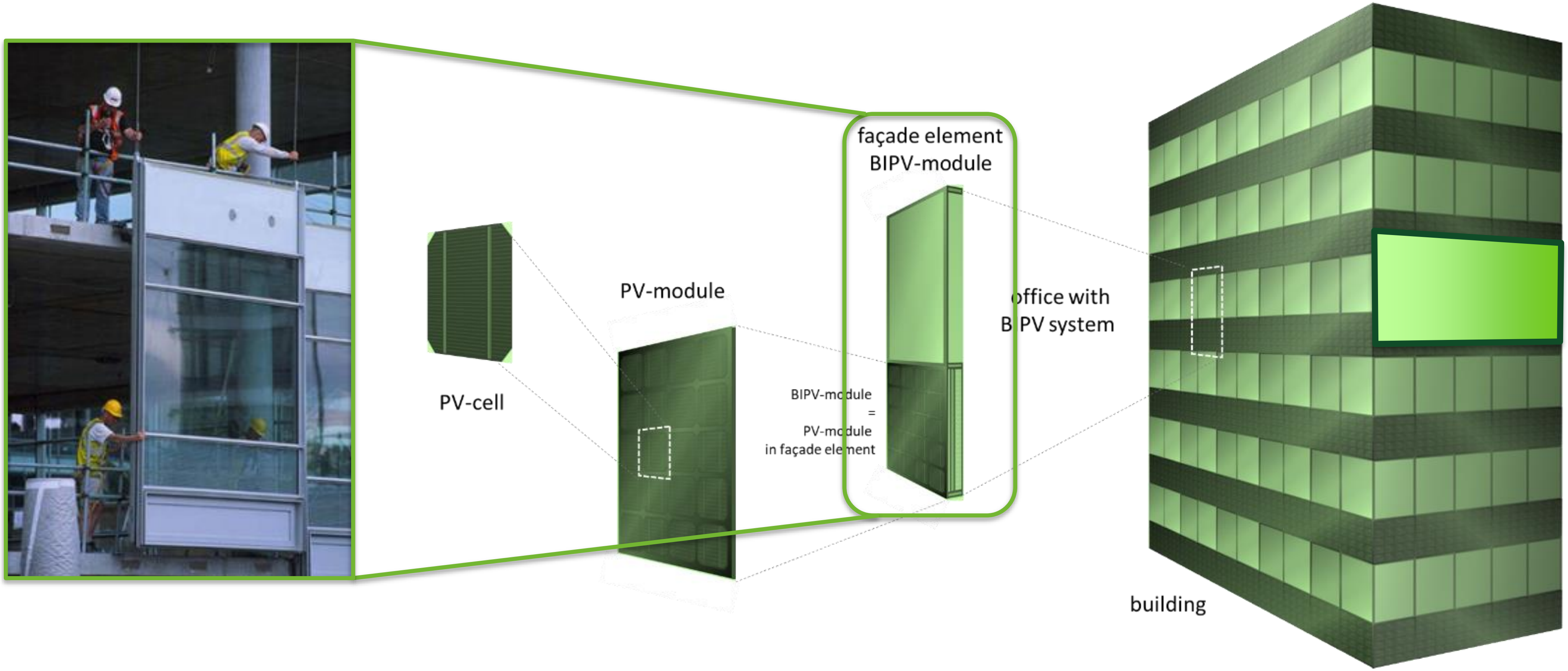


Framework integration to other WPs



Definition of a common case

- Multi-storey office building: simple but realistic



Long term Thermo-mechanical stress on PV modules

Macroscopic: glass-encapsulant-backsheet, frame, clamps, edge sealant, no interconnections and soldering

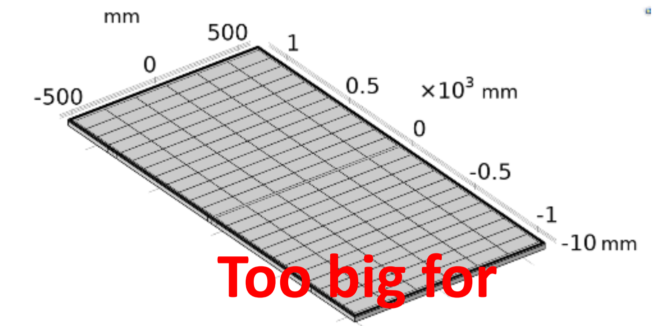
Input: Tcell, Pressure

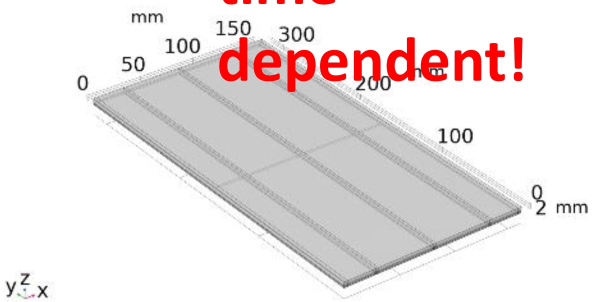
Output: von Mises stress (Thermo-Mechanical)

Microscopic: 2 cells interconnected with all the materials

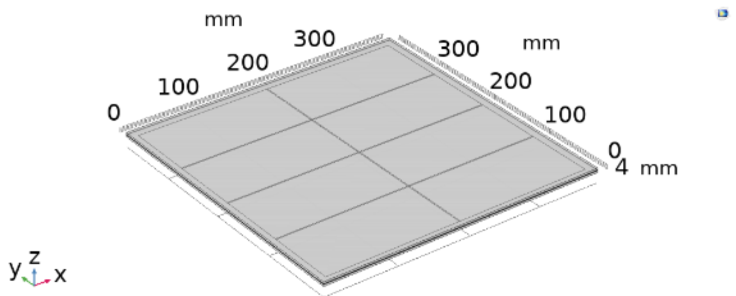
Input: Tcell, Pressure

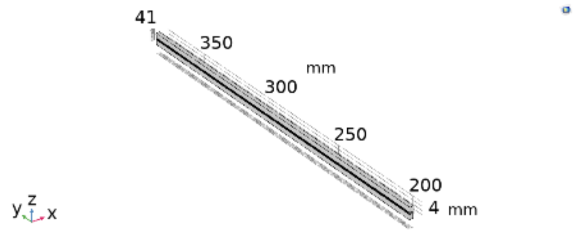
Output: von Mises stress (Thermo-Mechanical)

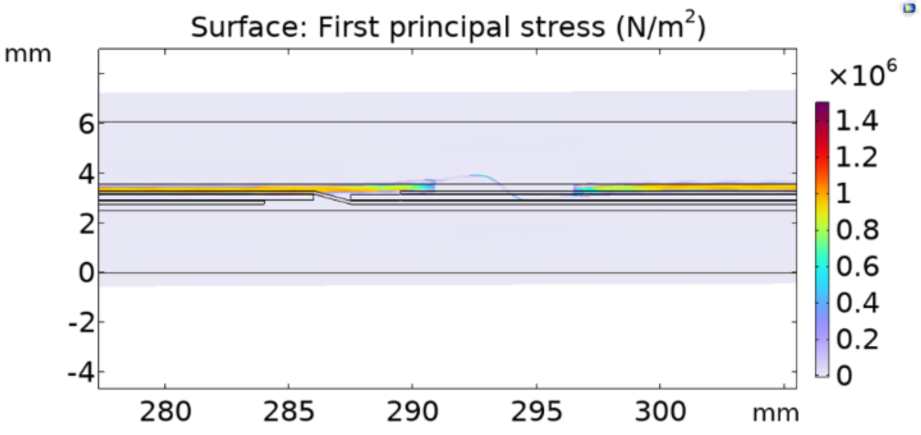


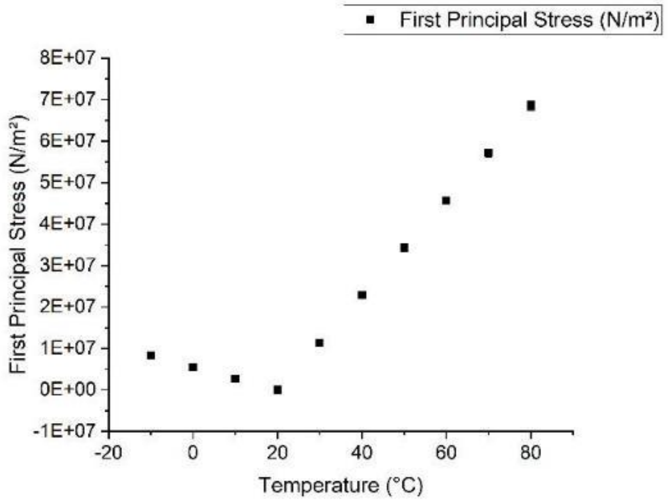


Too big for time dependent!



