VIPERLAB

FULLY CONNECTED **VI**RTUAL AND **P**HYSICAL P**ER**OVSKITE PHOTOVOLTAICS **LAB**

D 10.5

PROJECTED LEVELIZED COSTS OF ELECTRICITY FOR KEY DEVICE ARCHITECTURES

DELIVERABLE REPORT

Version: 1.3

Date: 29.11.2024

FULLY CONNECTED VIRTUAL AND PHYSICAL PEROVSKITE PHOTOVOLTAICS LAB VIPERLAB

DELIVERABLE

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Project References

Project Acronym	VIPERLAB
Project Title	Fully connected **vi**rtual and physical **per**ovskite photovoltaics **lab**
Project Coordinator	Helmholtz-Zentrum Berlin
Project Start and Duration	1st June 2021, 42 months

Deliverable References

Deliverable No	D 10.5
Type	Report
Dissemination level	Public
Work Package	WP10
Lead beneficiary	Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.v
Due date of deliverable	30 Nov 2024
Actual submission date	29 Nov 2024

Document history

Version	Status	Date	Beneficiary	Author
1	First Draft	10.11.2024	Fraunhofer	B. Goraya
1.1	Consolidated Draft	22.11.2024	Fraunhofer	B. Goraya
1.2	Reviewed Draft	29.11.2024	Fraunhofer	S. Nold
1.3	Final Draft	29.11.2024	Fraunhofer, HZB	B. Goraya, N. Maticiuc

DISCLAIMER

‘Fully connected virtual and physical perovskite photovoltaics lab' VIPERLAB is a Collaborative Project funded by the European Commission under Horizon 2020. Contract: 101006715, Start date of Contract: 01/06/2021; Duration: 42 months.

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EXECUTIVE SUMMARY

The overall goal of the work package 10 is to provide guidance for the infrastructure and technology development within VIPERLAB by evaluating and optimizing the environmental, social and economic impact of new perovskite-based technologies. To this end, this work package will:

- Provide the data (material, process flows etc.) necessary for such an evaluation
- Evaluate the environmental (Life Cycle Assessment, LCA), social and economic (Levelized Cost of Electricity, LCOE) impact of new perovskite-based technologies and how this impact is affected by the application, device design, choice of equipment and process.

This report presents the methodology followed to arrive at the projected levelized cost of electricity for the selected technology types, based on the key device architecture list detailed in deliverable report D10.1. The results of the LCOE (this report D10.5) and LCA (D10.4) are to be published in a peer reviewed journal as well as are aimed to be presented at an international conference in 2025. As such, this deliverable report will mainly focus on an introduction to the technologies evaluated and the methods followed to carry out the LCOE assessment and not contain any detailed results to maintain novelty and not hinder efforts to publish and/or present the results at a conference. However, the results of the analysis were presented and discussed with the project consortium at the final general assembly meeting held in Brussels in November 2024 and are briefly mentioned in this report. For both this report and deliverable report D10.4, detailing the environmental impact assessment, the methods followed to arrive at the results initiated from the same starting point. Firstly, Fraunhofer ISE's in-house, bottom-up total cost of ownership model, "SCost" [1], was used to assess the production cost for the selected technology types – two crystalline silicon (c-Si) based single junction technologies - n-TOPCon and n-SHJ, and two 2-T perovskite-silicon tandem technologies - pero-TOPCon and pero-SHJ. Extending the production cost model to the LCOE assessment for the residential case, it was found that the pero-SHJ based tandem can provide the lowest LCOE compared to all other technology types. A sensitivity analysis with key parameter variation including the BOS costs, Global Horizontal Irradiation (GHI), system lifetime, degradation rate and module efficiency amongst others was also performed to see their individual impact on the LCOE of the pero-silicon tandems.

