

**DELIVERABLE REPORT**



**4.1: Bankability report  
for a tandem PVS<sub>K</sub>/Si  
module based on  
outdoor measurements**

**Deliverable D4.1  
October 2025**

**PREPARED BY  
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NEXUS is a 3-year research and innovation project funded by the European Commission through the Horizon Europe Research and Innovation Action (RIA) grant N°101075330, responding to the call for a “Sustainable, secure and competitive energy supply” (HORIZON-CL5-2021-D3-02).

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.

<b>Project info</b>	101075330 – NEXUS – HORIZON-CL5-2021-D3-02-04
<b>Deliverable Title</b>	D4.1 : Bankability report for a tandem PVSK/Si module based on outdoor measurements
<b>Lead Beneficiary</b>	
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<b>Approved by</b>	
<b>Dissemination level</b>	Sensitive/Public
<b>Due date</b>	October 2025
<b>Submission date</b>	
<b>Version</b>	V1
<b>Linked to WP - task</b>	Task 4.1: Device Modelling and Energy Yield (EY) Modelling Task 4.3: Performance and reliability assessment of perovskite/Si tandem technology under real-life conditions Task 4.4: Towards a Bankable Pero/Si Tandem PV Power Plant WP5 on resource efficiency and sustainability, economic and life cycle assessments

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### How to Cite

J. Veirman and C. Polacchi (2025). Deliverable 4.1. in Project NEXUS: Next Generation of Sustainable Perovskite-Silicon Tandem Cells (No. 101075330). European Union. SENSITIVE [Communicate on DD/MM/YYYY].

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## Abbreviations and acronyms list

Abbreviation	Meaning
ALD	Atomic Layer Deposition
BOM	Bill-of-Materials
BOS	Balance-of-System
c-Si	Crystalline silicon
DH	Damp Heat
HJT	Silicon Heterojunction
IEC	International Electrotechnical Commission
LCC	Life Cycle Cost
LCOE	Levelized cost of electricity
MCDA	Multi criteria decision analysis
NEXUS	Next generation of sustainable perovskite-silicon tandem cells (Horizon Europe project)
NPV	Net present value
O&M	Operation and Maintenance
PCE	Power conversion efficiency
PST	Perovskite-silicon tandem
PR	Performance Ratio
PV	Photovoltaic
HJT	Silicon heterojunction
PVD	Physical Vapour Deposition
STC	Standard Test Conditions
TC	Thermal Cycling
WACC	Weighted Average Cost of Capital
WP	Work Package

### 1. Executive Summary

In this report, we gather the information available at the conclusion of the NEXUS project to provide a basis for an early bankability assessment of the tandem perovskite–silicon (PST) technology developed within the consortium. We begin by reviewing and discussing the main strengths and weaknesses identified during indoor and outdoor testing (Section 2). After recalling the Levelized Cost of Energy (LCOE) framework and model assumptions established in Deliverable D5.1 (Section 3), we present updated and extended LCOE calculations (Section 4). These are based on the latest cost estimates and outdoor stability data generated in the project, for a 1 GWp fixed-angle utility-scale PST plant located in Southern Europe.

Specifically, we use the degradation rates observed on practical devices during their first year of outdoor monitoring (from WP4) and define two additional long-term degradation scenarios informed by both literature and project results. The concluding section (Section 5) provides a general call to action for the next steps towards technology bankability.

Recent indoor results confirm the solid progress achieved throughout the project, with encouraging stability under Damp Heat and Thermal Cycling tests. Outdoor results demonstrate a year-on-year degradation rate of approximately 13% for the best device. Although this represents an improvement compared with literature, it still calls for further enhancement, as such degradation directly impacts the attainable LCOE. The analysis of different scenarios conducted here confirms the strong potential of PST to outperform mainstream crystalline silicon (c-Si) technologies—provided that operational lifetime and degradation rates meet the expected targets, the values of which are discussed in detail for different starting efficiency levels. Based on the overall findings, we briefly highlight the remaining

techno-economic gaps that must be addressed to enable a robust bankability assessment.

### 1.1. Description of the deliverable content and purpose

This deliverable combines data collected from the different tasks in WP5, WP4 and WP3 to 1) identify key technology strengths and weaknesses in indoor/outdoor operation, 2) “long-term” energy yield estimates, as available by the time of reporting. These data will be used to determine LCOE including an assessment of exceedance probability of LCOE and energy to provide the first elements towards an assessment of the PST bankability.

### 1.2. Relation with other activities in the project

D5.1 – LCC assessment from cradle to cradle with LCOE target of 2 cents/kWh (South Europe): methodology and input parameters

WP3 – Indoor testing results

D3.1 - Cost model for industrial scale production of perovskite/silicon tandem solar cells: methodology and input parameters

## 2. Summary of key results from indoor and outdoor testing

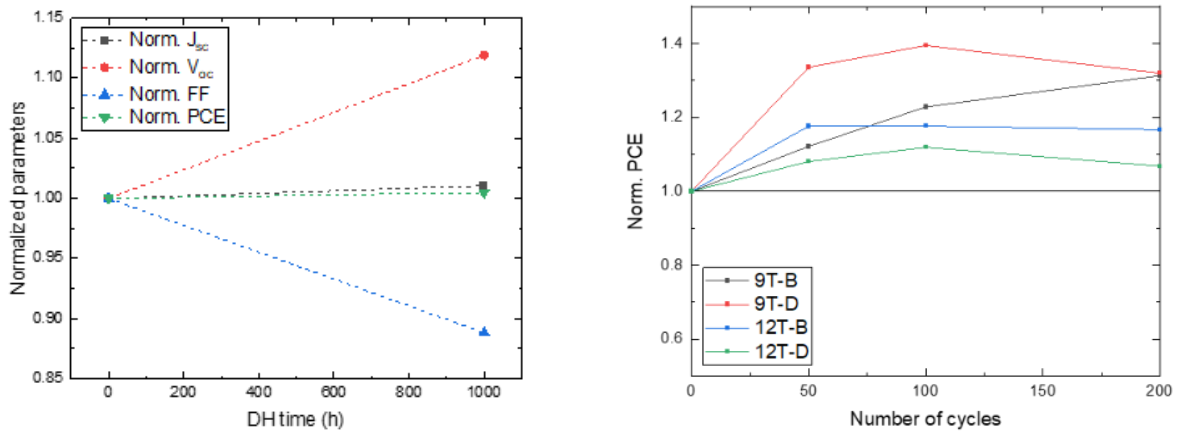
### 2.1. Indoor testing results

The IEC has established a series of standard test to ensure the performance, safety and durability of photovoltaic modules under real world conditions. During the NEXUS project, some of these standard tests, such as Damp Heat and Thermal Cycling, have been evaluated.

Damp Heat (DH) testing is designed to reveal a module’s susceptibility to humid conditions by exposing the photovoltaic panel to 85°C and 85% relative humidity for 1000 hours, while Thermal Cycling (TC) assesses if the module is affected by temperature fluctuations by subjecting it to repeated cycles ranging from -45°C to 85°C, typically 200. Those tests were performed on single 1 cm<sup>2</sup> tandem cells built by different partners in the consortium and laminated at CEA, where the reliability was also investigated. A power degradation exceeding 5% is considered a failure under IEC qualification standards.

