MILESTONE REPORT

NEXUS

Key performance indicators for energy yield, reliability and outdoor characterization determined and delivered to Task 5.5 for the perovskite tandem sustainability roadmap.

Milestone 8 Report
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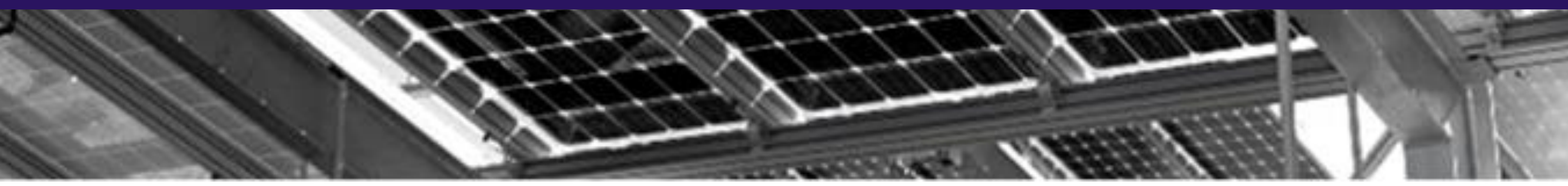
PREPARED BY
Eurac Research
COORDINATED BY
CEA



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NEXUS aims to accelerate Europe's energy transition by developing perovskite-silicon tandem photovoltaic technology, via a new European paradigm: an eco-design approach, based on efficiency, cost, sustainability, circularity and social aspects and using abundant materials. NEXUS aims to develop stable, 2-terminal perovskite-silicon tandem solar cells and modules with high power conversion efficiencies, using sustainable, coherent and competitive European PV production, to create a viable economic pathway for the European commercialisation of this technology.

NEXUS is formed of a multi-disciplinary consortium: 13 partners from 10 countries; 6 industrial partners & 7 RTOs, covering the whole value chain of innovation from research centres to technology providers, end-users and market and policies.

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NEXUS Consortium

Organization name	Short name	Country
COMMISSARIAT A L'ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA	FR
ACCADEMIA EUROPEA DI BOLZANO	EURAC	IT
KARLSRUHER INSTITUT FUER TECHNOLOGIE	KIT	DE
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Abbreviations and acronyms list

Abbreviation	Meaning	Abbreviation	Meaning
2T	Two-terminal	STC	Standard Test Conditions
PST	Perovskite Silicon Tandem	EY	Energy Yield
Rsh	Shunt resistance	PR	Performance Ratio
DF	Degradation factor	Si SJ	Silicon Single junction
HJT	Heterojunction		

1. Executive Summary

This report provides the means of verification of the achievement of Milestone 8 of the project NEXUS: *Key performance indicators for energy yield, reliability and outdoor characterization determined and delivered to Task 5.5 for the perovskite tandem sustainability roadmap.*

1.1. Description of the deliverable content and purpose

This report contains the KPI's for energy yield (EY), reliability and outdoor characterization of NEXUS perovskite silicon tandem (PST) devices, that were determined using a combined effort of EY modelling and outdoor testing of PST cells.

1.2. Relation with other activities in the project

This report relates to the outdoor monitoring activities (see internal deliverable D4.5) and EY simulations (see internal deliverable D4.4 and milestone 4 report) carried out in WP4 and provides input for the sustainability analyses and roadmap developed in WP5.

2. KPI Results

In this section, we present the EY of a two-terminal (2T) perovskite/Si tandem solar cell [1] subjected to combined thermal and light stress in three distinct locations: Phoenix (USA), Seattle (USA), and Bolzano (Italy). Section 2.1 describes the methodology used to obtain these results, while Section 2.2 summarizes and discusses the findings.

2.1. Methodology

Thermal stress is commonly modelled using the Arrhenius equation, while light-induced stress is typically described by a power-law relationship [2-5]. In this study, we adopt these widely used approaches and combine them by multiplying the two expressions to capture the simultaneous influence of both stress factors under real-world conditions:

$$K = A \times e^{-\left(\frac{E_a}{K_B \cdot T}\right)} \times I^{\gamma}$$

K: Degradation Rate
A: Pre-Exponential Factor
Ea: Activation Energy (eV)
K_B: Boltzmann Constant
T: Cell Temperature (K)

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I: Light Intensity (Suns)
γ: Light Exponent

Since degradation accumulates over time, the duration of stress exposure must be explicitly considered. To capture this time dependence, we define the degradation factor (DF) as an exponential function of time. It is important to note that degradation may follow trends other than an exponential decay; however, in this study, we adopt the trend observed in [2].