1. INTRODUCTION

The decarbonization and the transformation of the energy supply system involves both technical and economic efforts where the costs of electricity generation are a significant cost factor, varying by technology and depending on the construction and operational expenses of each power generation facility. Over the past 15 years, the costs for renewable energy technologies, including PV, have notably decreased, driven by technological innovations such as the use of cheaper and more efficient materials, reduced material usage, more efficient production processes, improvements in efficiency, and the automated mass production of components. At the end of 2023, the globally installed PV capacity exceeded 1400 GWp, with global additions in 2023 reaching approximately 413 GWp. This represents a market growth of 58% compared to 2022, when around 252 GWp were installed [2]. The global PV market is currently dominated by China, both in production and installation. However, more and more countries are installing PV on a significant scale, as PV systems increasingly succeed in free market competition, allowing them to be implemented independently of subsidy programs. As a result, PV market growth is increasingly driven by purely economic factors.

The Levelized Cost of Electricity (LCOE) method allows power plants with different generation and cost structures to be compared with each other. The LCOE is calculated by comparing all costs incurred over the lifetime of the power plant for the construction and operation and the total amount of energy generated [3]. The LCOE method has become a very practical and valuable comparative method to analyse different energy technologies in terms of cost and is internationally recognized as a benchmark for assessing the economic viability of different generation technologies as well as of individual projects and enables the comparison of different energy technologies with respect to their cost ([4], [5], [6], [7], [8]). From an economic point of view, the LCOE contains the most important factors contributing to the economic evaluation of a project [9] and since the LCOE is just one number, it causes a great reduction in complexity and allows for a quick and easy comparison of different alternatives.

2. METHODOLOGY

This section contains the procedure for arriving at the total cost of ownership (TCO) which contains all production related direct and indirect costs of the selected technologies – two crystalline silicon (c-Si) based single junction technologies n-TOPCon and n-SHJ, which currently have a dominant market share, and two 2-T perovskite-silicon tandem technologies pero-TOPCon and pero-SHJ. Once the TCO of the 4 technologies has been calculated, the analysis is extended to the LCOE assessment which includes the module and balance of system costs for a residential rooftop installation at a specific location followed by a sensitivity analysis of certain key parameters to observe their impact on the LCOE.

2.1. Total Cost of Ownership of Selected Technologies

Fraunhofer ISE has collected relevant cost data throughout the whole value chain for over 20 years. During that time, a sophisticated cost analysis tool “SCost” [1] covering the entire PV value chain has been developed which enables economic comparisons of different technology options. The economic analysis features a bottom-up calculation of the industrial PV value chain with the adaptation for individual production technologies. The underlying cost model is aligned with the SEMI standard E35 [10] for the calculation of Cost of Ownership (COO) for semiconductor and photovoltaic (PV) production equipment as well as the SEMI standard E10 [11] for reliability, availability, and maintainability (RAM). The equipment and process related input parameters (e.g., process throughput or material consumption) as well as equipment Capital expenditures (CAPEX) are primarily gathered from various PV stakeholders, primarily directly from the equipment manufacturers, but also from PV companies using the equipment in real production and especially for newly developed production technologies from conjoint research and development (R&D) activities with Fraunhofer ISE. Material input prices are primarily collected directly from the suppliers of the material. With the bottom-up Total Cost of Ownership (TCO) model “SCost” the process information of the single process steps is put into whole process sequences together with general production assumptions like the envisioned capacity and planned utilization of the production facility. A flow chart showing the simplified procedure for the cost calculation is shown in Figure 1.