The DH test resulted in an 11% degradation in fill factor (FF), which was offset by a 12% increase in open-circuit voltage ( $V_{oc}$ ), leading to no efficiency losses after 1000 hours of stressing. Additionally, no visible sign of moisture ingress in the laminates was observed. Similarly, TC stressing test showed an improvement in Power Conversion Efficiency (PCE) after 200 cycles, due to increased  $V_{oc}$  and stable fill factor, with no evidence of delamination. The evolution of the PCE for both stress is shown in Figure 1 (Figure 1 Evolution of cell parameters (short-circuit current  $J_{sc}$ ,  $V_{oc}$ , FF and PCE) upon DH stressing (left) and of PCE upon TC (right)).

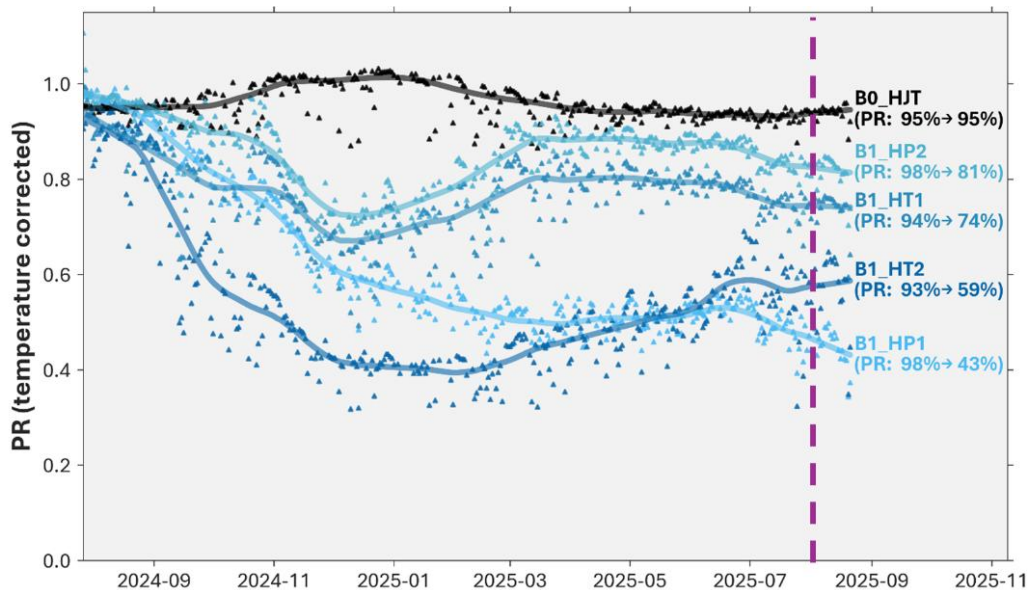
IEC stress tests play a crucial role in identifying potential weaknesses in the cell stack and materials chosen for encapsulation and to anticipate the behaviour under real world condition. **The reliability studies conducted during NEXUS demonstrate the potential of perovskite-silicon tandem cells by passing two of the most critical stress tests. These tests validate the selection of materials used to encapsulate the cells, demonstrating their ability to protect the cells against harsh environment.** As highlighted in Milestone 6 report, more critical stress test such as UV exposure should also be investigated for this type of technology, as they are part of the IEC standard. However, the outdoor performance testing discussed in the following paragraph is a complementary investigation that offers broader insights into the NEXUS cells behaviour beyond controlled laboratory conditions.



**Figure 1 Evolution of cell parameters (short-circuit current  $J_{sc}$ ,  $V_{oc}$ , FF and PCE) upon DH stressing (left) and of PCE upon TC (right)**

## 2.2. Outdoor testing results

As per July 2024, several PST devices were prepared by Oxford University and laminated either at CEA or within Oxford Uni’s premises. The samples were dispatched to FHNW, Eurac Research and Odtü-Günam for outdoor testing. In this deliverable, we focus on those results with significant outdoor monitoring days so that a yearly degradation rate can be estimated experimentally and used as input into the LCOE calculations detailed in section 4. Given some technical issues and delays in the delivery/installation of samples outdoors, sufficient monitoring durations could only be reached at Eurac Research, and for that reason, this report focuses here on those results obtained at Eurac Research, Bolzano, Italy.



**Figure 2 Samples with > 1 year monitoring at Eurac Research, Bolzano, Italy. The PR values shown between brackets correspond to the full monitoring duration plotted on the graph (13 months).**

These results, together with early results obtained at the other partners’ locations, are presented in detail in deliverable *D4.2 Full assessment of degradation mechanisms in NEXUS high performing*

PVSK/Si modules (> 12 months), and the reader is directed to that report for more information. Figure 2 shows the temperature-corrected Performance Ratio (PR) for 4 samples that feature > 1 year monitoring with no hard failure throughout that period, benchmarked with a silicon heterojunction (HJT) sample encapsulated with the same materials and in the same conditions as the PST samples. All samples are part of the first batch of samples that were delivered during summer 2024. They all feature a hybrid process for the perovskite deposition (“H”) performed either on polished (“P”) or textured (“T”) HJT bottom cells. As can be observed, the PR values reveal similar patterns, with a partly reversible winter dip superimposed to a background degradation. These features are discussed in more detail in *D4.2 Full assessment of degradation mechanisms in NEXUS high performing PVSK/Si modules (> 12 months)*.

Table 1 gathers the experimentally measured year-on-year (from beginning of August 2024 to beginning of August 2025) degradation rates for the 4 samples in Figure 2. While some samples suffered from very pronounced degradations up to 50% without obvious external root causes (suggesting inner cell degradation), B1-HP2 shows a more favourable behaviour with a year-on-year degradation of around 13%. This value constitutes actually the most promising result in the scientific literature [1]. According to the results in Figure 2, the HJT cell demonstrates a very good stability with virtually no year-on-year degradation. This result, expected from HJT product datasheets, suggests that the observed PR losses can be attributed to losses in the encapsulated cell power (excluding other non-module related effect like for instance degradation of the inverter efficiency, or MPP tracking issues). In the following, we will therefore assume that the degradation rates of the maximum power output (Pmax) required for the LCOE calculations are equal to the PR degradation rates reported in Table 1.

**Table 1 Summary of year-on-year degradation rates experimentally measured during the outdoor monitoring campaign at Eurac Research, Bolzano, Italy.**

#	Sample name	1 year PR degradation rate (%)
1	B1 – HP1	50.0
2	B1 – HT2	40.1
3	B1 – HT1	18.6
4	B1 – HP2	13.0

Since regular technological improvements have been made after installation of these devices in the course of the project, and more generally in the scientific community, there is strong hope that lower degradation rates will be demonstrated in the near future. This is also backed-up by the encouraging results obtained in WP3 regarding the stability of Nexus devices after indoor testing. Therefore, we postulate that Pmax degradation rates of 13% year-on-year must represent a clear worst-case scenario for the 1<sup>st</sup> year degradation rate to be input into the LCOE calculations presented in Section 4.

A striking feature in Figure 2 is the dip in PR during colder periods, in that case from fall to end of winter, approximately. This dip can be attributed to several effects, like the switch to more red-shifted spectra in winter, the effect of temperature coefficients and cell operating temperature, and the metastability of the perovskite (“Light-Soaking Effect”, actually believed to be the key driver), as reported in the literature [2] where more details on the effect of each on the single junction perovskite outdoor behaviour can be found. The observed PR dip logically leads to a poor harvesting of the sun’s energy in those days. However, we calculated (see deliverable *D4.2: Full assessment of degradation mechanisms in NEXUS high performing PST/Si modules*) that the energy loss associated with this dip likely contributes only to the second order to the global energy loss, owing to the comparatively lower solar energy to tap in Bolzano in those months and with the chosen tilt angle of 30°C. Instead, the

overall energy loss was calculated to be mostly driven by the year-on-year “hard” (i.e. non reversible) degradation. Additionally, there are sound reasons to hope that these effects may be solved in the future, as metastability could already be solved in some single junction perovskite devices by engineering their internal structure [3]. Therefore, these effects are neglected in the forthcoming LCOE calculations, which should therefore be considered as upper bounds for each degradation scenario that will be considered.