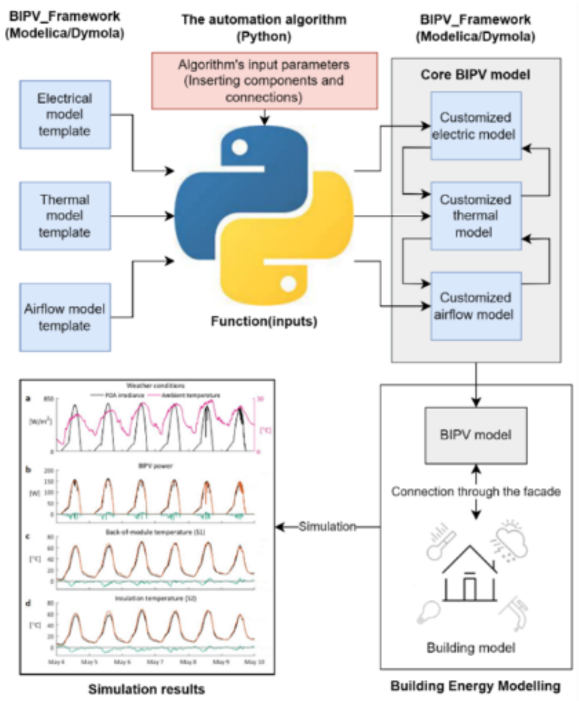


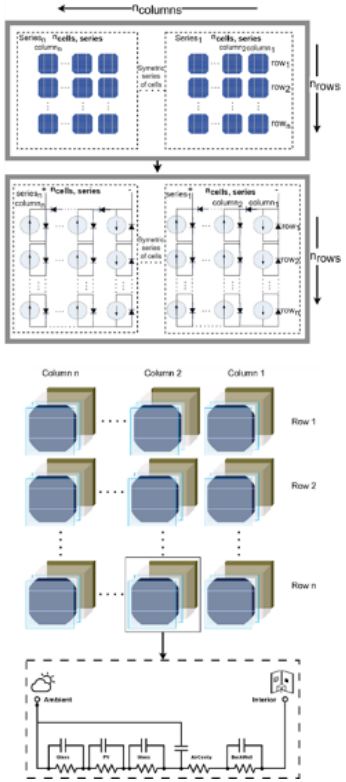


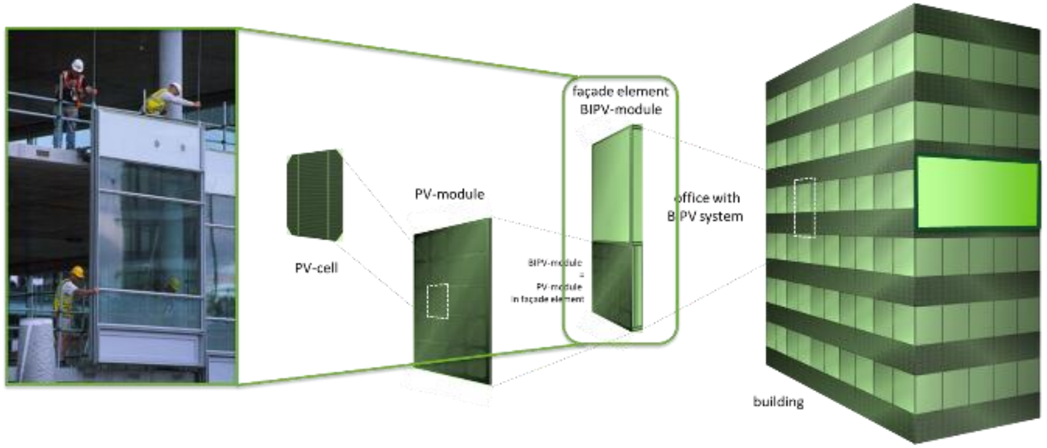


Lessons learned

- Successful development of BIPV co-simulation environment
  - Allows to automatically generate customized BIPV models with different complexity
  - Model is validated for different cases
- Models proved useful for other DAPPER research questions and work packages
  - Definition of common office use case
  - Calculation of thermal induced mechanical stress
  - Boundary conditions for BIPV degradation assessment
  - Boundary conditions for electronics







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Fault diagnosis of PV systems

Importance

- Fault diagnosis = early detection & identification of faults
- ~30% of PV systems suffer from faults
- Cell cracks, wiring degradation, short circuits, …
  → Energy losses & risk of fire
- Fault identification is key for maintenance scheduling, but very challenging

Conventional techniques

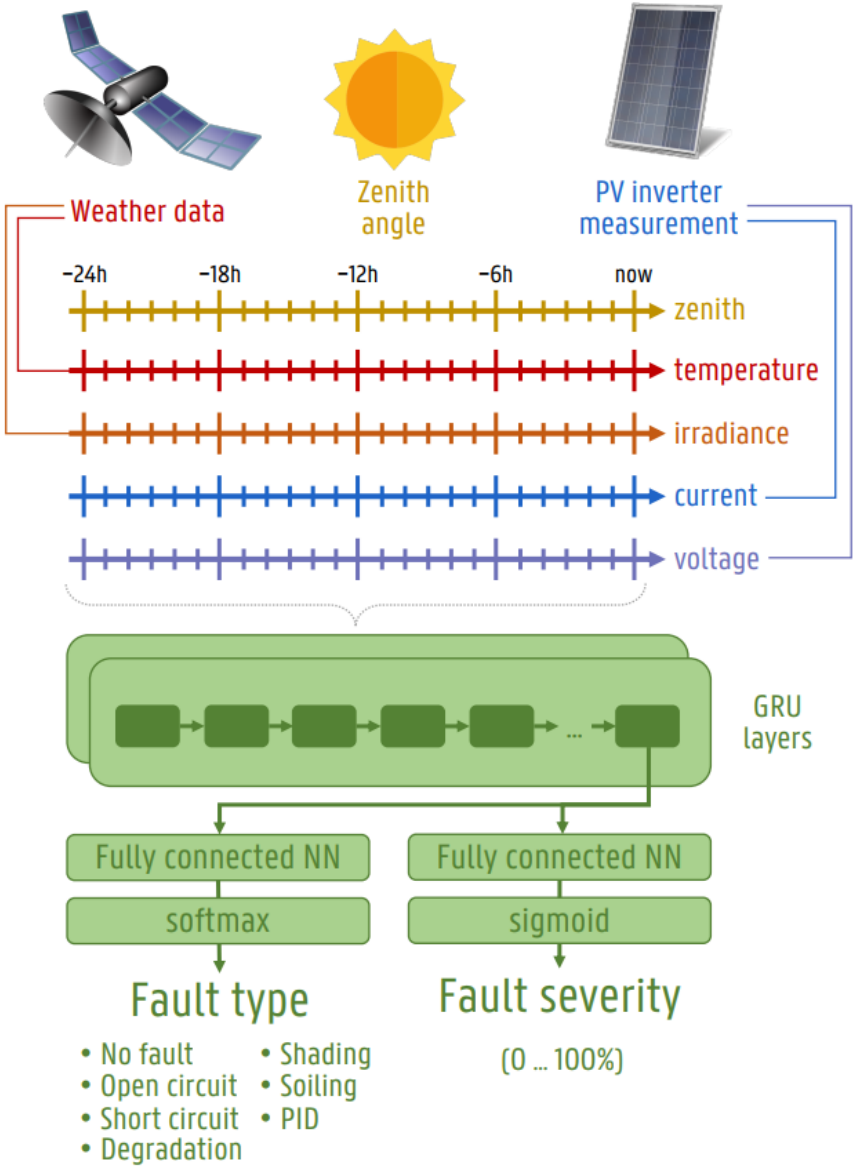
Visual inspection & infrared imaging via drones
→ Not cost-effective
→ Automatic method required

Large-scale systems can afford sensors and inspections;
building systems usually cannot.

Our approach #1: single site + satellite weather

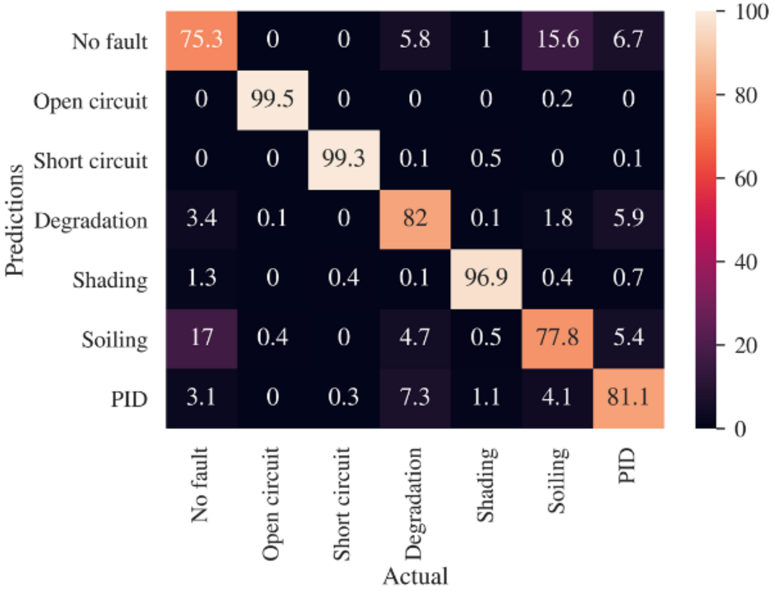
Method

- Relies on satellite & inverter measurements
  → No installation of sensors required
  → Widely applicable & cost-effective
- Classification based on past 24 h instead of single measurement
- Recurrent neural network
- Predicts both fault type & severity



Results

- Over 86% accuracy
- Validated on real PV systems without faults & with wiring degradation



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IDLab INTERNET & DATA LAB

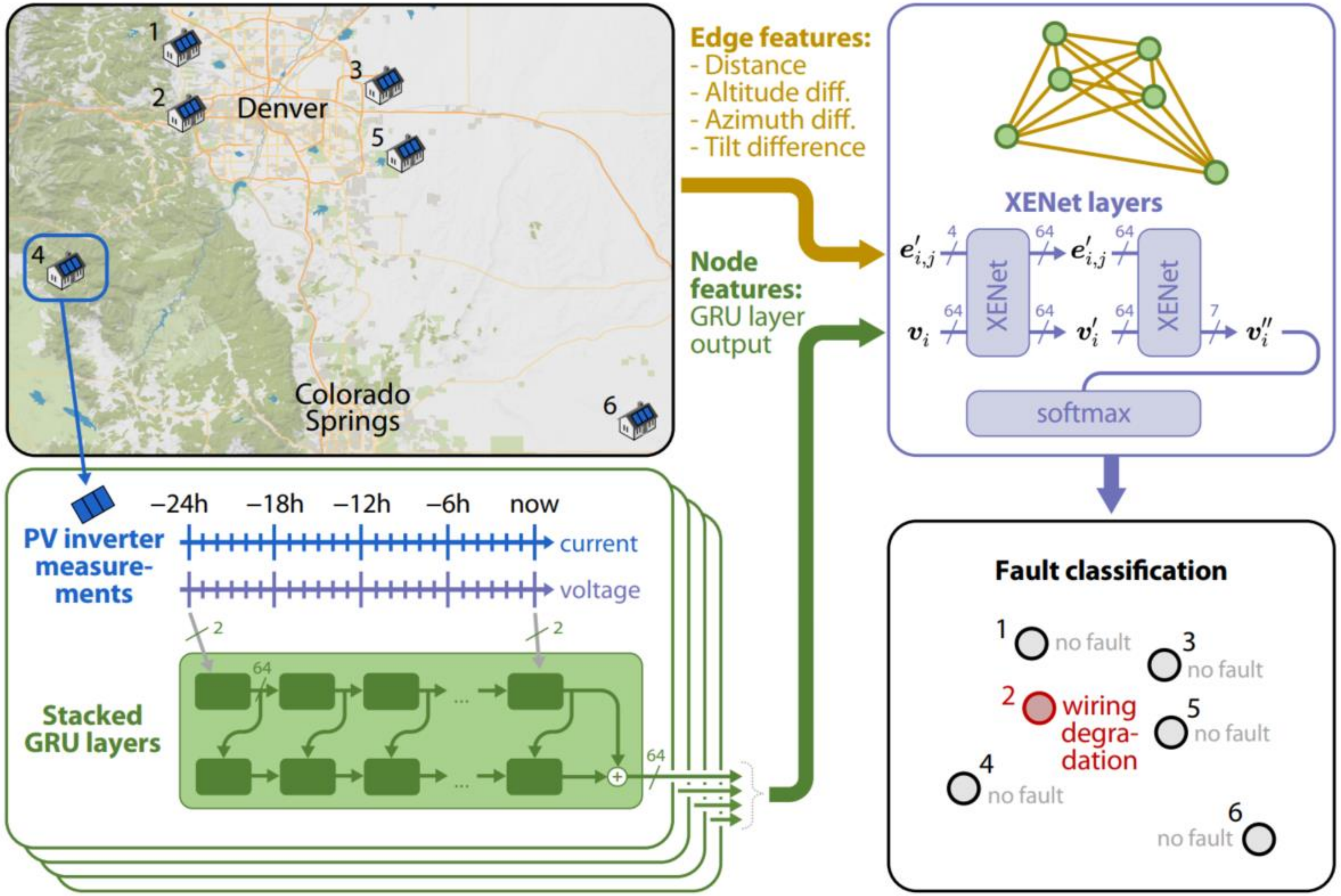
Our approach 2: Compare multiple sites

Method

- Compare I & V produced by nearby PV systems
  → No weather data required
- Graph neural network
- Single model can monitor PV systems of entire city
- No retraining required to include new PV systems