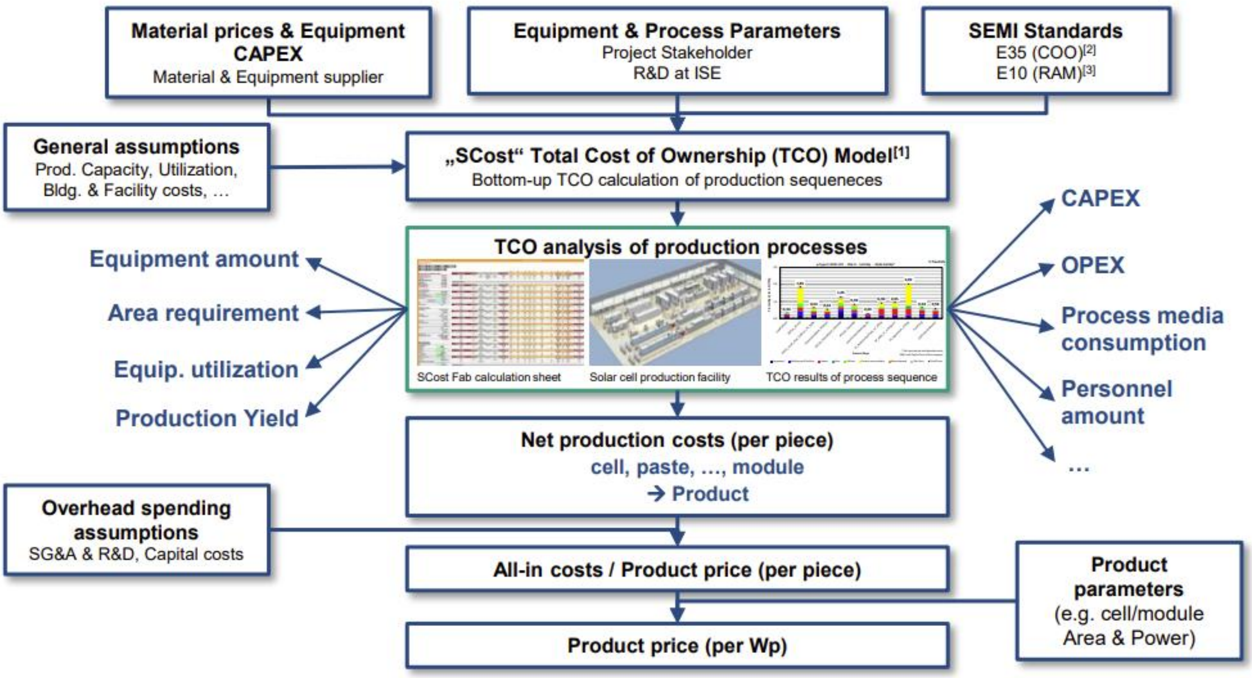

Figure 1: Methodology for cost calculation with the cost calculation tool SCost developed at Fraunhofer ISE.

The result of the SCost TCO analysis of the process sequence is the "Net production costs" per manufactured piece of product, which include all cost of production. The net production costs are divided in cost categories with their cost components as shown in the following overview:

- *Equipment:* Production equipment and automation incl. delivery, installation, qualification.
- *Building & Facilities:* CAPEX, cost of capital and OPEX of fab building & facilities: HVAC, gas farm, DI water production, chemical supply, waste disposal, warehouse, offices, canteen, Infrastructure personnel.
- *Utilities:* Power, Cooling, CDA, Exhaust, DI water, water, N_2, … ▪ Parts: Spare and wearing parts.
- *Process consumables:* Solids, Liquids, Gases, etc.
- *Waste Disposal:* Materials for fab internal disposal, costs for external disposal.
- *Labor in Production:* Operators, Technicians, Supervisors, Engineers, Scientists.
- *Cost of Yield Loss (CYL):* Breakage and pieces not meeting quality requirements.

Not included within the net production costs are overhead costs for Selling, General, and Administrative (SG&A) expenses and for R&D, as well as cost of capital of the corporate unit. For SG&A and R&D, market benchmark values are taken (as share of revenues from annual reports from PV manufacturers). For the cost of capital, the weighted average cost of capital (WACC) approach is used, including debt payments but also an assumed equity returns of the company. The cost of capital is calculated on the average employed capital of the company, including the fixed capital for production equipment, building and facilities as well as for tied inventory capital in incoming and outgoing products, parts and process consumables and waste materials. Thus, after adding the overhead costs to the “Net production costs”, one arrives at the final “Product price”. Finally, the main product quality parameter is included as the conversion efficiency of the cell or module, which is calculated from the peak power output and area of the device. An additional module to the SCost cost analysis tool allows the calculation of the expected PV system costs and Levelized Cost of Electricity (LCOE) on system level for specific and individually specified locations and use cases (utility, commercial or residential rooftops).