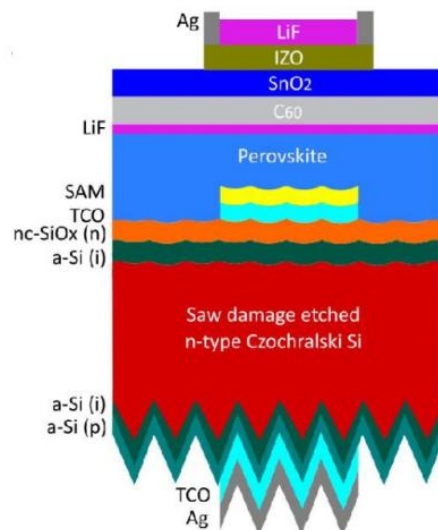
### 3. LCOE calculation methodology, input parameters and assumptions

#### 3.1. General methodology and main input parameters

The methodology used to calculate the LCOE within this report, is in line with that used for the Life Cycle Cost (LCC) analysis withing D5.1 of NEXUS project. In the analysis, all the costs for the module production, utility plant installation, use phase and end of life treatment are included, for a 1 GW<sub>p</sub> PST fixed-angle utility-scale plant in Southern Europe. For the sake of completeness, we recall here the salient features of that methodology. For more detail, the reader is referred to the above-mentioned D5.1 deliverable.

In the module production costs, the HJT bottom cell is considered to be purchased as a product, then all the manufacturing stages from the application of the top cell layers to the module assembly are evaluated. In particular, the materials, labour, depreciation of factory building and equipment, maintenance, electricity and other auxiliary costs, consumables, testing equipment, packaging waste and transport are included as production costs.

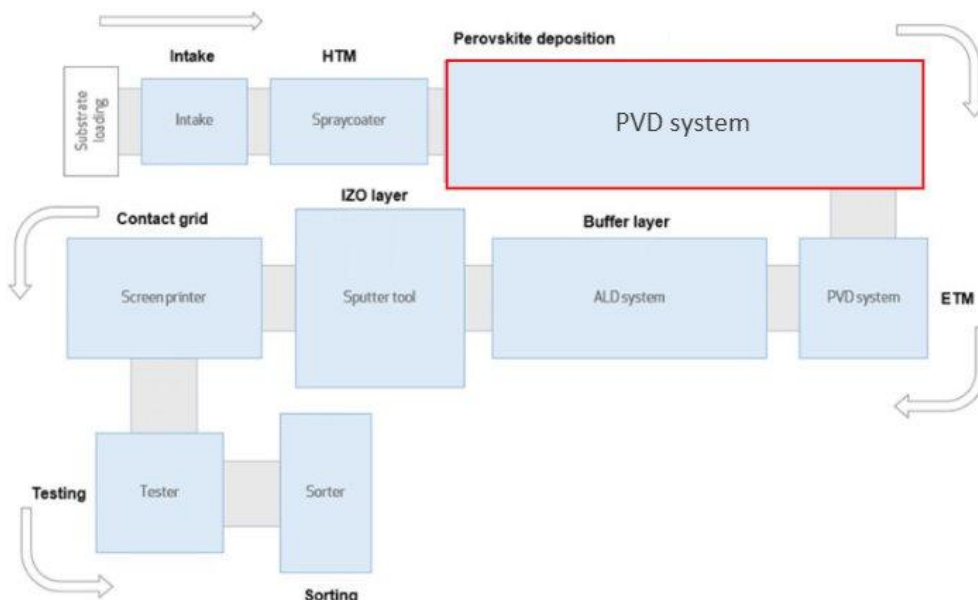
A reference tandem stack was selected in line with typical devices processed in NEXUS, with an architecture and Bill-of-materials (BOM) compatible with large scale manufacturing and high electrical performances, based on Xu et al. study [4] as schematized in Figure 3.



**Figure 3 Reference stack selected for the LCOE calculation, based on Xu et al [4]**

Regarding the wafer-to-cell steps, a HJT n-type Czochralski bottom cell was selected, while the processes considered for the top cell manufacturing are schematized in Figure 4. For top cell layers, PVD, Atomic Layer Deposition (ALD), spray coating-based processes, and screen printing for contact grid deposition were selected. Compared to the previous cost calculations within the project, the present study considers a solvent-free Physical Vapor Deposition (PVD) co-evaporated in vacuum for

the perovskite absorber layer, changing from what was earlier assumed (in D5.1), i.e. slot-die coating process followed by a post thermal treatment.



**Figure 4 Schematic illustration of top cell production line for reference stack.<sup>1</sup>**

To update the costs, primary data available within the NEXUS consortium, valid for a large-range PVD systems were used. Since the cost of the PVD process depends on the material utilization efficiency - meaning the percentage of the target material that is evaporated and stays on the cell, over the total used material - it was assumed for simplicity a material utilization efficiency for the PVD process of 50%. This percentage represents the breakeven point beyond which the PVD process becomes economically competitive over the slot-die coating process, even if the current industrial benchmark for material utilization efficiency of PVD process is still around 40%. Despite that, looking at the overall cost of the PST photovoltaic module, a variation between 40 and 50% in material utilization efficiency would have a minor influence in the global cost per W (as inferred from Table 2). This is also due to the fact that the perovskite absorber layer deposition itself only accounts for at most a few percent (2%) of the total PST module material costs (Figure 6Figure 5).

<sup>1</sup> Courtesy of Oxford PV

Material utilization efficiency (%)	Cost per Watt (€/W )	Total Cost of Ownership
100	0.20384	211 million EUR
50	0.20571	213 million EUR
10	0.22060	229 million EUR
Slot die coating	0.20426	214 million EUR

Table 2 Cost for PVD process for perovskite deposition, depending on material utilization efficiency

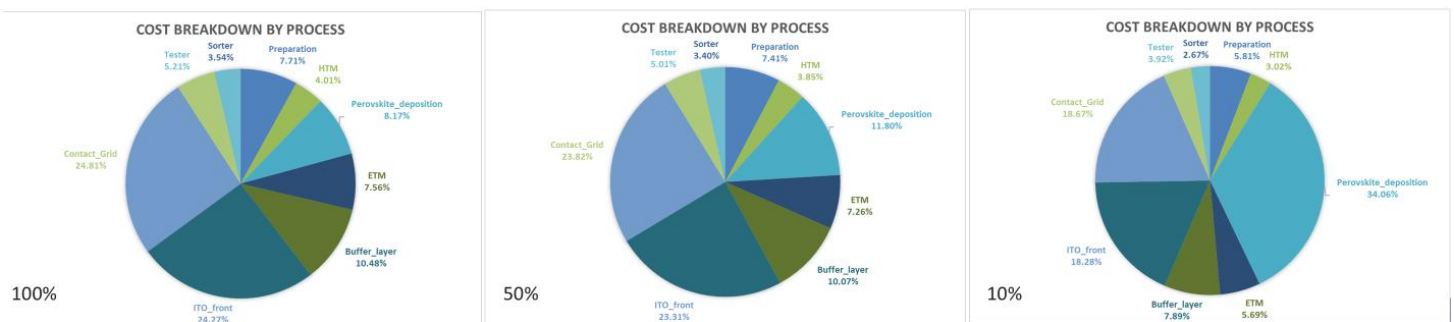


Figure 5 Cost breakdown of top cell manufacturing, with different material utilization efficiencies for PVD deposition of perovskite absorber layer. <sup>2</sup>