$DF(t) = C \times e^{-K \times t}$

DF: Degradation Factor
K: Degradation Rate
t: Time
C: Pre-exponential Factor

Under real-world conditions, unlike the constant stress applied in ISOS tests, temperature and light intensity vary dynamically. In our model, these profiles are available on an hourly basis. To account for this variability, the overall degradation factor is expressed as the product of hourly contributions:

$$DF(t) = C \times \prod_{t=0}^{t=tn} e^{-K \times t}$$

Our model investigates degradation at the level of diode parameters, where thermal and light stresses primarily influence properties such as shunt resistance (Rsh), series resistance, collection efficiency, and dark saturation current density. These parameter variations directly influence the solar cell performance metrics (J_{SC}, V_{OC}, and FF) and, consequently, EY [6].

In this work, we focus specifically on the Rsh as an example. It is important to note that the results shown in the next section can be derived using other diode parameters. Considering that the degradation factor evolves over time, the time-dependent collection efficiency is expressed as:

$Rsh\ (t) = Rsh_0 \times DF\ (t)$ Rsh_0: Initial shunt-resistance (measured under STC)

* It is important to note that the initial value of the pre-exponential factor (A) and activation energy are taken from a reference [2] that reports these values under combined thermal and light stress.

2.2. Results

In this section, we present the EY of the 2T perovskite/Si tandem solar cell under combined thermal and light stress at three different outdoor locations. The reference perovskite/Si tandem device was that developed by Longi and achieving an efficiency of 33.7%. Detailed performance specifications of this device are available in [1]. Standard measured PST temperature coefficients were assumed for J_{SC} and V_{OC}.

The reference activation energy considered for this study is 0.495 eV as described in [2]. We present these results for three locations to ensure that our analysis is applicable across different geographical regions and climate zones.

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For the locations in USA, we use the NREL TMY3 meteorological data [7] which is only available for USA, and for Bolzano we use the meteorological data provided by ECMWF [8] for year 2019 (GPOA = 1477 $kWh/m^2/a$).

Phoenix (USA) represents an arid environment, characterized by high temperatures and intense solar irradiance. In contrast, Seattle (USA) has a temperate climate with milder temperatures and lower light intensity. Bolzano (IT) also lies within a temperate climate zone, exhibiting conditions broadly similar to those observed in Seattle.

We first present the annual EY of the perovskite/Si tandem devices under real-world conditions. For a tandem device with a standard test condition (STC) efficiency of 33.7%, our analysis shows that Phoenix achieves an annual EY of approximately 663 kWh/m^2. This value corresponds to a device tilted at the optimal angle of around 27°, which maximizes annual energy output. In comparison, the annual EY for Seattle and Bolzano; both with an optimal tilt angle of around 28°, is approximately 406 kWh/m^2 and 416 kWh/m^2, respectively. As previously discussed, Phoenix yields significantly higher energy due to the greater solar irradiance it receives throughout the year (See Table 1).

Moreover, to provide a benchmark for comparison of the EY received by perovskite/Si tandem to that of a silicon single junction (Si SJ) solar cell, we also indicate the EY of a reference Si SJ solar cell with an efficiency of 26.81% [9]. Our analysis shows that Phoenix is associated with an annual EY of ~496 kWh/m^2, while Seattle and Bolzano yield ~330 kWh/m^2 and ~345 kWh/m^2 respectively (See Table 1).

Our analysis reveals that the degradation in power ratio is most pronounced in Phoenix compared to the other locations (see Figure 1). The results indicate that Phoenix (column a)) experiences a 40% degradation within one year, whereas Seattle (column b)) and Bolzano (column c)) show only a 14% degradation over the same period. This difference is expected, as Phoenix is characterized by higher temperatures and light intensities than Seattle and Bolzano. The degradation observed in Seattle and Bolzano is nearly identical, reflecting their similar climatic zones and comparable temperature and light profiles.