For the tandem cell processing routes, the perovskite top layer was taken as the latest, most promising industrial structure as presented in the key device architecture list in deliverable report D10.1 and was implemented on the TOPCon and SHJ silicon bottom cells in a 2-terminal configuration, which is currently envisaged to be the closest to market entry. These perovskite-silicon tandem stacks were compared to their respective stand-alone c-Si single junction technologies – n-TOPCon and SHJ for the production cost, LCA and LCOE assessment. The analysed cell production sequences for both the LCA and LCOE assessment are shown in Figure 2 below. For the cell processing in each case, an n-type 130µm thick M10 wafer was used as the input base material considered to be purchased from the spot market. The cell efficiency for single junction TOPCon and SHJ were taken as those currently available in mass production – 24.5% and 25% respectively.

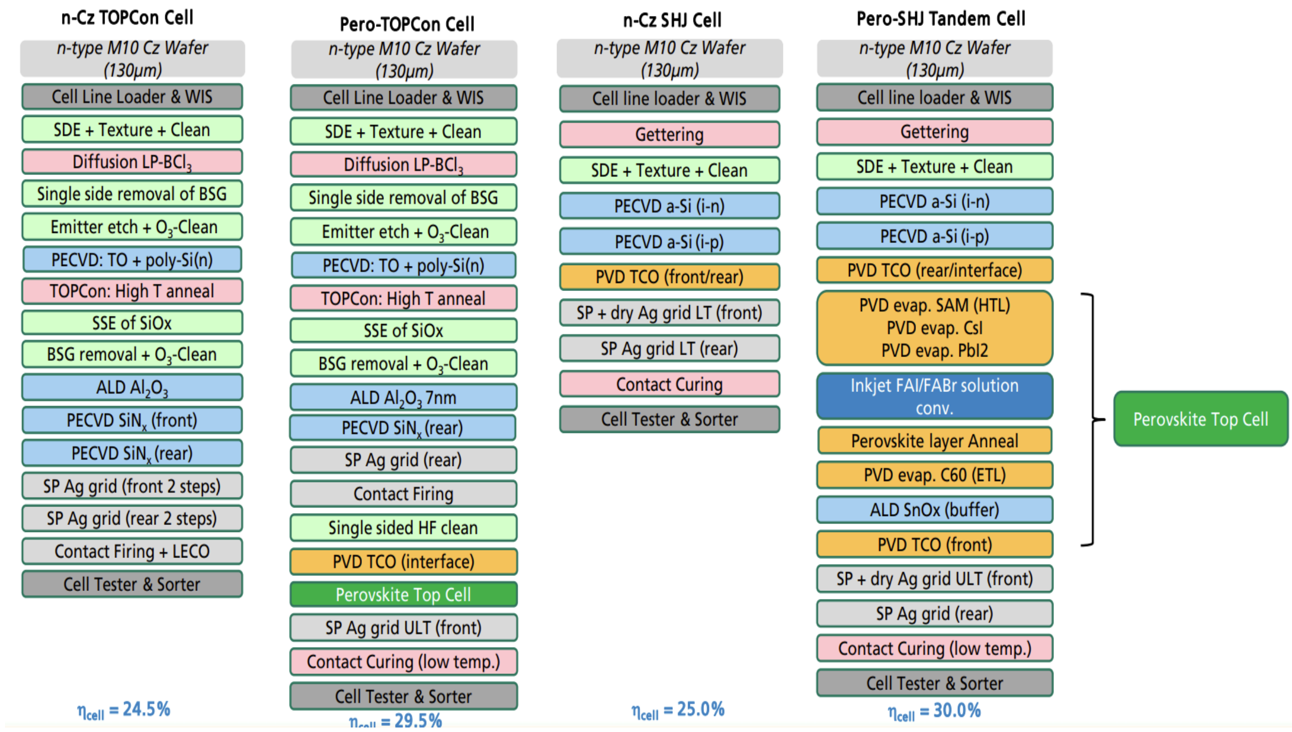

Figure 2: Analysed cell production routes for both LCA (D10.4) and LCOE (D10.5) assessment along with the assumed respective cell efficiency used.