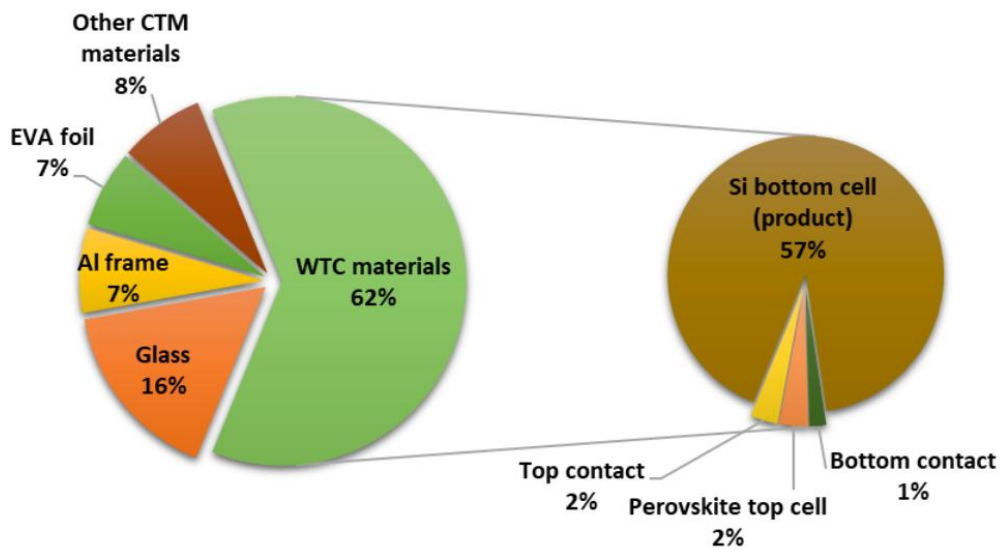


Figure 6 Material cost breakdown of PST modules (WTC = wafer to cell, CTM = cell to module)<sup>3</sup>.

<sup>2</sup> Courtesy of Oxford PV

<sup>3</sup> NEXUS D5.1

For the cell-to-module manufacturing stages, the cell is assumed to be laminated with a standard encapsulant, a front and back glass, interconnections, electrically conductive adhesives (ECA) and ribbons, -before an aluminium frame and junction box are applied.

The installation costs include the costs of module production plus the Gross Margin, and the Cost of the Balance of System (BOS) components. In the BOS components, the inverters, mounting structure, electrical components such as cables and wiring are included, together with installation costs and other soft costs such as permitting, fees sales tax, etc. Naturally, the BOS costs depend on the total surface of the system, which is included in the calculations. The installation costs are assumed to be valid for a utility-scale PV plant installed in Southern Europe, with a solar irradiation of 1,700 kWh/m<sup>2</sup>, to be in line with the project objectives.

The recycling costs were evaluated considering the recovery of high mass fraction materials (e.g., glass, aluminium, copper), high-value recycling materials (e.g., silver, silicon), as for conventional c-Si modules, with the addition of Pb recovery costs based on aqueous extraction relying on primary data collected within the project.

All these individual cost components are used to calculate the Net Present Value (NPV) of the lifecycle costs and the energy produced over the system lifetime, for an assumed Weighted Average Cost of Capital (WACC) of 2 to 8%. Finally, the Levelized Cost Of Electricity (LCOE) is calculated, which is a key-metric to evaluate the cost-effectiveness of electricity-generating technologies. The LCOE for a 30 year lifetime system is expressed in euros per unit of electricity generated (€/kWh), calculated using the equation below.

$$LCOE = \frac{NPV \text{ of life cycle costs over lifetime}}{NPV \text{ of life cycle energy produced over lifetime}} = \frac{Investment + \sum_{t=2}^{30} \frac{O\&M \text{ costs}_t}{(1+WACC)^t}}{\sum_{t=2}^{30} \frac{\text{sum of electricity}_t}{(1+WACC)^t}}$$

To benchmark the economic performance of the Nexus PST technology, the projected LCOE for a 1 GW fixed-angle utility-scale plant is compared against a best-in-class PV technology of mono c-Si PV, as detailed in Section 4.

Since the PST technology is yet to be industrialized, practical cost and yield parameters are still missing. As a consequence, three NPV costs scenarios were considered for different combinations of cost and yield, and the following key cost parameters are included in the scenario analysis:

- Gross margin of producer
- Contribution of PV system operation and maintenance (O&M) to life cycle costs
- Weighted Average Cost of Capital (WACC)
- PR of PST systems

The three investigated NPV costs scenarios are the following (see learnings from D5.1):

- Optimistic: ratio of low cost and high energy scenarios. The optimistic scenario considers a gross margin of 10%, O&M as 0.5% of investment, a WACC of 2% and a PR of 85%.
- Average: ratio of average cost and average energy scenarios. The average scenario considers a gross margin of 15%, O&M as 1% of investment, and a WACC of 5% and a PR of 80%.
- Conservative: ratio of high cost and low energy scenarios. The conservative scenario considers a gross margin of 20%, O&M as 1.5% of investment, and a WACC of 8% and a PR of 75%.

Whitin this study, the presented NPV cost scenarios were additionally combined with three degradation rate scenarios: for each of the three NPV cost scenarios, a low, medium and high degradation rate scenario was assumed, as explained in more details in Section 3.2.3.

Note that the experimental initial PR data presented in Figure 2 were not used for the cost calculation, due to their high uncertainty. Indeed, the Pmax values measured indoors (STC conditions) were leading to highly inconsistent PR values, which could stem from measurement uncertainties, aging of the samples between measurements and installation outdoors, or changes made to the samples during installation (for some samples, the tape around the active areas was removed, possibly leading to increases in Pmax).

In the following section we describe the parameter space investigated by numerical simulation.

### 3.2. Variable parameters and corresponding assumed values

Efficiency, lifetime and degradation rates are known to be the key module-related LCOE drivers [5]. In the following, we address these parameters one-by-one and assign them individual ranges of values based on the project objectives, on the results obtained from the project (Section 2) or from state-of-the-art literature.

#### 3.2.1. Efficiency

The objectives set out in the project are 30% efficient modules. In the following, we will encompass this value starting from 22% (typical of current c-Si commercial modules) and up to 35% which corresponds to the best PST devices (cell) achieved today [6], in order also to contemplate the potential of PST and in particular how low their associated LCOE could become on the long run.

#### 3.2.2. Operational lifetime

The duration during which the module is up and running has an obvious impact on the LCOE. We assume here that the module will be producing electricity for a duration from 5 up to 30 years, the latter value corresponding to the best (yet rather standard nowadays) performance lifetimes offered by c-Si modules manufacturers, defined as the duration after which their power output drops to 80% of initial value (for higher degradation rates, it is obvious that the efficiency retention at the end of the lifetime will be <80%).

#### 3.2.3. Degradation rates

Degradation rates, by progressively reducing the efficiency of the module over time under operation, are driving the LCOE down and are identified as the key challenge for PST in the future [7].