Results

Over 88% accuracy



Fault types identified: Open or short circuit, shading, soiling or other degradation, potential-induced degradation

Faults, faults, faults…

Why a close look matters:

- "Based on a sample of hundreds of commercial scale rooftop inspections performed by Clean Energy Associates globally, including some of the largest commercial-scale rooftop installations worldwide, **up to 97% of inspected rooftops had significant safety and fire risks.**"
- "The good news is [that fixing] the **most common and most serious issues** usually involve **replacing components** - connectors and wires - **not entire solar panels**."
- "Undetected Damage in PV Modules Continues to Pose a **Significant Risk** to the Solar Industry"

Source: Clean Energy Associates
https://www.cea3.com/commercial-rooftop-solar-safety
https://www.cea3.com/cea-blog/solar-pv-module-quality-risks-report

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Trends in PV towards the edge of the design window

- **Larger cells**, increasing stresses in the module
- **Thinner wafers**, now trending below 150 µm towards 110 µm
- **Cut cells** are now the standard, and not all cuts are (or at least were) done carefully without microcracks
- **Cell gaps got smaller**, and contacts between wires and cell edge are possible
- **Glass got thinner** by a lot
- **Silver is being minimized**, increasing stress on the solder joints

Failure Modes and Effects Analysis

A prerequisite for Design-for-Reliability

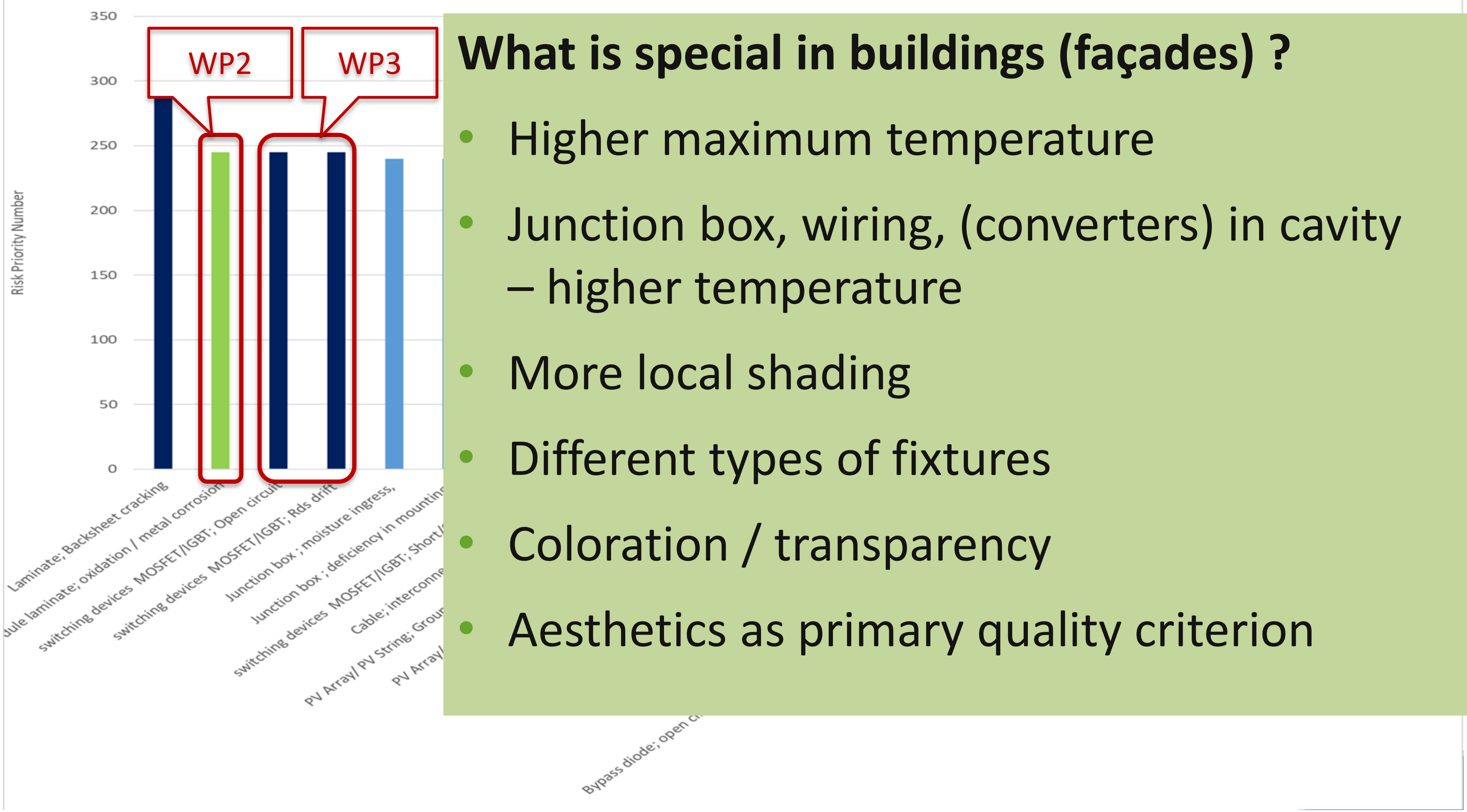
- Starts with design assumption
- Failure mode:
  root cause → contributing factors → end effect = fault
- Understanding physics-of-failure is key
- Tests for each specific Failure Mode, accelerated tests
  – 30 years in < ½ year?

Failure Modes and Effects Analysis

Ranking of faults:

- We determine 3 factors for each Failure Mode
  - S = *severity* (consequence)
  - O = probability / rate of *occurrence*
  - D = ability to *detect* the failure before the impact is realized
- Risk priority number
  - $RPN = S \times O \times D$
  - Scale 1…10 for each factor

Failure Modes and Effects Analysis



What is special in buildings (façades) ?

- Higher maximum temperature
- Junction box, wiring, (converters) in cavity – higher temperature
- More local shading
- Different types of fixtures
- Coloration / transparency
- Aesthetics as primary quality criterion

Electronics: Integrate converters into the façade?

Project Solaris 416

https://solarchitecture.ch/solaris-416/

Architect Erika Fries

Reliability of power electronic components

Design | Commissioning | Operation

Lifetime estimation

Simulate the **lifetime** of a converter design subjected to a **mission profile**

Select the most reliable architecture

Condition monitoring

Estimates the **state of health** of the most critical components

- Preventive maintenance
- Control for lifetime techniques

Design determines reliability

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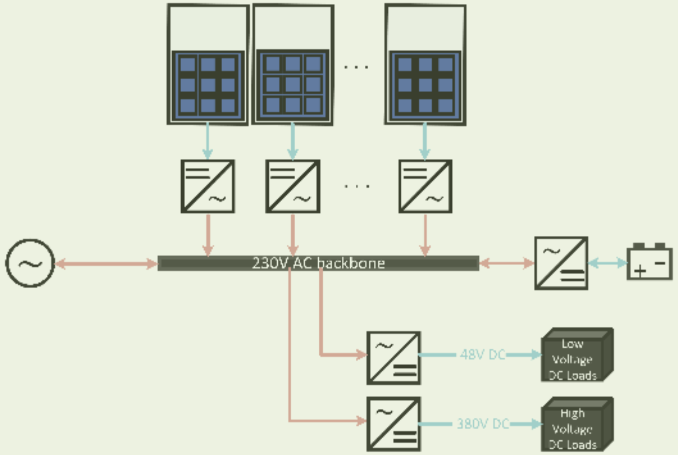
Lifetime estimation models