We further compare these findings with the well-known [10] ISOS-L2 tests (1Sun, 85 ˚C) (see Table 1). The comparison between degradation observed under accelerated tests such as ISOS-L2 and that in real-world locations indicates that ISOS-L2 tests correspond to a substantially higher acceleration factor. For example, the T90 measured in ISOS-L2 tests is 15 to 30 times shorter than that observed under real-world conditions. It should be noted that ISOS-L2 employs continuous illumination without day/night cycling, whereas the real-world data naturally includes diurnal variations in light exposure. In addition, ISOS-L2 specifies a fixed test temperature of 85 °C, which is significantly higher than the typical operating cell temperatures recorded at the considered. This difference in light cycling and temperature partly explains the strong acceleration observed under ISOS-L2 relative to outdoor operation.

Finally, we report the T90 of our reference Si SJ solar cell to provide a benchmark for evaluating the degradation of these cells relative to tandem devices. For this comparison, we assume a degradation of 1.5% in the first year, followed by a relative annual degradation rate of 0.4% in subsequent years, which are standard values found in current high-efficiency silicon-based PV module datasheets. Under these conditions, the Si SJ solar cell reaches a T90 of approximately 22 years.

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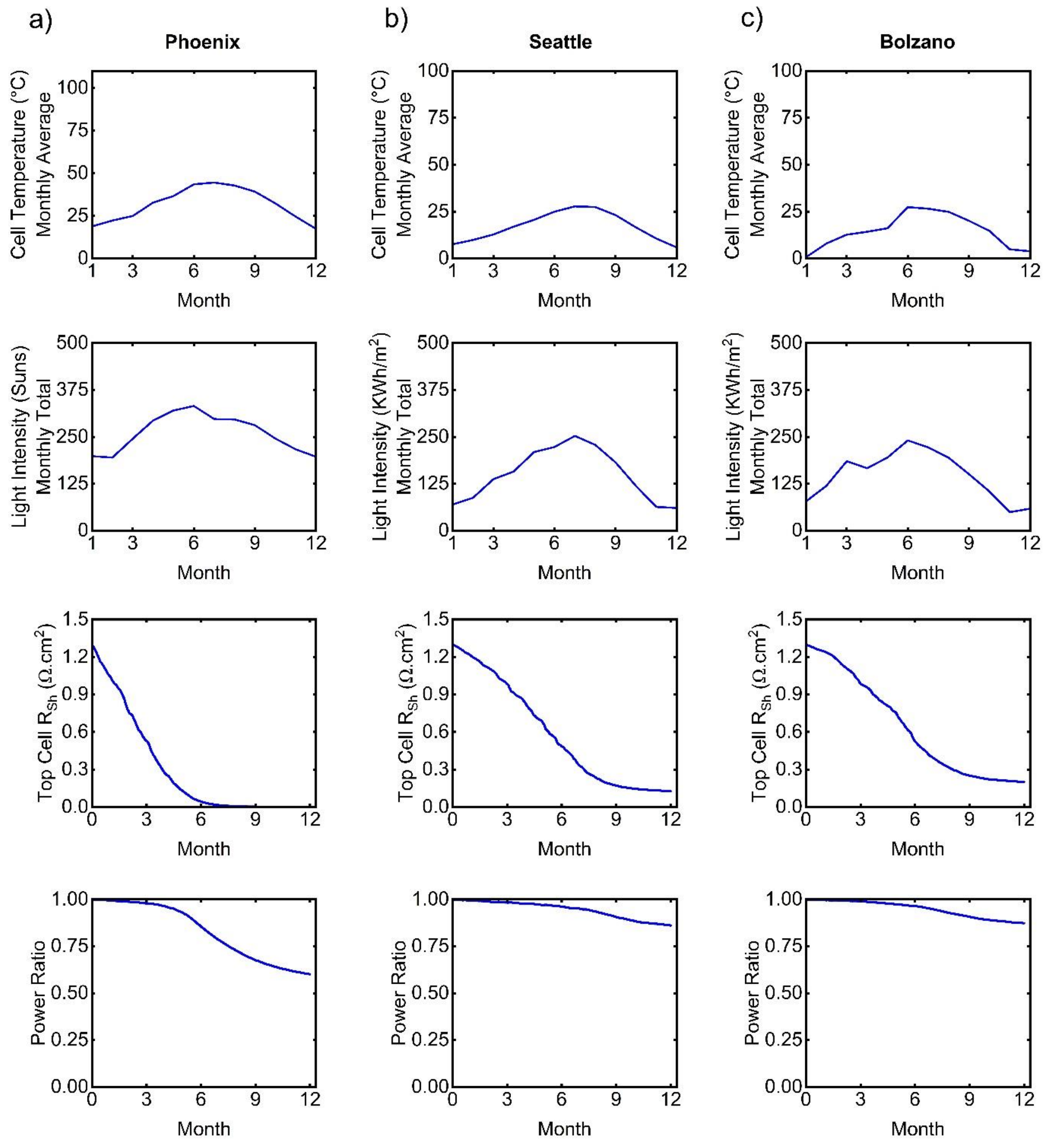