In this report, we define three degradation rate scenarios presented in Table 3.

**Scenario 1 is a pessimistic scenario** based on the results presented in Section 2.2. It features a 13% first year (N1) degradation, as observed on device B1-HP2 monitored outdoor at Eurac Research, and which constitutes to the best of our knowledge the best outdoor stability reported as per today of a PST encapsulated cell. As no degradation data are yet available for subsequent years (N>1), we further postulate a long-term degradation of a third of that value (i.e. 4.3%). This latter value of 4.3% is motivated by the report from [8] of an approximate 15% performance degradation over 4 years for a perovskite single junction encapsulated device, which results into an approximately 4%/year overall

degradation. Additionally, this “rule-of-third” represents a good average of degradation rate ratios between year  $N > 1$  and year  $N = 1$  for c-Si. Although degradation mechanisms are expected to be different between c-Si and PST modules, we postulate that similar behaviour could be observed in the future for PST devices, whereby the efficiency degradation rate stabilizes to a more favourable value after an initial period characterized by a stronger degradation (sometimes referred to as the “burn-in” period).

**Scenario 2 represents an intermediate degradation rate** of the PST solar cells. It assumes a 4.2% first-year degradation rate, followed by a 1.4% degradation rate in subsequent years. This degradation rate is placed between the pessimistic (Scenario 1) and the optimistic (Scenario 3) degradation rates. Given the latest stability results presented in section 2.1 and also the promising outdoor results obtained on the last installed samples, there is hope that such intermediate scenario can be reached in the near future for PST.

To estimate these values, we use the kinetic degradation data for an inorganic perovskite solar cell reported by Zhao et al. [9]. The reference study examines devices with and without a 2D  $\text{Cs}_2\text{PbI}_2\text{Cl}_2$  capping layer. For this intermediate scenario, our analysis uses data from the device without the capping layer. The PCE decay in the source study follows a double-exponential trend:

$$\text{PCE}(t) = A_1 * \exp(-k_{\text{fast}} * t) + A_2 * \exp(-k_{\text{slow}} * t) + B$$

The degradation parameters ( $A_1$ ,  $A_2$ ,  $B$ ,  $k_{\text{fast}}$ , and  $k_{\text{slow}}$ ) for this model were derived by fitting the equation above and the degradation trends observed from accelerated aging tests under constant illumination ( $1200 \text{ W/m}^2$ ) and at elevated temperatures ( $35\text{--}110 \text{ }^\circ\text{C}$ ). The study reports two distinct activation energies, corresponding to a fast ( $0.248 \text{ eV}$ ) and a slow ( $0.243 \text{ eV}$ ) degradation process. These values were implemented directly into the degradation function developed in the project (see Milestone 8). A key assumption in our model is that degradation occurs exclusively in the perovskite top cell. To translate the laboratory findings into real-world performance, we used the open-access energy yield modelling software, EYCalc [10]. The simulation was run using 1 year of cell temperature and light intensity data from Bolzano, Italy.

Since the degradation rate in the reference study is measured under constant illumination of  $1200 \text{ W/m}^2$ , we rescale the degradation rate at other light-intensity levels using the acceleration factor defined as  $AF = \frac{I_{\text{acc}}}{I_{\text{ref}}}$ , where  $I_{\text{ref}}$  is the reference light-intensity  $1200 \text{ W/m}^2$ , and  $I_{\text{acc}}$  is the actual light-intensity at a given hour.

We calculate the degradation rate for each hour of the year, accounting for the combined effects of the cell's operating temperature and incident light intensity. These hourly degradation rates were then accumulated over time to compute the annual degradation rate for that scenario.

**Scenario 3 refers to an optimistic scenario** where the degradation rates of the PST modules is set to the values found in the best-in-class c-Si module datasheets as per today, to the best of our knowledge. It assumes a 1% first year degradation followed by a 0.35% degradation rate for the subsequent years. Such top-notch values can be found for instance for the module AIKO-A-MAH54Mb proposed by Aiko Solar (N-Type ABC – Black Hole Series) with an area of  $1.95 \text{ m}^2$  and 23%+ efficiency [11]. Since a PST device is made of both a c-Si and a perovskite components, each potentially featuring their own degradation mechanisms affecting the intrinsic component's performance but also that of the full device (mismatch...) these values clearly constitute practical lower bounds.

**Table 3 Scenarios defined regarding the power degradation rates, that will serve as input to the LCOE**

### calculations

#	Scenario name	First year degradation rate (%) (N=1)	Degradation rate for the subsequent years (%) (N>1)
1	High Degradation Rate	13%	4.3%
2	Medium Degradation Rate	4.2%	1.4%
3	Low degradation Rate	1%	0.35%

## 4. Results towards a first LCOE assessment based on outdoor results

### 4.1. Reference LCOE (Mono c-Si benchmark)

The c-Si module picked to serve as a reference is the *Aiko Solar N-Type ABC – Black Hole Series* module as described above. For the comparison with the LCOE for the PST system, the following baseline values were assumed for that reference:

- Annual solar irradiation of 1,700 kWh /m<sup>2</sup> ( $\cong$  194 W /m<sup>2</sup>)
- Module production of 3,886,602 m<sup>2</sup>
- Module lifetime of 30 years (datasheet)
- Average PR of 80%
- BOS including inverter of €43 /m<sup>2</sup>
- Average O&M percentage of investment of 1%
- Annual O&M growth rate of 2%
- Average WACC of 5%

Using these baseline values, the Mono c-Si benchmark costs €83 /m<sup>2</sup> for a power output of 231 W/m<sup>2</sup> and 33,000 GWh /lifetime considering the degradation rate from Table 3. **The resulting LCOE for the reference c-Si module is €ct 3.4 /kWh. This LCOE value of €ct 3.4 /kWh will be assumed in the rest of the report whenever the PST LCOE results will be compared to the benchmark c-Si module.** Note that this benchmark module was defined in D5.1 earlier in the project. Although today's module average efficiency has shown some improvements, 23% efficiency remains in the top 10 module efficiency on the c-Si market and therefore remains highly relevant as a benchmark module [12].