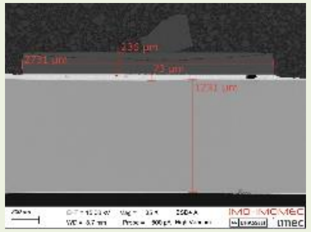
Electrical model

Is known from the system architecture

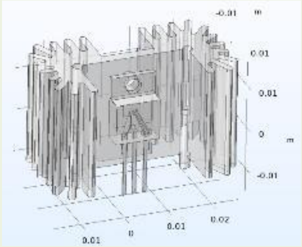


Thermal model

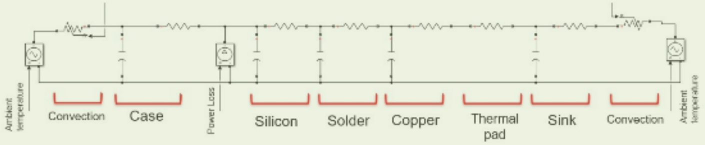
SEM images



Finite element models

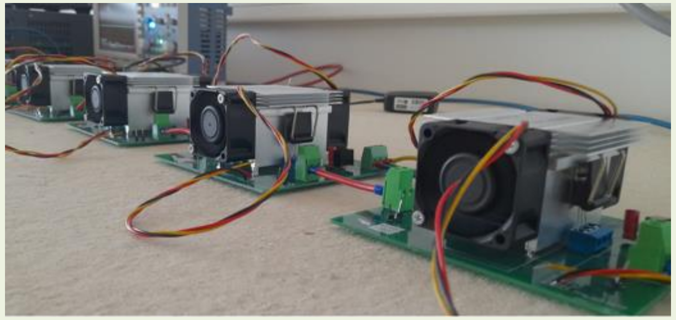


Lumped thermal networks

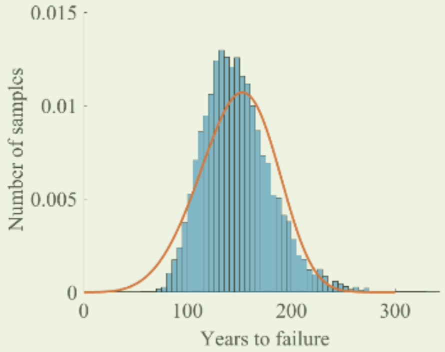


Reliability model

Accelerated power cycling tests



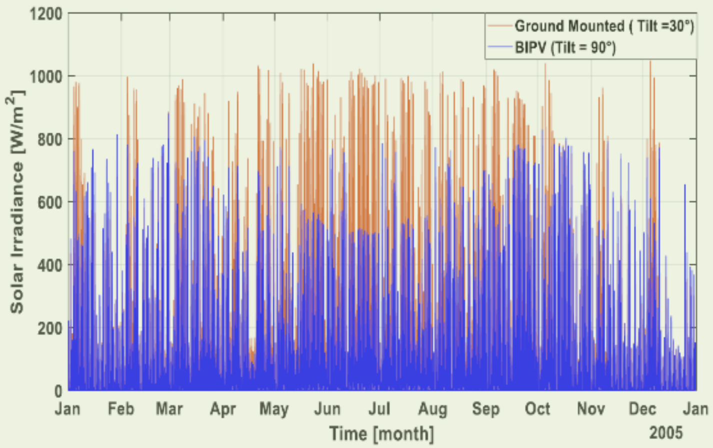
Failure distributions



Lifetime estimation cases

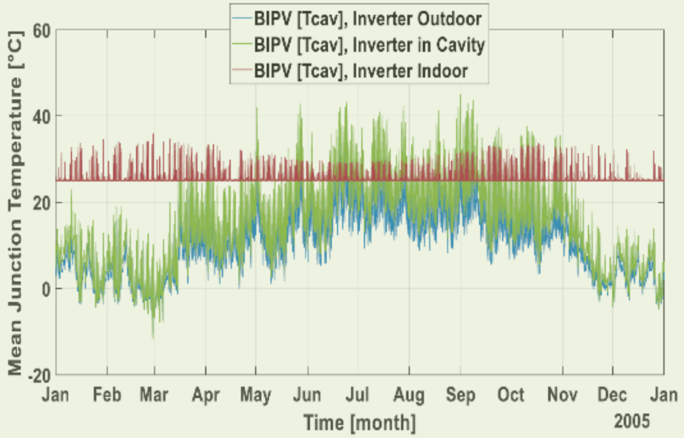
Mission profile

Input data is collected from the DAPPER test setup such as temperature and irradiance profile



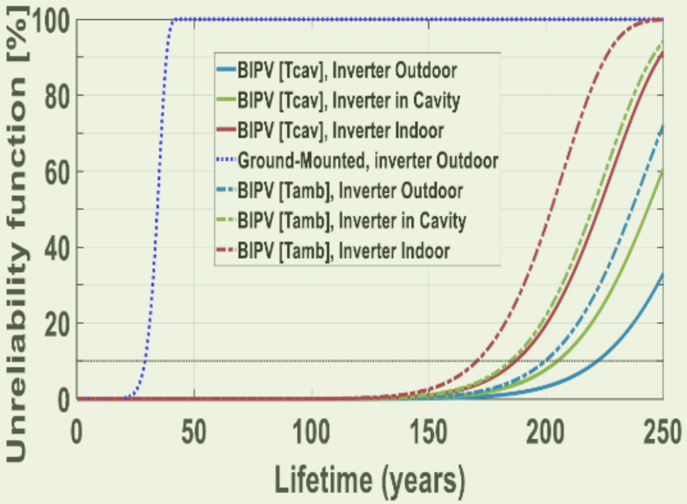
Component internal temperature

The thermal model is used to convert the input data to the component internal temperature for different cases



Unreliability function

Based on the component temperature the expected lifetime can be calculated



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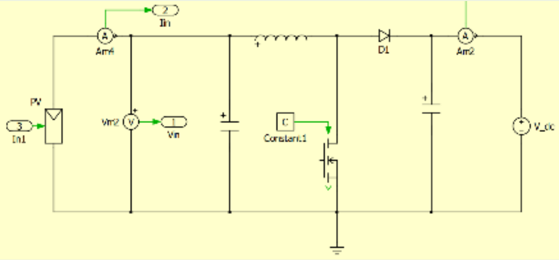
Lifetime estimation cases

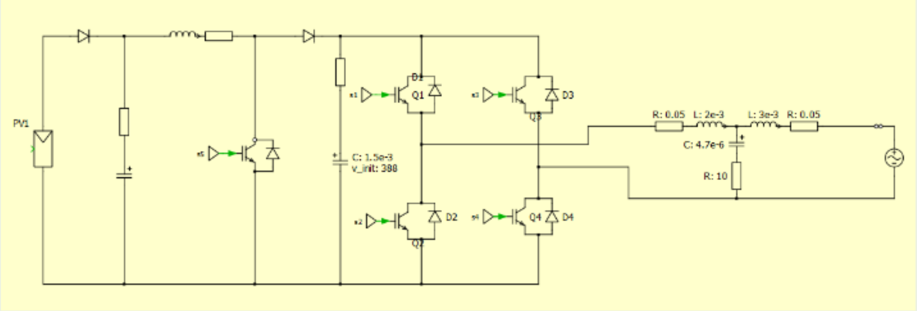
Case study building physics simulation

System architecture

Power optimizers



String inverters



Converter placement

BIPV cavity

Ventilated

Unventilated

Separate zone

Plenum

Plaster

Partially open

Maintenance room

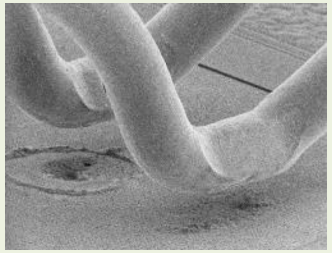
Condition monitoring

Using external parameters to derive the condition of a device

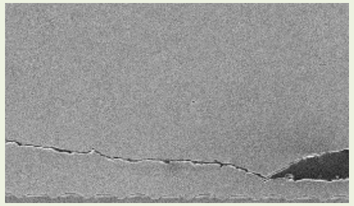
Switching devices are highly important in BIPV

Failure modes

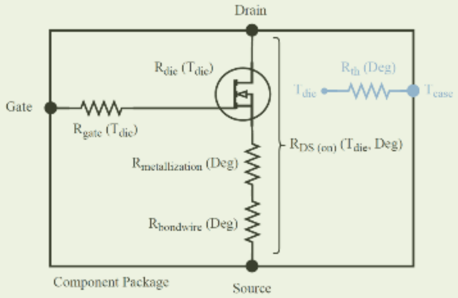
Bond wire degradation



Solder layer delamination



Influenced parameters

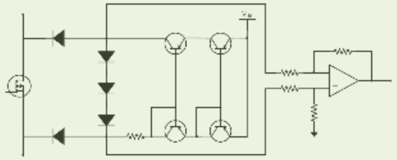


Drain to source resistance

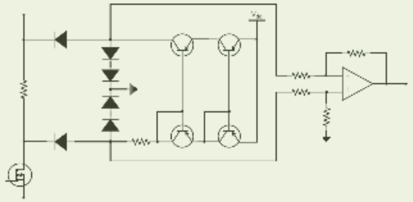
Thermal resistance

Measurement circuits

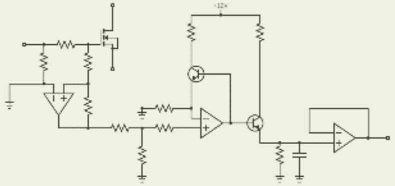
Voltage



current

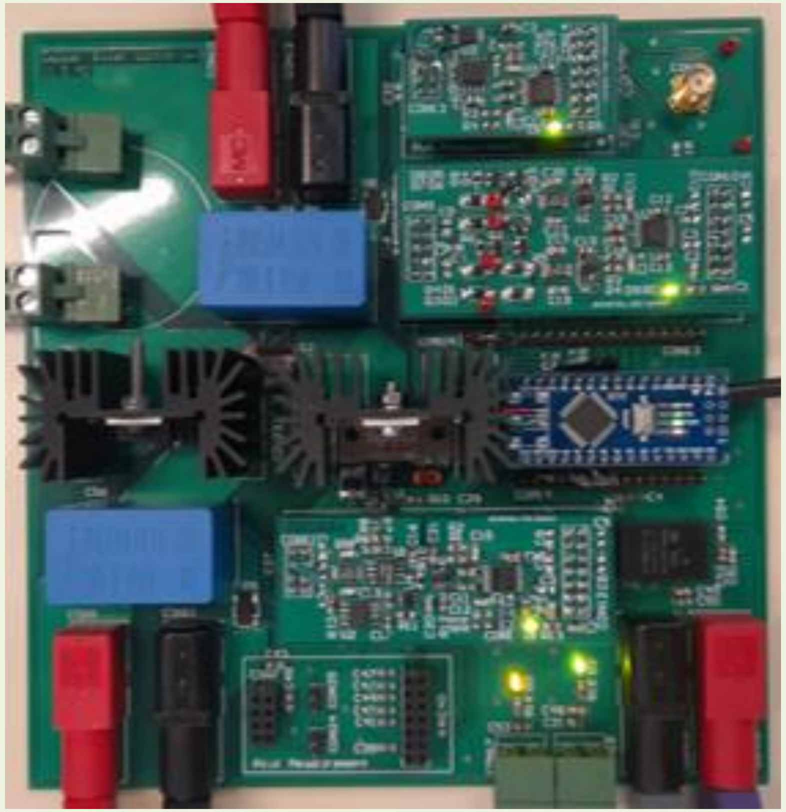


Gate resistance

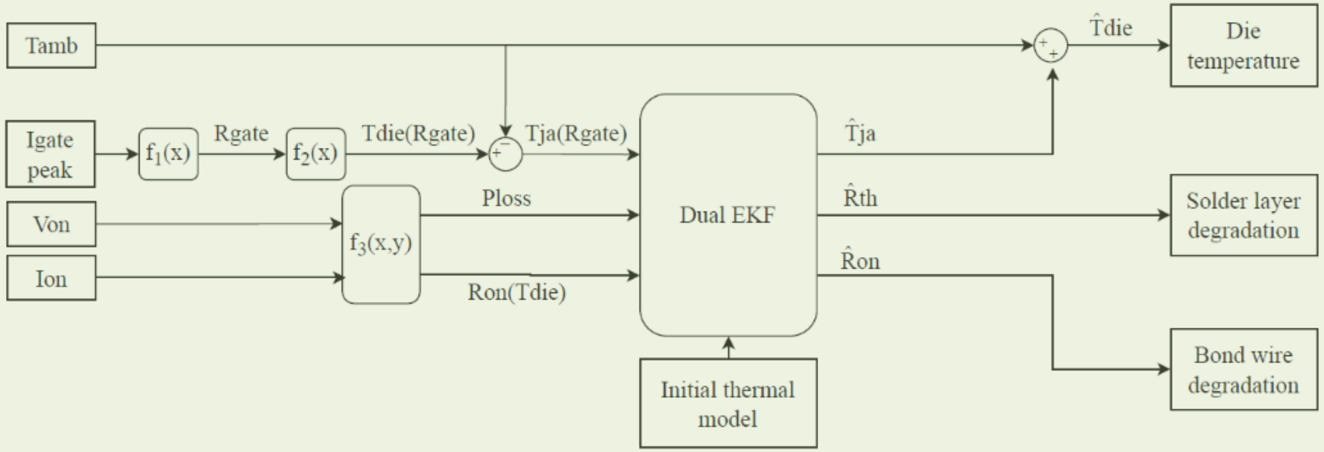


Condition monitoring experimental results

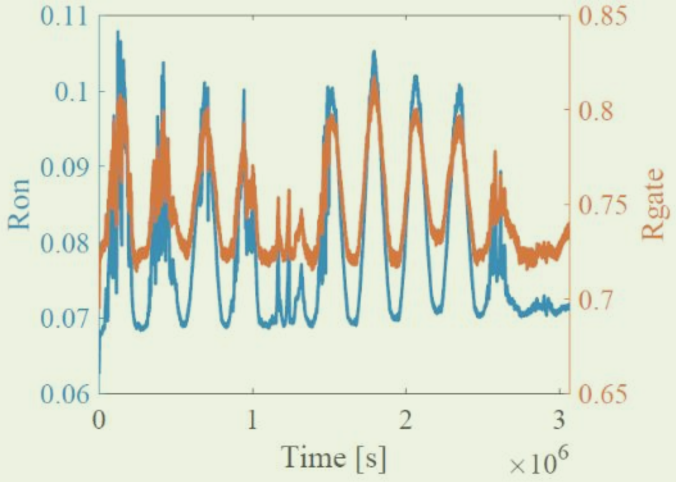
Prototype of module level PV converter with condition monitoring measurements