For the tandems, an additional efficiency advantage of 5% was assumed for the pero-TOPCon and per-SHJ cells resulting in a final cell efficiency of 29.5% and 30% respectively. The materials amounts and prices were used from the data collected within MS29 and MS 30 respectively. For the perovskite material prices, two scenarios were considered with high and low prices, based on the expected minimum and maximum impact of scaling effects on the price when ordering large volume of materials. The low-price scenario expected the price to reduce by 50% whereas the high scenario assumed the price to drop by a tenth of the current, researched low volume price for the novel, perovskite materials. This scaling was necessary as the current price for perovskite materials, especially that for C60 (as ETL), SAM 2-PACz (as HTL) and the CsI (as part of the perovskite absorber) were found to be exceptionally high for mass production. The perovskite materials prices used for the high and low scenario are shown in Figure 3.

Perovskite Materials	Researched Price (low volume)	Assumed price with min. scaling effects	Assumed price with max. scaling effects	Unit	Comment
C60	41,400	20,700	4,140	€/kg	Max scaling leads to price regression of 1/10th and min scaling leads to half the low volume price.
Butanol 100%	*38*	*38*	*38*	€/l	
FaI	1,167	584	117	€/kg	
FaBr	1,460	730	146	€/kg	
Ethanol 99.8%	*33.35*	*33.35*	*33.35*	€/l	
SAM 2-PACz	470	235	47	€/g	
CsI	13,600	6800	1,360	€/kg	
PbI2	3,500	1750	350	€/kg	

Figure 3: Main perovskite material prices for low volume and the respective low and high price development scenarios used in the analysis.

For the module production, a 72-cell glass-glass module was assumed as the technology of choice for both the single junctions and the tandems. All 4 selected technologies were considered to have the same production sequence and bill of materials (BOM) with the main difference in the type of sealant used - for tandems, a double layer of the butyl edge sealant was used to provide better protection against moisture ingress. The analysed production sequence along with the price of the main module materials and the final module power in watt-peak, accounting for cell-to-module losses is shown in Figure 4.

72 cell Glass-Glass module
Glass loader1
Lay-up POE1
Combined tabber stringer + Auto bussing
Lay-up Cells / POE2 / Glass2
Module Lamination
Edge trimming and Framing
Junction box mounting + seal
Curing line
Module Flasher & Sorter
Labelling & Packaging

→ Butyl edge sealant for Pero-Silicon tandem module instead of silicone for SJs

Cell-type	Eta cell	Eta module / P_{mpp} (72 cells/mod)
n-TOPCon	24.5 %	22.5 % / 581 Wp
Pero-TOPCon	29.5 %	26.84 % / 693 Wp
n-SHJ	25 %	22.96 % / 593 Wp
Pero-SHJ	30 %	27.3 % / 705 Wp

Main module materials	Price	Unit
PV Glass 2 mm	4.5	€/m²
POE	1.5	€/m²
Al-frame	1.5	€/m
Junction box	2.8	€/unit
Silicone sealant	2.2	€/l
Butyl edge sealant	0.1	€/cm³

Figure 4: Analysed Module production sequence, final module efficiency and price of main module materials used for LCOE and LCA of the 4 selected technologies.

The results of the TCO showed that even though the tandems require additional processing steps to deposit the perovskite layer on top of the silicon bottom cells, due to the higher efficiency potential of the perovskite-silicon tandems, a cost differential of +1 to 45% higher than the c-Si single junctions on a Watt-peak basis is foreseen. The range in the cost relates to the low and high perovskite material price scenarios considered.

2.2. Levelized Cost of Electricity of Selected Technologies

The LCOE is calculated by comparing all costs incurred over the lifetime of the power plant for the construction and operation and the total amount of energy generated, as shown in Figure 5, using the net present value method [3].

$$LCOE = \frac{\overbrace{PC_0 - \sum_{t=1}^{T}\frac{DEP + INT}{(1+DR)^t}TR + \sum_{t=1}^{T}\frac{AO}{(1+DR)^t}(1-TR) - \frac{RV}{(1+DR)^t}}^{\text{Lifecycle cost}}}{\underbrace{\sum_{t=1}^{T}\frac{Initial\ kWh * (1-SDR)^t}{(1+DR)^t}}_{\text{Lifetime energy production}}}$$

PC_0	Project cost (in t=0)	T	System lifetime
DEP	Depreciation	INT	Interest paid
DR	Discount Rate	TR	Tax Rate
AO	Annual operational cost	RV	Residual value
SDR	System degradation rate		

Figure 5: Formula for calculating the levelized cost of electricity.