Figure 1- Example illustrating the impact of combined thermal and light stress on the shunt resistance of the perovskite top cell and its effect on the performance of a tandem solar cell at three real-world locations: Phoenix (USA), Seattle (USA), and Bolzano (Italy).

Table 1 – Calculated key energy yield and reliability KPIs for NEXUS PST technology, assuming the degradation behaviours reported in Fig. 1.

#	KPI	Bolzano, Italy	Seattle, USA	Phoenix, USA	ISOS-L2
1	Energy Yield PST (kWh/m2/a)	416.5	406.5	663.0	-
	(Energy Yield Si SJ (kWh/m2/a))	*344.9*	*330.2*	*496.0*	
2	Energy Yield PST (kWh/kWp)	1235.9	1206.3	1967.3	
	(Energy Yield Si SJ (kWh/kWp))	*1287.0*	*1232.0*	*1850.9*	
3	First year degradation PST (%/yr)	13.7%	14%	40%	NA
4	T90 PST (months)	~10	~9.5	~5.5	10 (Days)
5	T30 PST (Years)	9	8	3	20 (Days)

2.3. Comparison with experimental results

From the 3 chosen locations in the previous section, Bolzano – Italy - actually hosts several PST devices for extended monitoring. We propose in this section to confront the calculated data from Table 1 with actual outdoor data monitored in Bolzano in the frame of the NEXUS project.

The outdoor testing setup at Eurac Research in Bolzano was designed to assess the performance and reliability of encapsulated PST cells. This setup has been operational and measuring NEXUS samples since July 26th, 2024, so actually rounding to slightly over a year by the time of writing of the present document. Similar setups have been implemented at NEXUS partners UVEG, in Valencia, Spain, and ODTÜ-GÜNAM, in Ankara, Türkiye. The test setup is shown in Figure 2. Monitoring data over more than 1 year is currently available from Eurac Research, so we focus this report on the latter data.

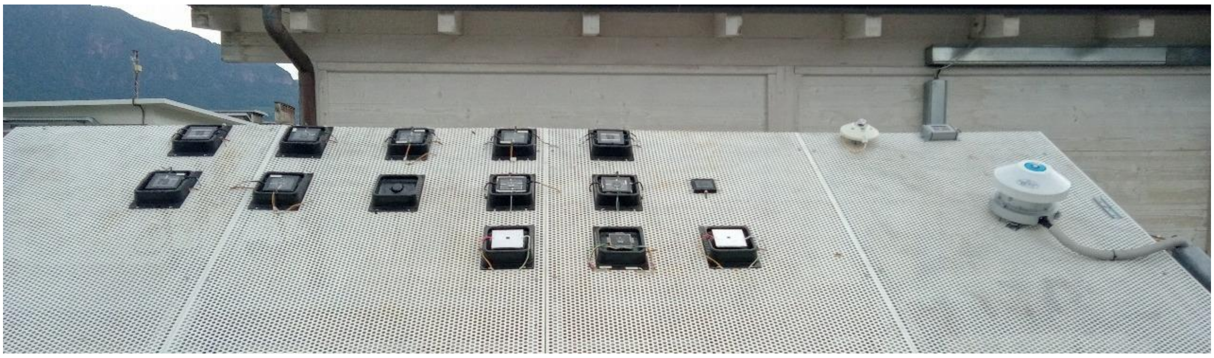

Figure 2- Test setup at Eurac Research

The test equipment for NEXUS' monitoring purposes installed at EURAC includes a mounting frame installed at a tilt angle of around 30° from horizontal and an azimuth of 190° from North (i.e., 10° offset from geographic South), a micro-MPPT (µMPPT) system for monitoring the electrical parameters of devices, and a meteostation (pyranometer and reference cell sensors to measure solar irradiance and environmental conditions).