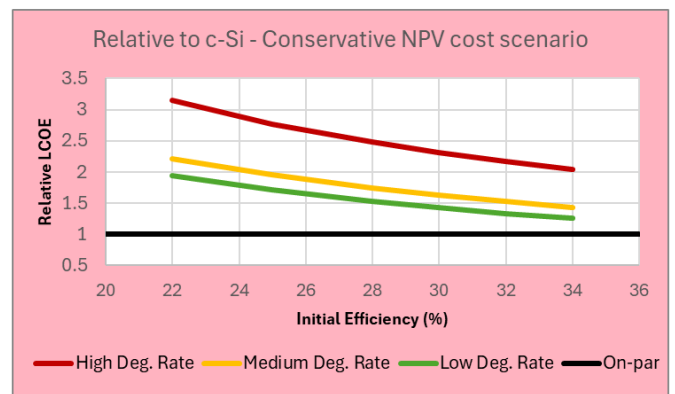
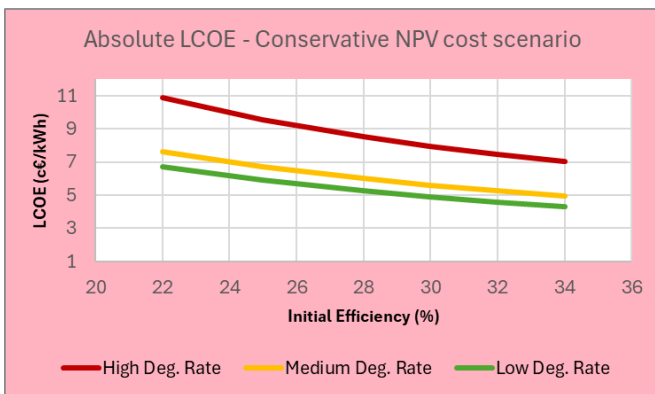
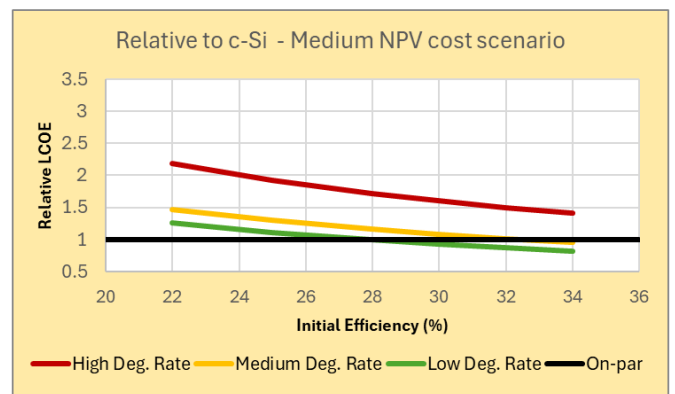
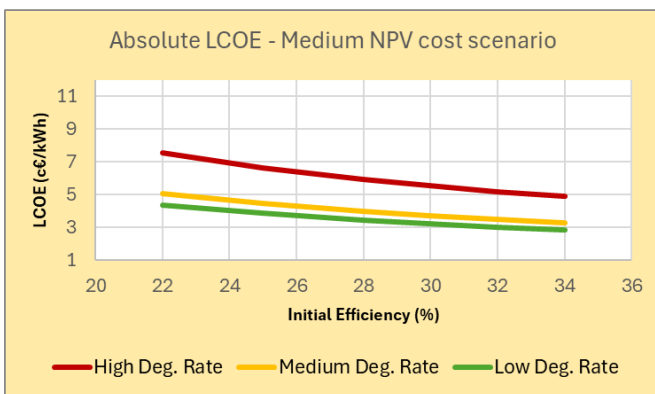
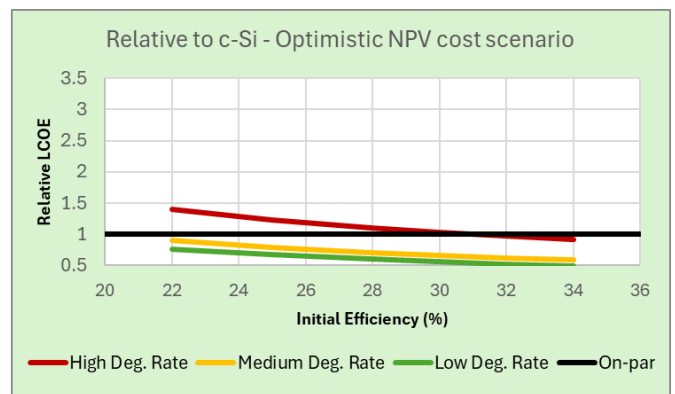
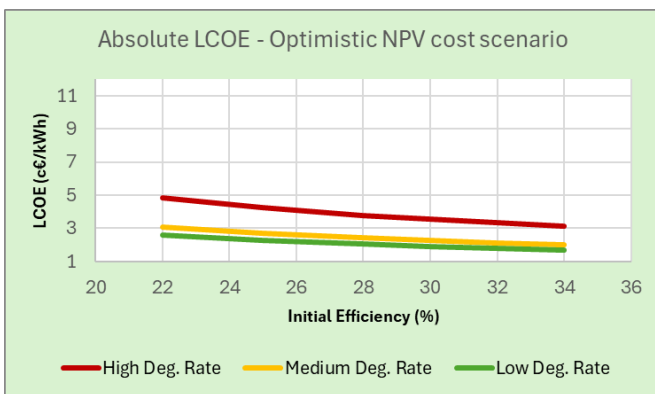
### 4.2. LCOE of PST modules: Influence of degradation rates and initial efficiency

In this section, the LCOE values are calculated for each NPV cost scenario (optimistic, medium, conservative), varying the degradation rates and the starting efficiencies within the ranges defined and discussed in Section 3. Importantly, the lifetime is kept constant and equal to 30 years throughout the calculations presented in this section.

Figure 7 presents the overall results for the three NPV cost scenarios.

a)

b)



**Figure 7: a) Absolute and b) relative LCOE results. Relative LCOE results are the ratio between absolute LCOE for PST (column a)) and the LCOE calculated for the reference c-Si module (3.4 c€/kWh).**

Figure 7 calls for several comments:

- First, it can be seen that – as expected – both increasing the initial efficiency and decreasing the degradation rates is favoring low LCOE values.
- Second, the effect of the selected NPV cost scenario on the LCOE is very tangible. For a 30% module for instance, featuring the medium degradation rate and a 30 years lifespan, the LCOE increases from 2.27 c€/kWh (i.e. < LCOE c-Si) to 5.61 c€/kWh (i.e. >LCOE c-Si) when going from the optimistic to the conservative NPV costs scenario (i.e. a twofold variation approximately). These results indicate the first-order influence of the NPV cost scenario that will be ultimately achieved. More calculation details are given in Table 4 for this 30% initial efficiency case.
- Third, the initial efficiency level can also be seen as a first-order parameter. Indeed, if we assume the medium NPV costs scenario, a 30 years lifetime, and the medium degradation rate, the figure above reveals that a LCOE of around 5.07 c€/kWh (>LCOE c-Si) for the 22% initial efficiency scenario and down to 3.28 c€/kWh (< LCOE c-Si) for the 34% scenario (also very roughly a twofold variation).

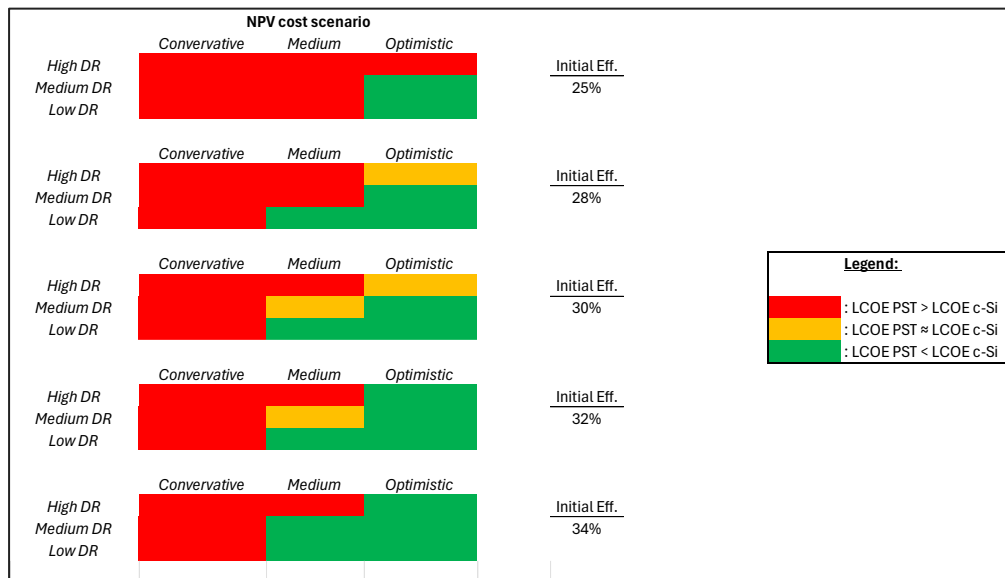
**Table 4 Comparison of module performance and costs between PST PV and the c-Si benchmark module. PST projection refers to optimistic (green), average (orange) and conservative (red) NPV costs scenarios (as defined in section 3), each of them declined into three Degradation Rate scenarios (see section 3). Assumed lifespan is 30 years.**