When applying the net present value method, the expenses for the investment, as well as the payment flows of revenues and expenditures during the power plant's lifetime, are calculated by discounting related to a shared reference date. For this purpose, the present values of all expenses are divided by the present value of electricity generation. A discounting of power generation initially seems incomprehensible from a physical point of view but is a consequence of financial mathematical transformations. The underlying idea is that the generated electricity implicitly corresponds to the revenue from the sale of this energy. Thus, the further this income is in the future, the lower the associated present value. The total annual expenditure throughout the entire operating period consists of the investment expenditure and the operating costs, which arise during the lifetime. rough discounting all expenditures and the quantity of electricity generated over the lifetime to the same reference date, the comparability of LCOE is assured.

Extending the results of the TCO model to the LCOE assessment for the residential case (GHI 1300 kWh/m^{2}a, 10 kWp system size, 30-year system lifetime), it was found that the pero-SHJ based tandem provided the lowest LCOE compared to all other technology types. The main LCOE calculation parameters including the BOS cost categories considered are shown in Figure 6.

LCOE calculation parameters	Value	Unit
Global horizontal irradiation	1300	kWh/m^{2}a
Degradation (1st year/2nd year on)	1 / (0.5/1)	%/a
Temperature coefficient	-0.27/-0.32	%/K
System life	30/20	years
System performance ratio	83.6/84.4	%
WACC	5	%

BOS cost category	Residential
Inverter Costs	13 €ct/W$_p$
Area Proportional BOS Costs	125 €/m²
Power Proportional BOS Costs	13.5 €ct/W$_p$
Soft BOS Costs	28.8 €ct/W$_p$
Annual Costs (as a percentage of system investment)	1.6%
Assumed margin on Total PV system costs	15 %

Figure 6: Key LCOE calculation parameters along with the balance of system cost categories used.

A sensitivity analysis with key parameter variation including the BOS costs, GHI, system lifetime, degradation rate and module efficiency amongst others was also performed to see their individual impact on the LCOE of the pero-silicon tandems. The results showed that the module efficiency and the system lifetime have the highest impact on the LCOE and are inversely proportional to the LCOE i.e., higher the module efficiency and system (or module) lifetime, lower is the LCOE. All other key parameters are directly proportional to the LCOE implying that an increase or decrease in their values increases or decreases the LCOE respectively, with the cost of capital having the strongest impact in the directly proportional parameters. It is important to highlight that the calculated lowest LCOE of the Pero-SHJ tandem is strongly dependent on the module lifetime, module efficiency and degradation rate. Hence the stability of Pero-Silicon tandems is key to ensure this low LCOE and market acceptance.

3. SUMMARY

To summarize, firstly, the production cost or TCO of the 4 selected technology types was carried out using Fraunhofer ISE's in-house, bottom-up total cost of ownership model, "SCost" for the cell and module processing routes detailed in the previous sections. The perovskite top layer for the tandem structures was based on the key device architecture list detailed in deliverable report D10.1. The TCO analysis indicated that due to the higher efficiency of pero-silicon tandems, their cost could be 1-45% higher than c-Si single junctions with the range in the cost related to the low and high perovskite material price scenarios considered. Extending the TCO model to the LCOE assessment for the residential case, it was found that the pero-SHJ based tandem can provide the lowest LCOE compared to all other technology types as long as similar lifetimes and degradation rates as single junction c-Si modules are achieved for the perovskite-silicon tandem modules. A sensitivity analysis on the LCOE with key parameter variation showed that the module efficiency and the system lifetime have the highest impact on the LCOE and are inversely proportional to the LCOE i.e., higher the module efficiency and system (or module) lifetime, lower is the LCOE. Further detailed results of the analysis are to be presented in a subsequent journal paper and/or international conference in 2025.

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