Figure 3 shows the overall monitoring results of all devices present on the monitoring bench at Eurac Research. Apart from the Si heterojunction (HJT) reference (in black), 9 PST devices are being monitored, with different elaboration processes (different fabrication techniques for the perovskite

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top cell: E=evaporation, H=hybrid process and different morphologies of the Si bottom cell: T=Textured, P=Polished) and sizes (all cells were laminated at CEA). Three sets of samples are being monitored. The first set (in blue tones) has been monitored now for a year, while the monitoring of the second and third sets was first initiated during spring 2025. In order to maximize the relevance of the comparison between simulation and monitoring results, we focus here on those devices from the first set ("B1"), whose monitoring was kicked off roughly a year ago.

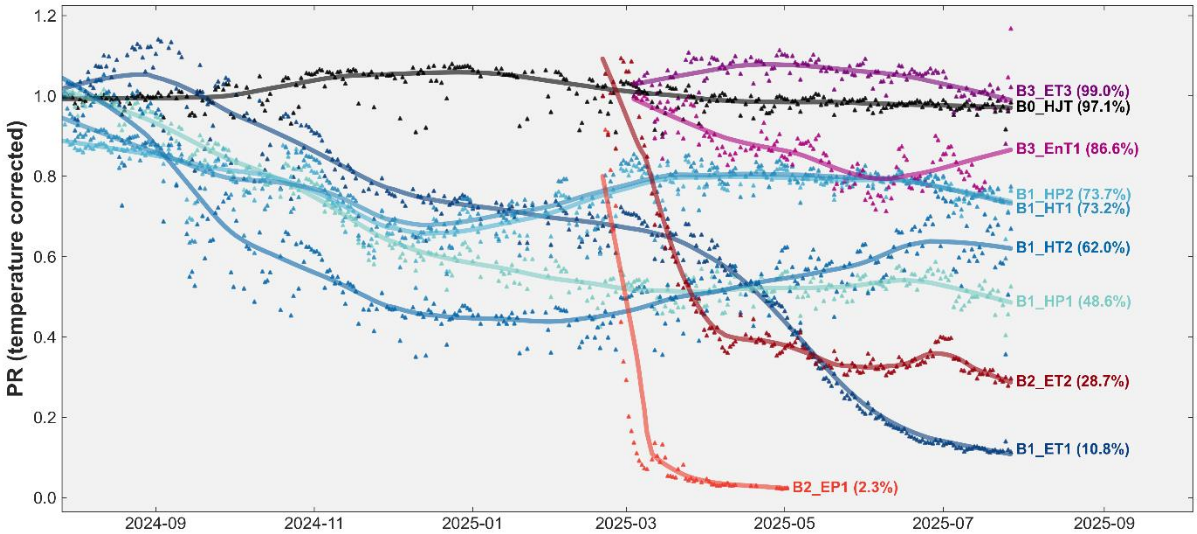

Figure 3 - Overall results at roughly 1 year of monitoring at Eurac Research. Only those samples with one full year of monitoring were used in this report, thereby excluding B2_EP1, B2_ET2, B3_EnT1 and B3_ET3.

As shown in Figure 3, degradation trends are very device-dependent. It is obvious that the mechanisms at play varies greatly from one device to the next. It can also be expected that the degradation mechanisms (not just their amplitude) are rather diverse for all samples.

Table 2 shows a comparison of the simulated 1st year Performance Ratio (PR) losses with the different values measured on monitored devices. Regarding the reference HJT sample, the first year PR loss is around 2%, which is in line with expectations for such devices and supports the validity of the monitoring setup. Turning to PST samples, the PR losses for this first year are between 12.0% (B1 HP2) and 90.4% (B1 ET1). With losses spanning such a large range, it does not come as a surprise that a unique activation energy (for the working hypothesis of a Rsh degradation) is not able to reproduce all results. Nevertheless, the simulated value of 13.7%, derived assuming the activation energy from literature, appears to be in fair agreement with the 1-year degradation measured for the two most stable devices, B1 HP2 (12.0% degradation) and B1 HT1 (18.6%)[1]. It can also be observed that the PR evolution also shows some improvement periods, which suggests that part of the PR losses may be reversible.

[1] The discerning eye will have noticed the difference in trends, with simulated results showing continuous degradation over the year, while some devices actually do show some extent of recovery in late spring/summer. Understanding the healing/recovery mechanisms and the influence of external stressors, as well as modeling them, are surely topics of high relevance to better predict and increase the annual energy yields.