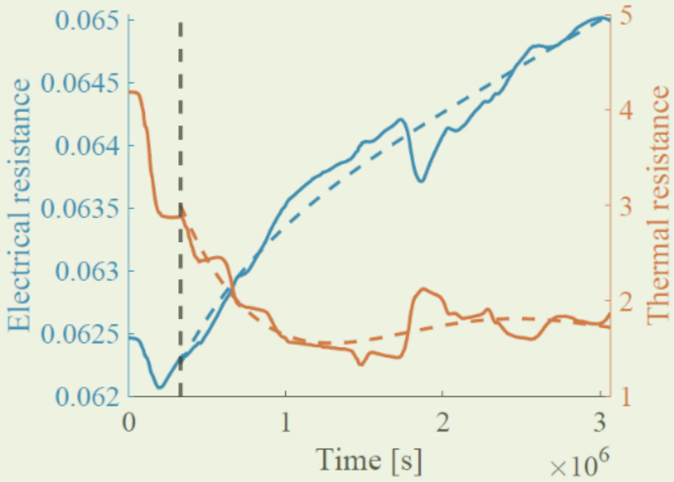
Measurement post processing



Measured signals



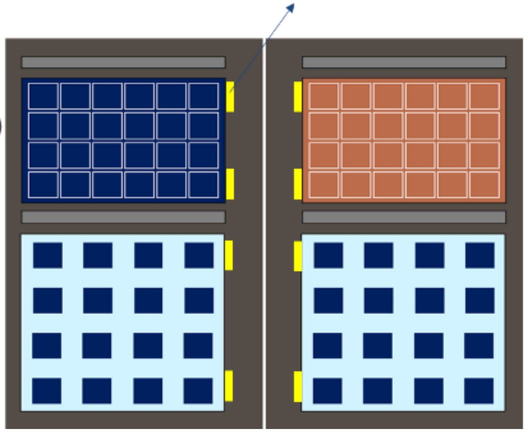
Estimated resistance increase



Demonstrator / test setup

- Simulation and experimental validation of thermal effects in BIPV settings
- Model the effect on lifetime energy yield (degradation)
- Fast E-yield estimation model for systems with many modules and shading patterns

Edge junction box



4x6 cells MW
1010x725 mm2 (with edge j-box)
ClearVision-Black (2x4mm)

4x6 cells MW
1010x725 mm2 (with edge j-box)
Magenta5%-Black (2x4mm)

4x4 cells 5BB
1010x1000 mm2 (with edge j-box)
ClearVision-ClearLite (2x4mm)
➔ For IGU with low-e glass

4x4 cells MW
1010x1000 mm2 (with edge j-box)
ClearVision-ClearLite (2x4mm)
➔ For IGU with low-e glass

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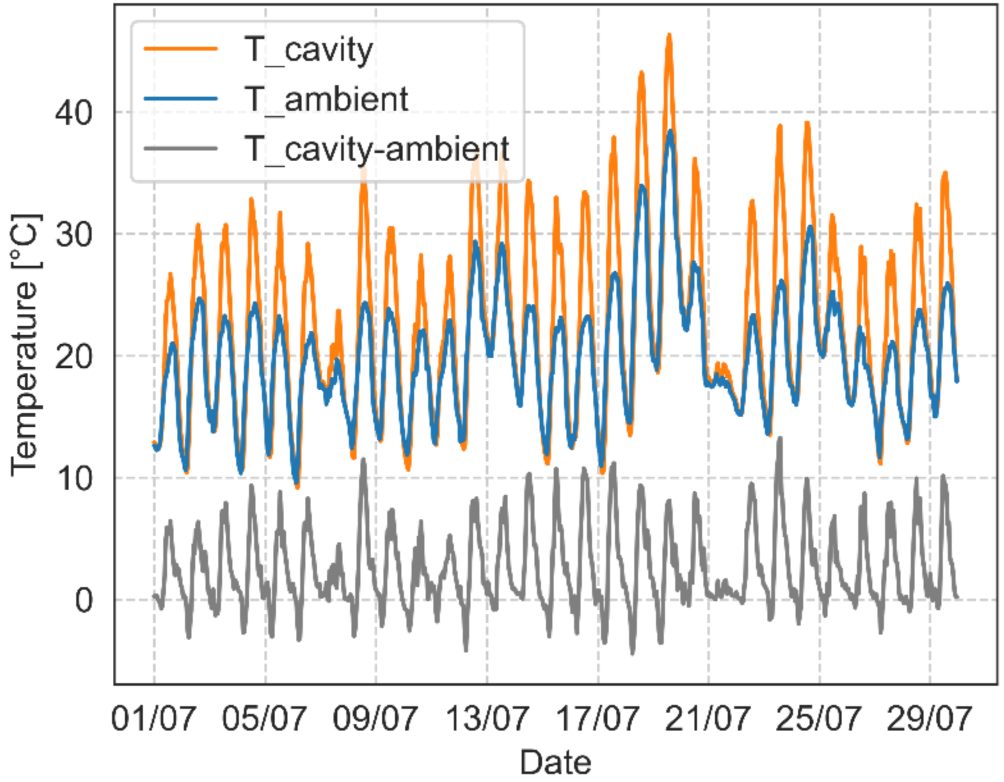
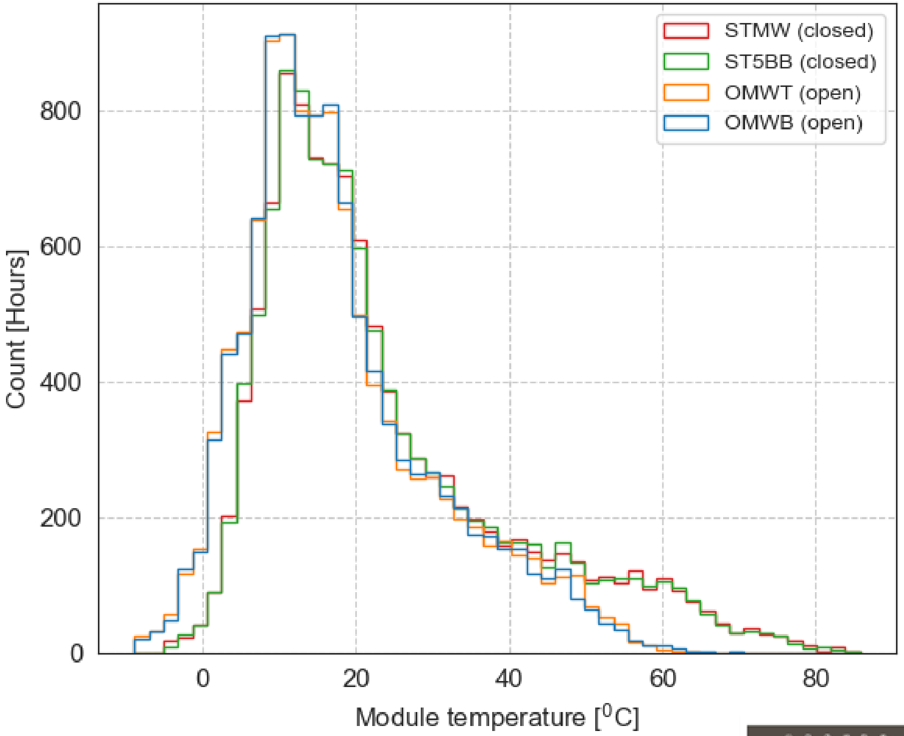
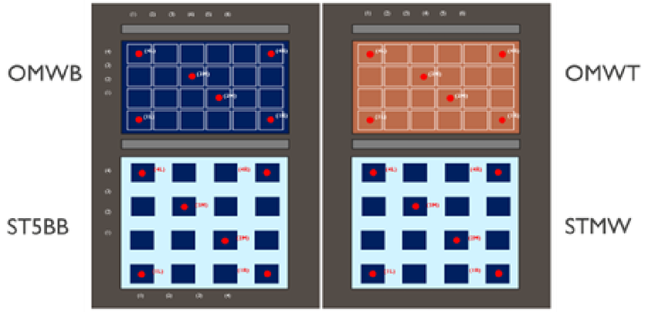
imec