Product	NPV costs scenario	Type	Power output	Degradation rate (first year/ subsequent years)	Life cycle energy	LCOE	
			[W <sub>p</sub> /m <sup>2</sup> ]	[%]	[GWh]	[€ct /kWh]	
<b>Aiko Solar N-Type ABC Black Hole Series</b>		Mono c-Si	231 (23.1% eff.)	1/0.35	33,459	3.45	
<b>PST Projection</b>	Optimistic	PST	300 (30% eff.)	Low	1/0.35	45,913	<b>1.91</b>
				Medium	4.2/1.4	38,150	<b>2.27</b>
				High	13/4.3	23,503	3.54
<b>PST Projection</b>	Medium	PST		Low	1/0.35	43,212	<b>3.20</b>
				Medium	4.2/1.4	35,905	3.72
				High	13/4.3	22,121	5.52
<b>PST Projection</b>	Conservative	PST		Low	1/0.35	40,512	4.90
				Medium	4.2/1.4	33,662	5.61
				High	13/4.3	20,738	7.97

In order to better picture which conditions are required for a PST projection to be on-par with or more profitable than the chosen c-Si reference module, we propose here to plot the LCOE as a function of NPV costs and degradation rate scenarios, for selected initial efficiency levels (30 years lifetime). The results are plotted in Figure 8 with the cases where LCOE PST>LCOE c-Si in red, those close (from 1x to 1.1x on-par) in orange and those where LCOE PST<LCOE c-Si in green.

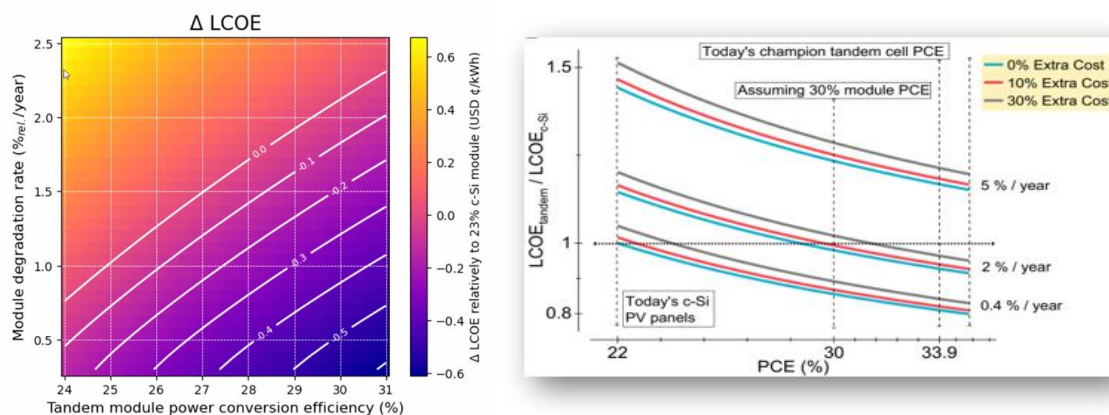
Figure 8 calls for the following comments:

- In the conservative NPV costs scenario, none of the degradation rate scenarios manages to outperform – or even approach - the LCOE of the reference c-Si, regardless of how high the initial efficiency is within the 22-34% range.
- In the medium NPV costs scenario, an initial efficiency of 28% would be sufficient, provided that the degradation rate remains very low (optimistic case). Any further increase in initial efficiency would then yield additional benefits for the PST LCOE.
- In the optimistic NPV costs scenario, 25% starting efficiency may be enough to outperform the c-Si reference, provided however that degradation is contained to scenarios “Low” or “Medium”. From 28% initial efficiency on, all degradation rate scenarios yield benefits compared to the reference one.



**Figure 8: Overview of global (NPV costs and Degradation Rate (DR)) scenarios and their ability to offer on-par or lower calculated LCOE than the reference c-Si LCOE. The colour code is given in the Figure.**

The results presented in Figure 7 align quantitatively well with the existing literature on the LCOE of PST devices. Two particularly striking findings can be highlighted [5][7]. From the first study, it can be observed that for a 30% tandem module to match the LCOE of a state-of-the-art 23% c-Si module, the annual degradation rate must not exceed 2.1%. This is consistent with the second study, where a 30% module reaches parity with the c-Si reference (22% efficiency in that case) if the degradation rate is around 1.8% per year, assuming a +30% cost scenario for the PST vs c-Si technology. These findings are in reasonable agreement with our own calculations in Figure 7, from which it can be inferred that a 30% tandem module would break even at a maximum degradation rate of 1.2% per year under medium NPV costs, and up to 5% under optimistic NPV costs (by extrapolating the graphs, not shown here). Naturally, the underlying assumptions differ between studies (e.g., localisation, module lifetime, reference c-Si degradation rate, cost structures, and whether balance-of-system costs are included, etc). Overall, however, the literature consistently confirms the critical role of the degradation rate in determining the final LCOE.



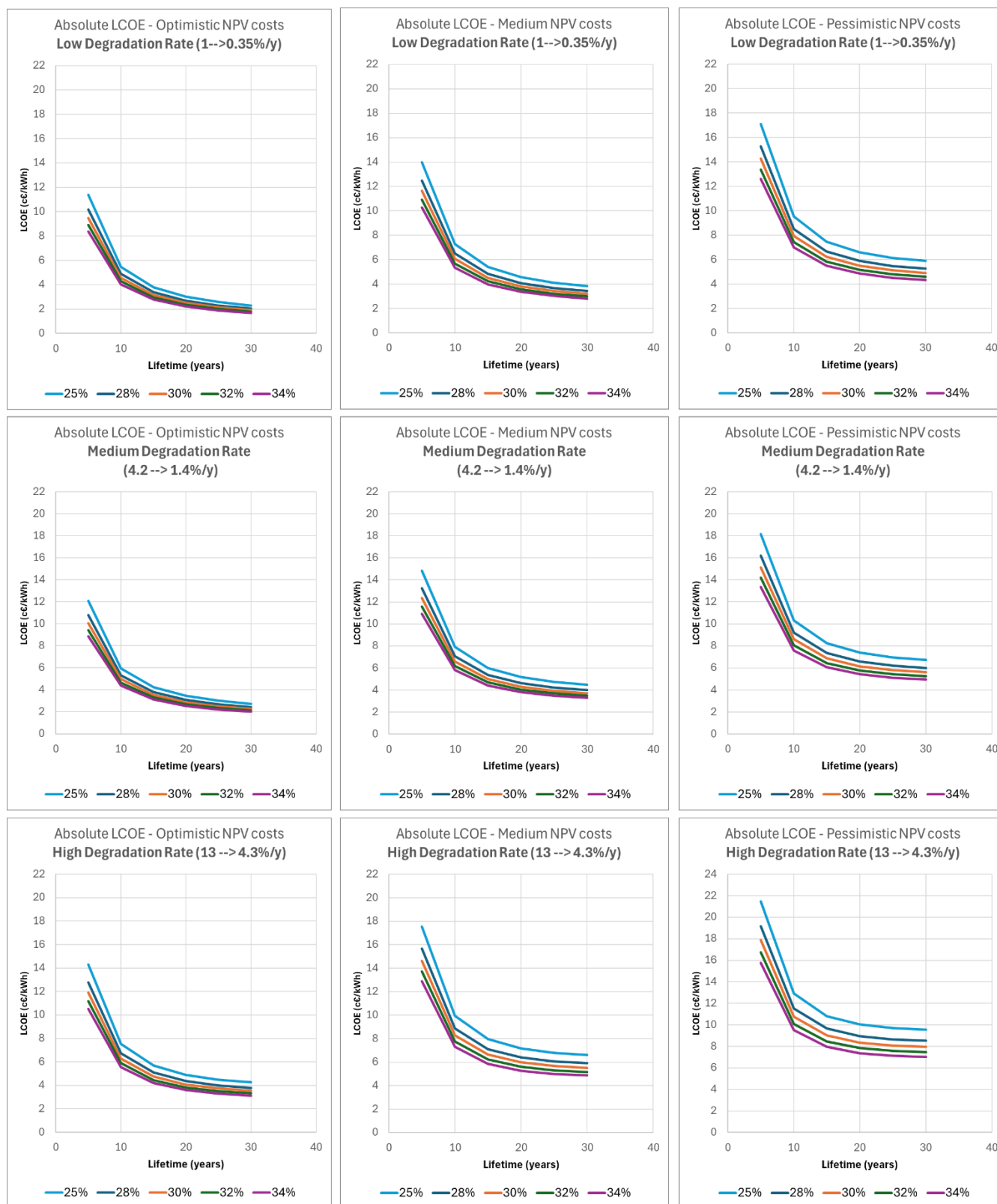
**Figure 9: LCOE calculations extracted from literature (right [5], left [7]) for a fixed lifetime (25-30 years) and as a function of two key module parameters, namely the initial efficiency (PCE) and the degradation rate.**