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The result of this comparison calls for two comments. First it provides credibility to the annual degradations given in Table 1, and paves the way for longer-term degradation models. Second it confirms current knowledge that device stability is a key challenge and that there is still room for improvement in this direction.

Table 2 – Comparison of the first-year loss as derived from simulations and outdoor monitoring for the localisation of Bolzano, Italy.

	First year loss %		Annual EY year 1 (kWh/kWp)	
	Experimental	Simulation	Experimental	Simulation
B1 HP1	50.0	13.7	882.0	1236
B1 HT2	40.1		784.6	
B1 HT1	18.6		1102.6	
B1 HP2	12.0		1215.6	
B1 ET1	90.4		777.5	
Ref HJT	*2.0*	*1.5*	*1341.3*	*1287*

Table 2 also shows the Annual EY for the 1st year for both the PST and the HJT cell for the 3 selected locations. The EY are expressed in kWh/kWp in order to rule out the effect of the different starting efficiencies assumed in the simulation vs the practical devices, thereby allowing to intrinsically quantify how much energy can a given technology generate per unit peak power installed. The experimental data were corrected to account for the difference in GPOA between simulation (1477 kWh/m^2/a) and experiments (1421 kWh/m^2/a) using a simple rule of thumb. As can be seen, the EY calculated for the ref HJT sample is in fair agreement with simulation, once again supporting the validity of simulation and monitoring. In a similar fashion as for the 1st year PR losses, the simulated EY shows a very good agreement with the experimental values for the best device (B1 HP2), with 1236 kWh/kWp vs 1215 kWh/kWp. While such agreement is a *per se* a good achievement, it may yet appear somehow fortunate given the differences in the trends between simulation and measurements (the latter showing ups and downs which is not reflected in the simulations), and given the variety of behaviors observed in this study. Nevertheless, this underlines the potential of the modelisation platform developed here towards the simulation of the outdoor behavior of PST devices.

3. Concluding remarks

A first version of the KPI for the PST technologies investigated in the NEXUS project was provided and compared with experimental data.

Using simulation, PR losses (i.e., degradation rates) from 13.7 to 40% for the first year was found for the different locations investigated here, namely Bolzano, Phoenix and Seattle. The result for Bolzano (13.7%) was compared to first-year degradation results measured on the test bench installed at Eurac Research. A good quantitative agreement was found for the most stable monitored devices, that feature first-year degradations in the range of 12.0 to 18.6%. This fair agreement supports to some extent the validity of the simulated first year degradation rates provided herein. It also underlines the significant room for improvement that still exists with regards to improving device outdoor stability.

Note that the wide range of PR losses observed in practice reveals strongly device-dependent degradation amplitude and mechanisms, suggesting that simulating such devices would require a

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deeper knowledge of the degradation pathways and failure modes of the different PST devices. It also suggests that any attempt to calculate PR losses on the mid- to long-term likely lack generality/accuracy. To improve simulation the situation, monitoring data over longer timescales, narrowing sample-to-sample variability and improving knowledge of the degradation mechanisms (among others) should be of paramount importance to ultimately develop better degradation models.

The 1st year EYs were also calculated from simulation results for the 3 locations and confronted to experimental values for the case of Bolzano. A fair agreement was found between simulation and best devices, and residual discrepancy sources were listed. In good agreement with simulation, it is also found that the investigated PST devices do not produce more kWh per kWp than the ref SJ, which should be a direction for future research (transient behaviours over the course of the day, or shunt issues may pin the production down).

The key take-away values are recalled here below for the sake of clarity of the document.

#	KPI	Bolzano, Italy	Seattle, USA	Phoenix, USA	ISOS-L2
1	Energy Yield PST (kWh/m2/a)	416.5	406.5	663.0	-
	(Energy Yield Si SJ (kWh/m2/a))	*344.9*	*330.2*	*496.0*	
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	(Energy Yield Si SJ (kWh/kWp))	*1287.0*	*1232.0*	*1850.9*	
3	First year degradation PST (%/yr)	13.7%	14%	40%	NA
4	T90 PST (months)	~10	~9.5	~5.5	10 (Days)
5	T30 PST (Years)	9	8	3	20 (Days)

Due to the variation in sample behaviours in the field, these results rather reflect the behaviour of the best samples of this study, and a wider use of these KPIs should therefore be considered with due care. In any case, as the PST technology is improving fast, the KPIs will have to be updated on a regular basis.

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