Temperatures in our demonstrator





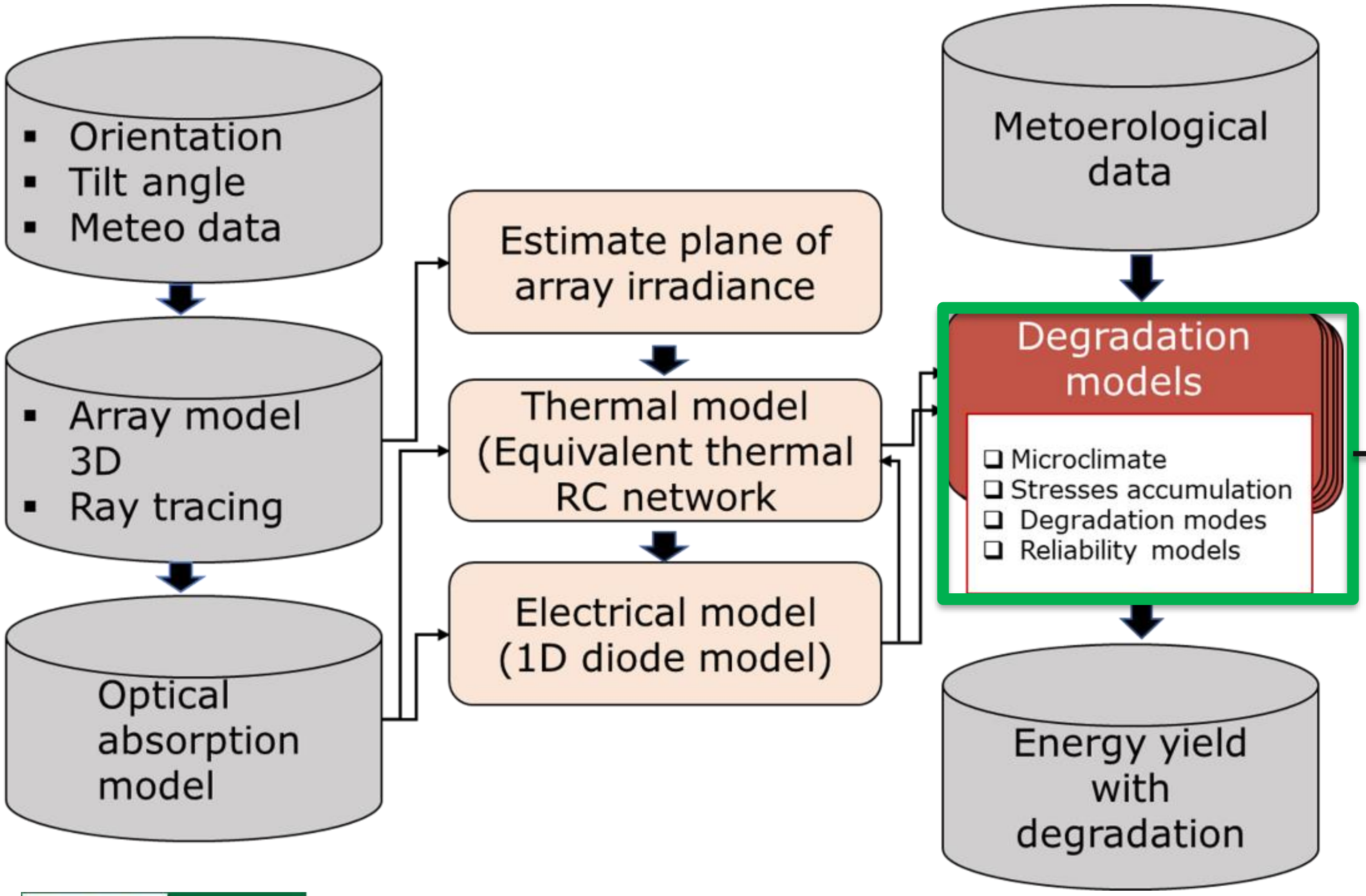


- **Cavity temperature is 5…10° C higher than ambient temperature**
- **Temperature of the magenta module is 0.5…2° C higher than that of the blue module**

Energy Ville

Energy yield framework with degradation

The operating climate conditions will influence the degradation rate and lifetime of PV module → How to account for this in yield simulation?



Bill of material dependency is simulated using the activation energy in the physics-based empirical models

where; $DR_H(\mathrm{T}, RH) = A_H \cdot \exp\left(\frac{-E_{aH}}{k_B \cdot T}\right) \cdot RH^n$,

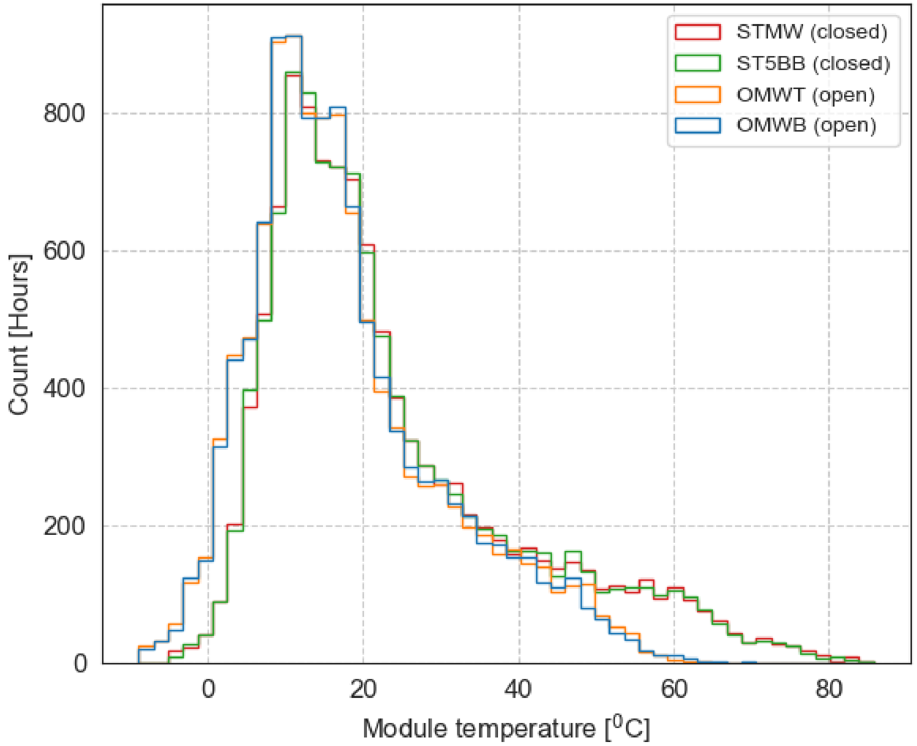
$$DR_P(\mathrm{UV, T, RH} = A_p \cdot UV^y \cdot (1 + RH^{n_1}) \cdot \exp\left(\frac{-E_{aP}}{k_B \cdot T}\right)$$

$$DR_{Tm}(\Delta\mathrm{T}, T_{max}) = A_{Tm} \cdot (\Delta\mathrm{T} + 273)^x \cdot C_r \cdot \exp\left(\frac{-E_{aT}}{k_B \cdot T_{max}}\right)$$

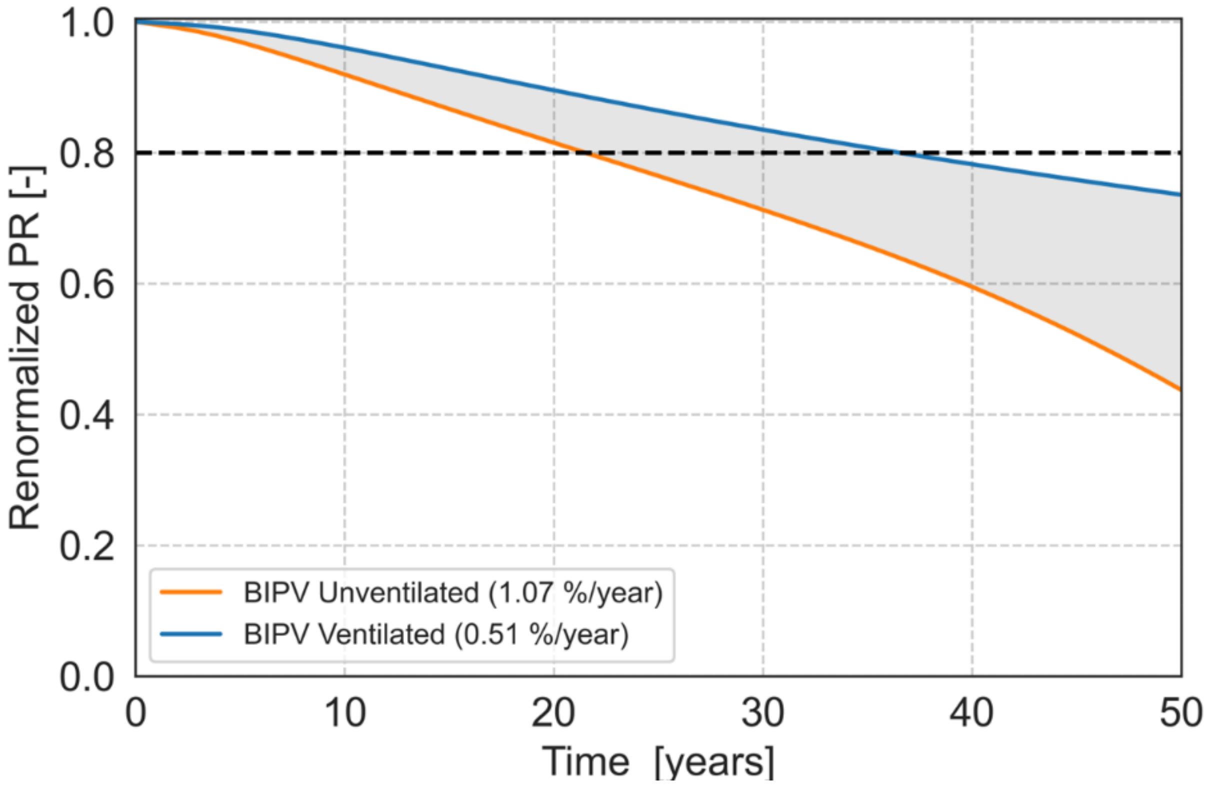
Energy yield framework with degradation

Example → What will be the reliability implication of open Vs closed cavity

Measured module temperature with closed and open cavity for 1 year



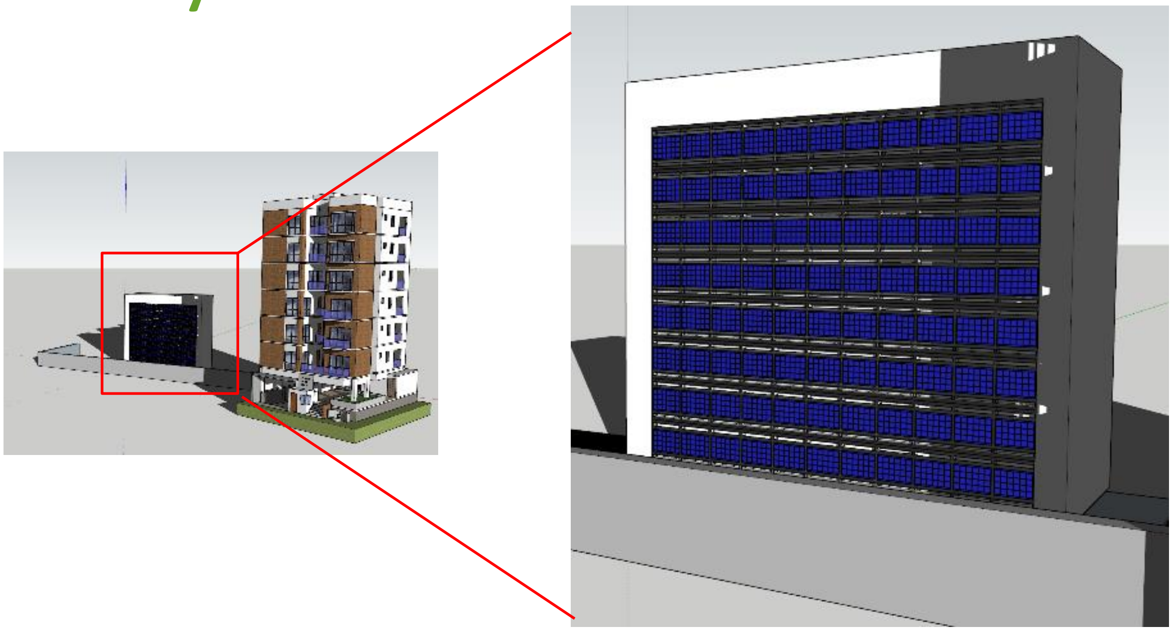
Simulated Performance ratio (PR) degradation for closed and open cavity, Genk