### 4.3. LCOE of PST modules: Influence of module lifetime

The LCOE projections presented in the previous section assumed a typical lifetime for conventional benchmarks, i.e., 30 years. This 30-year benchmark reflects the standard warranty period commonly offered for conventional PV modules. However, since PST PV is a novel technology, there is currently no field data available regarding its actual operational lifetime. It is therefore instructive to examine how the assumed lifetime affects the resulting LCOE values.

Intuitively, a longer lifetime leads to a lower LCOE, as the total electrical energy produced over the system’s lifetime appears in the denominator (see section 3), while the vast majority of costs are incurred upfront during module fabrication—meaning that the numerator increases only marginally over time.

Figure 10 illustrates the evolution of LCOE as a function of module operational lifetime for all three NPV costs and degradation-rate scenarios. In every case, the LCOE decreases exponentially with increasing lifetime. The reduction is most pronounced in the early years of operation and gradually levels off, with only marginal (a few percent) improvements beyond 20 years operation. Figure 10 further indicates that the relative decrease in LCOE between 5 and 30 years of operation becomes larger under more favourable NPV costs or degradation scenarios. For instance, the reduction is approximately five-fold for the most optimistic case (low degradation and optimistic NPV costs) and about two-fold only for the most pessimistic one (high degradation and conservative NPV costs). Should the overall optimistic scenario eventually materialize, it would then imply that repowering must be carefully designed and strategically planned.



**Figure 10: LCOE values as a function of lifetime for initial efficiencies ranging from 25 to 34% and computed for all NPV costs and degradation rate scenarios investigated in this report. Left, middle and right columns show the results for the Optimistic, Medium and Conservative NPV costs scenarios, respectively. The first, second and third rows are associated with the Low, Medium and High degradation rate scenarios,**

*respectively.*

## 5. Conclusions

In this report, we evaluate the LCOE of a 1 GW<sub>p</sub> PST fixed-angle utility-scale plant in Southern Europe, that we benchmark with respect to a mainstream high efficiency c-Si plant representative of today's market. To this aim, we build on the findings and methodology presented in the Nexus deliverable *D5.1 – LCC assessment from cradle to cradle with LCOE target of 2 cents/kWh (South Europe)* to adapt the LCOE calculations to 3 degradation rate scenarios. The relevance of these scenarios was motivated on the basis of literature and of actual year-on-year degradation data from outdoor monitoring performed within WP4. We also conducted a sensitivity analysis on other critical key parameters such as the influence of the PST initial efficiency (22 to 34%) and module lifetime (from 5 to 30 years) on the final expected LCOE.

We derived from our findings the following take-away messages:

- The study of available outdoor data generated in the project reveals a **best-in-class year-on-year outdoor degradation of 14%**, as well as a **demonstration of compliance with IEC61215 DH1000 and TC200** (different devices for both indoor and outdoor, however fabricated with very similar materials and processes). Even if in both cases there is large room for improvement (in the case of indoor testing, the individual IV parameters showed marked evolutions throughout testing, also suggesting instabilities in the devices), these results overall highlight the achievements of the NEXUS consortium and constitutes important milestones towards bankability.
- Using LCOE calculations, we evidence the **critical role of all three parameters**: NPV costs, operational lifetime (in line with D5.1 findings) and degradation rate (investigated here in detail).
- More particularly, within the ranges of scenarios defined here, and all else being equal, navigating through the different scenarios for the NPV costs, operational lifetime and degradation rate can lead to a 250%, 500% and to a 200% variation in the resulting calculated LCOE.
- We presented **bankability matrices to ease the requirement definition** regarding NPV costs, operational lifetime and degradation rate, in order not to exceed the c-Si benchmark LCOE (Figure 8).
- The matrices revealed that in the conservative NPV costs scenario, even the more favorable degradation rate degradation scenario and the highest (as of today) initial device efficiency **do not allow to outperform** – or even approach - the LCOE of the reference c-Si, emphasizing on the necessity to keep costs down.
- In the medium NPV costs scenario, an initial efficiency of **28% would be sufficient**, provided that the **degradation rate remains very low** (optimistic case). Any further increase in initial efficiency would then yield additional benefits for the PST LCOE.
- In the optimistic NPV costs scenario, **25% starting efficiency may be enough** to outperform the c-Si reference, provided however that degradation is contained to **scenarios “Low” or “Medium”**. From 28% initial efficiency on, all degradation rate scenarios yield benefits compared to the reference one. This is undeniably the techno-economic sweet spot that should be aimed at!

- Regarding the influence of operational lifetime on LCOE, our calculations pointed to a stronger influence of operational lifetime on LCOE as we move towards optimistic costs and degradation rate scenario. We concluded that, in general, repowering should be carefully planned to optimize the project viability, and all the more if such optimistic scenarios (hopefully) materialize.

These results allow to narrow down the ranges of costs, degradation and lifetime scenarios that allow for the PST technology to outperform their high efficiency c-Si counterparts in Southern Europe. In conjunction with D5.1, they reveal that all actors in the value chain of the PST technology have a role to play, from cell and module engineers, equipment providers, material/components providers etc. As an outlook, improving the bankability of the PST technology — and the robustness of its assessment — still requires significant efforts. These include (non-exhaustive list): the transition towards commercial-scale modules and their long-term outdoor monitoring; the elucidation of failure pathways to accelerate the development of outdoor stable devices; the implementation of accelerated testing protocols tailored to the specific weaknesses of the technology; and the systematic investigation of environmental, material and social compliance.

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