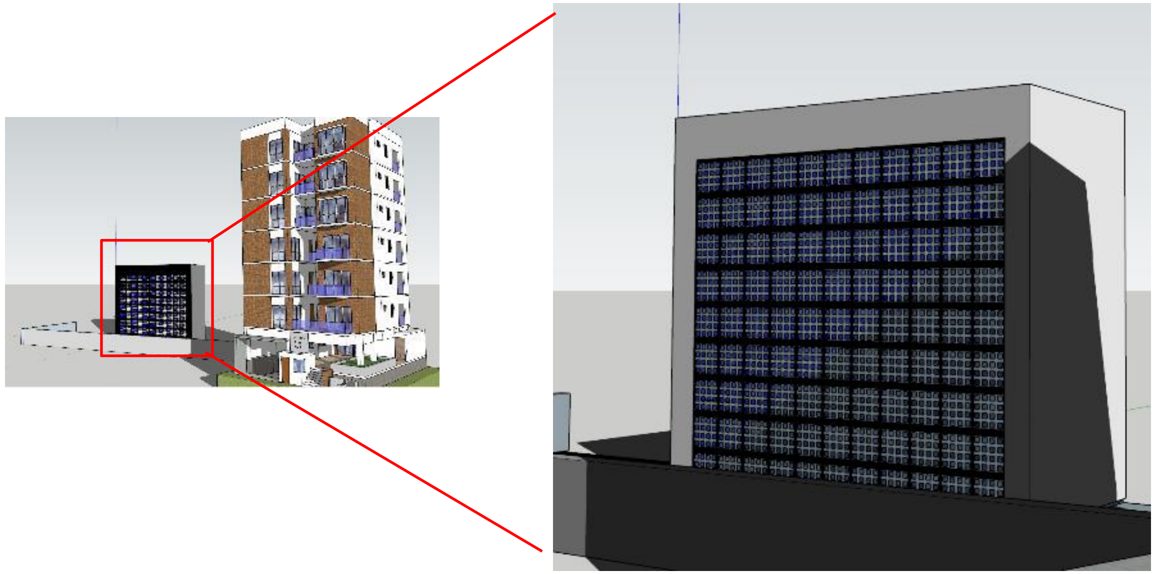


Energy yield model for complex systems

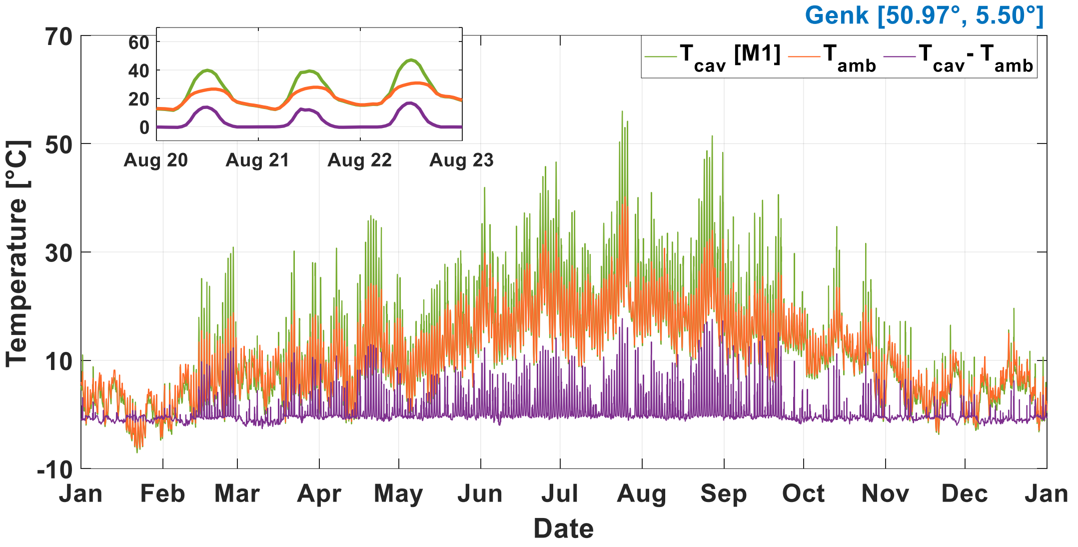
What-if Analysis:

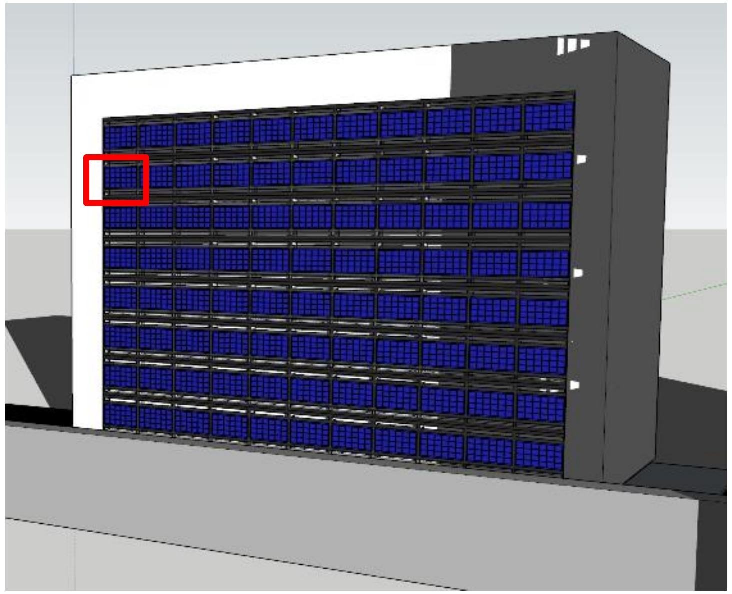
- Analysis 1: Identifying the optimal module interconnection topology for a shaded facade.
  - Different shading scenarios will be considered.
- Analysis 2: Studying the thermal behavior of the partially shaded facade.
  - Performance estimation of shaded and unshaded facade at Belgian and Kuwait climatic conditions.
- Design recommendations will be provided based on the simulation results.

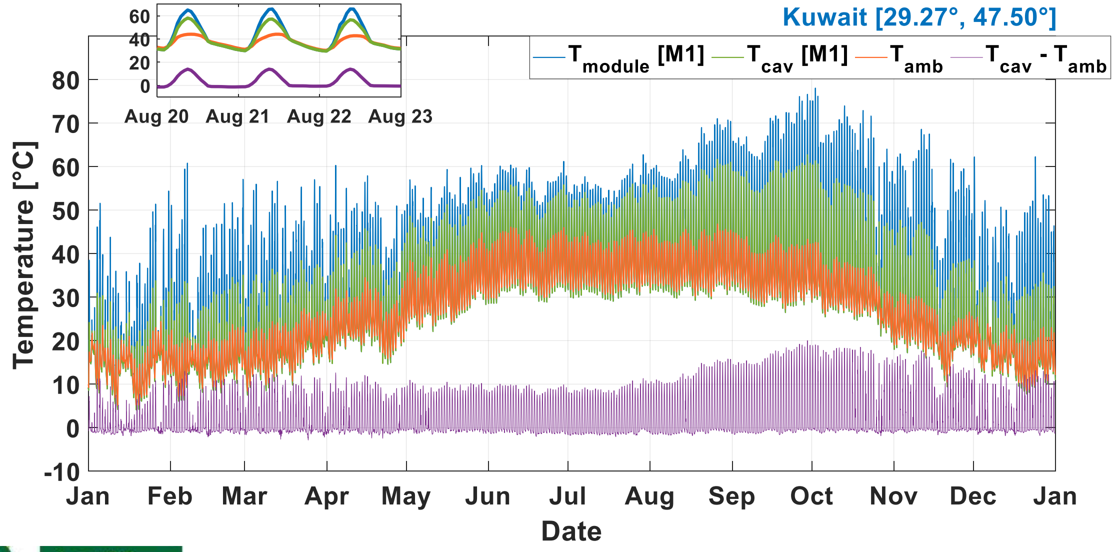


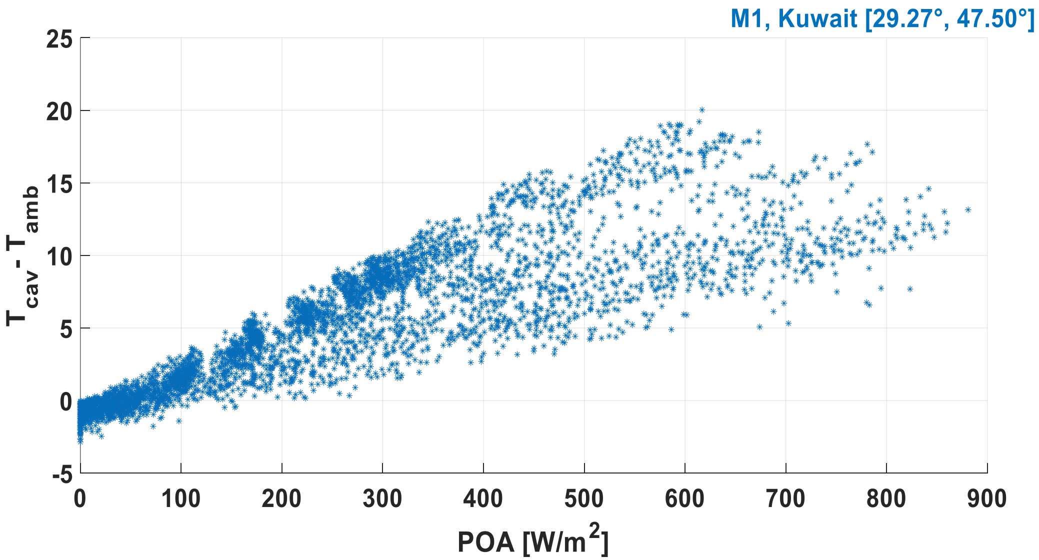


Temperature simulations



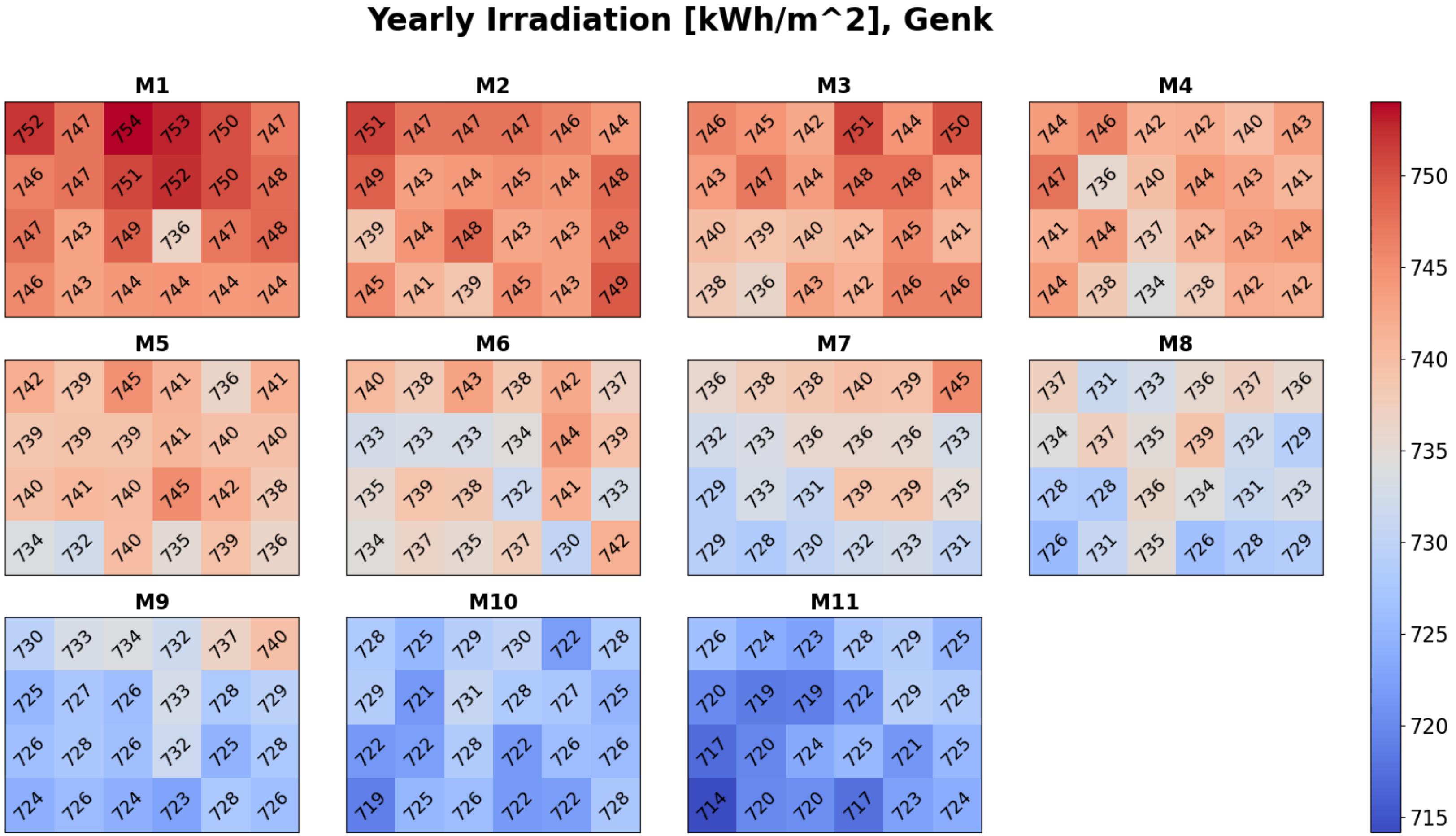






Ville

Energy yield results



Our contributions | More to come

Desire → Plan → Design → Build → Install → Operate

Actor
- Desire: Owner, Project planner
- Plan / Design: Architect ⟷ Engineer
- Build: Module manufacturer, Façade builder
- Install: Construction company, Electrician
- Operate: Owner O&M contractor

Current status

Showcase proj… perf… relia…

Building design …special, …nee… …por…

individu… system …por… …n

…ividual …allation & …ng

No / long-time aggregate monitoring

Impediments

No clear view on options, unknown …

Custom engineering requi…

Co… custom fabrication, …ice of …ectronics

training, too m… i… n…

& … o… n…

Targets / Opportunities
- Proven portfolio NZEB standards
- BIM Standardized offering (cf. windows)
- Modularization, reduced individual engineering
- "Customized mass manufacturing" (semi-automated) dedicated electronics
- Prefabricated bus system, standardized components, training
- automated monitoring, predictive maintenance, integration into BEMS, generation forecasting

Our contributions:
- Co-modeling of PV and building
- Design for reliability
- Performance prediction
  - design
  - operation
  - lifetime effects
- Condition monitoring and fault detection

More to come:
- Test & demonstration
- Link to energy management
- Plug & Play solutions
- Geo-based physics-informed forecasting

KU LEUVEN ConstrucThor Proeftuin voor klimaatneutraal bouwen

Funded by the European Union NextGenerationEU

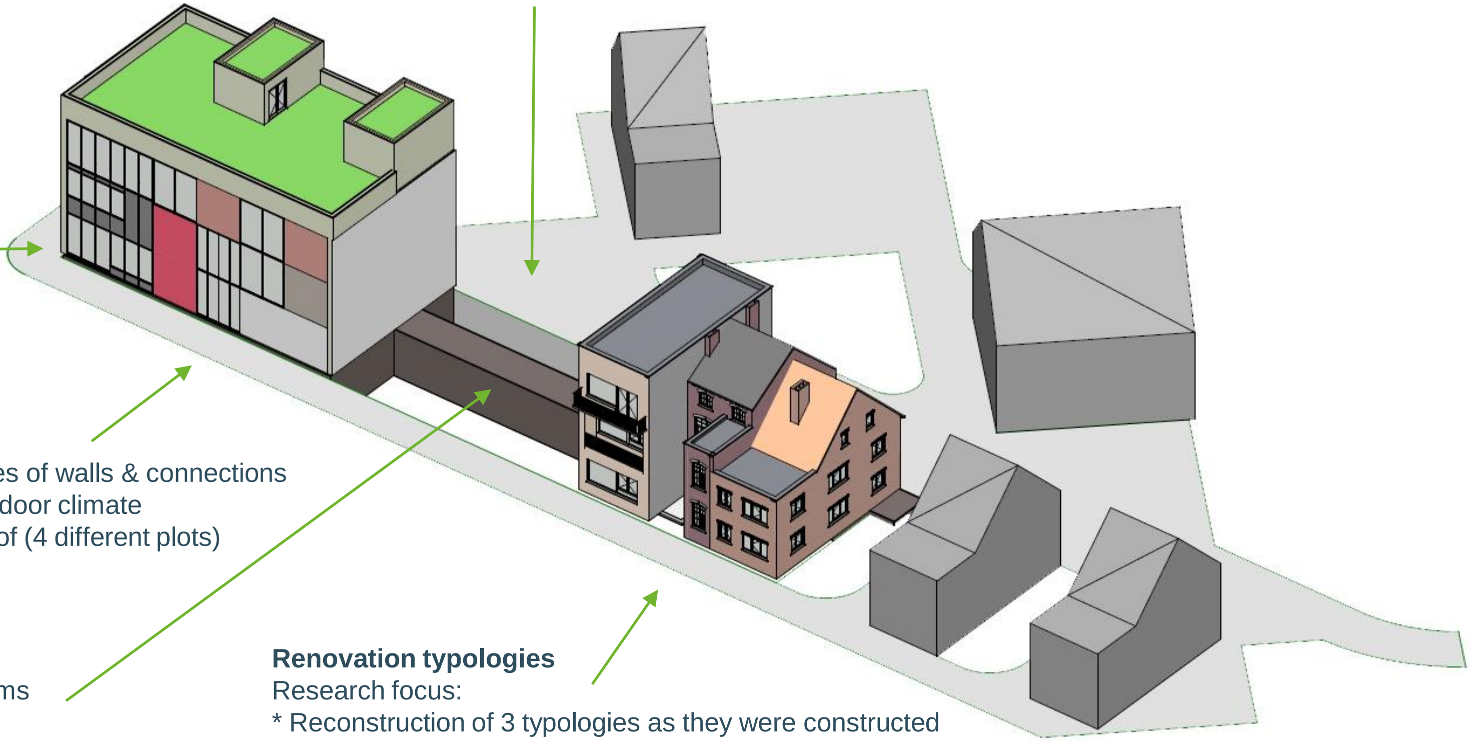
DE VLAAMSE VEERKRACHT

Newly built housing 'plot' & extension possibility for renovation

Research focus:
* New types of housing (eg. Prefabricated units)
* Modularity and circularity
* Maximising DC electricity grid integration
* Energy efficiency proof of concept

Office building with 3 floors

Research focus:
* MPC strategies
* Comfort/stress measurements
* Indoor environment quality with real users
* Interchangeable facades for office typology
* Integration of BIPV shading solutions



Test facade & test roof

Research focus:
* 3,6 x 3,6m grid for tests on different types of walls & connections
* Constant indoor climate, variation in outdoor climate
* Blue-green intelligent water retention roof (4 different plots) & integration of PV

Cellar
* Distribution of different energy systems and data to all the different modules (electrical (AC/DC), warm/cold, ..)
* Storage for batteries
* Connection with THOREAQ project
* Potential connection with district heating system CollecThor
* Space for HVAC installation

Renovation typologies

Research focus:
* Reconstruction of 3 typologies as they were constructed
* Base to test new (integrated) renovation strategies
* Mimicking difficult connections
* Integration of PV in exisisting dwellings
* Acoustical comfort in relation with solutions focused on energy efficiency
* Incorporation of virtual users
* Integration of MPC strategies

Blue-Green Infrastructure (BGI), RESILIO (NL)

Fraunhofer IBP (DE)

KUBIK, Tecnalia (ES)

Skilpod (BE)

KU LEUVEN

ConstrucThor
Proefltuin voor klimaatneutraal bouwen

Funded by the European Union
NextGenerationEU

DE VLAAMSE VEERKRACHT

Timeline

- Co-creation researchers: Aug 22 – Oct 22
- Start sketch design: Nov 22
- Start final design: Jan 23
- Start construction: Mar 24
- Start commissioning: mid 25
- Start first research: Jan 2026

Contact and collaboration

Tim.Verhetsel@kuleuven.be
Staf.Roels@kuleuven.be
Dirk.Saelens@kuleuven.be

https://bwk.kuleuven.be/constructhor

Open Thor Living Lab infrastructure

Onze labo's nog niet gezien?
Kom langs op de Dag van de Wetenschap!

Site KRC Genk stadium

District battery

PV + cha

ection

Residential district

Thermal network (incl

3 modular testbed dwellings (@Thor park)
Energy solutions for 33 dwellings (incl monitoring & BEMS)
Energy & water usage monitoring for 90 dwellings
Renovation 33 dwellings to energy+ level (incl innovative building elements)
Collective energy solutions for 4 dwellings (incl monitoring)

Sustainable energy hub building with integrated PV
Sustainable CHP (incl smart control)
Thermal network (incl heat and cold storage, thermal buffer, control system)
IT platform SmarThor

26 November
11:00 – 16:00

www.energyville.be/nieuws-events/dag-van-de-wetenschap-2

Thank you for your attention!

Questions?

DAPPER is a cSBO project funded by VLAIO under HBC.2020.2144