Total Cost of Ownership, LCA and LCOE Analysis of Perovskite-Silicon Tandems Compared to Single Junction Crystalline Silicon PV Technologies

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TCO, LCA and LCOE Analysis of Pero-Si Tandems vs. SJ c-Si PV Technologies

Key Questions

1. **What are the production costs, carbon footprint and electricity costs of Perovskite-Silicon tandems compared to single junction crystalline-Silicon technologies?**

2. **What to focus on for making Perovskite-Silicon tandems economically and environmentally competitive?**

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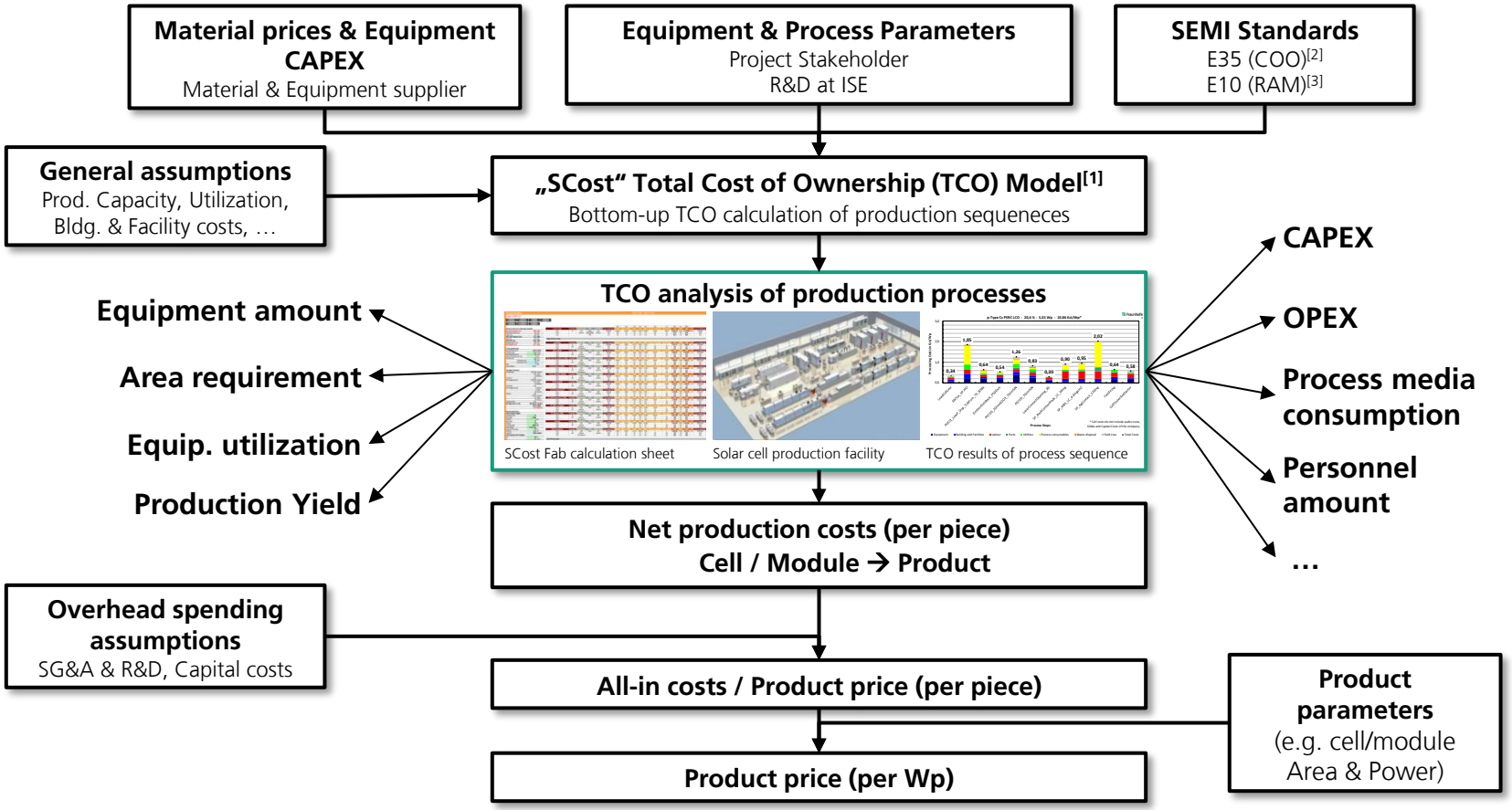
Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Methodology for Cost Modelling

Production cost assessment for single process steps and TCO for process routes [1].

Equipment and process data for state-of-the-art technology required.

→ Data acquisition for industrial production equipment is crucial for assessment!



[1] https://www.ise.fraunhofer.de/en/business-areas/photovoltaics-production-technology-and-transfer/technology-assessment-and-transfer.html
[2] Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment, SEMI E35-0618.
[3] Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability (RAM) and Utilization, SEMI E10-0814E.

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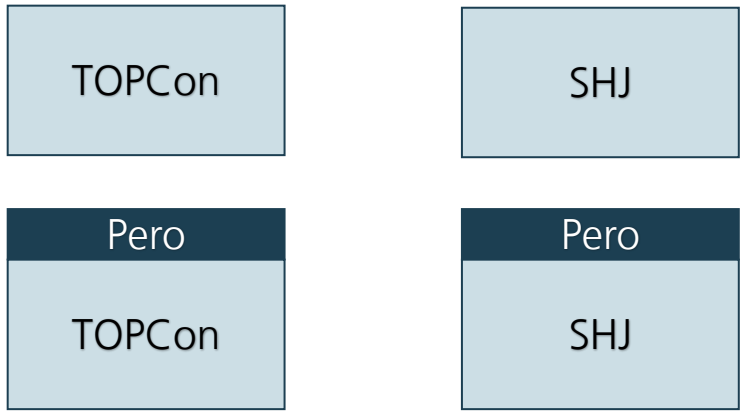
Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Analysed Technologies and Key Inputs for Modelling

4 technologies evaluated for cell (n-Cz 130µm M10 wafer) and module (72 cell glass-glass) production:

- **2 single junction crystalline-Silicon based:**
- **2 fully textured 2-Terminal tandems:**

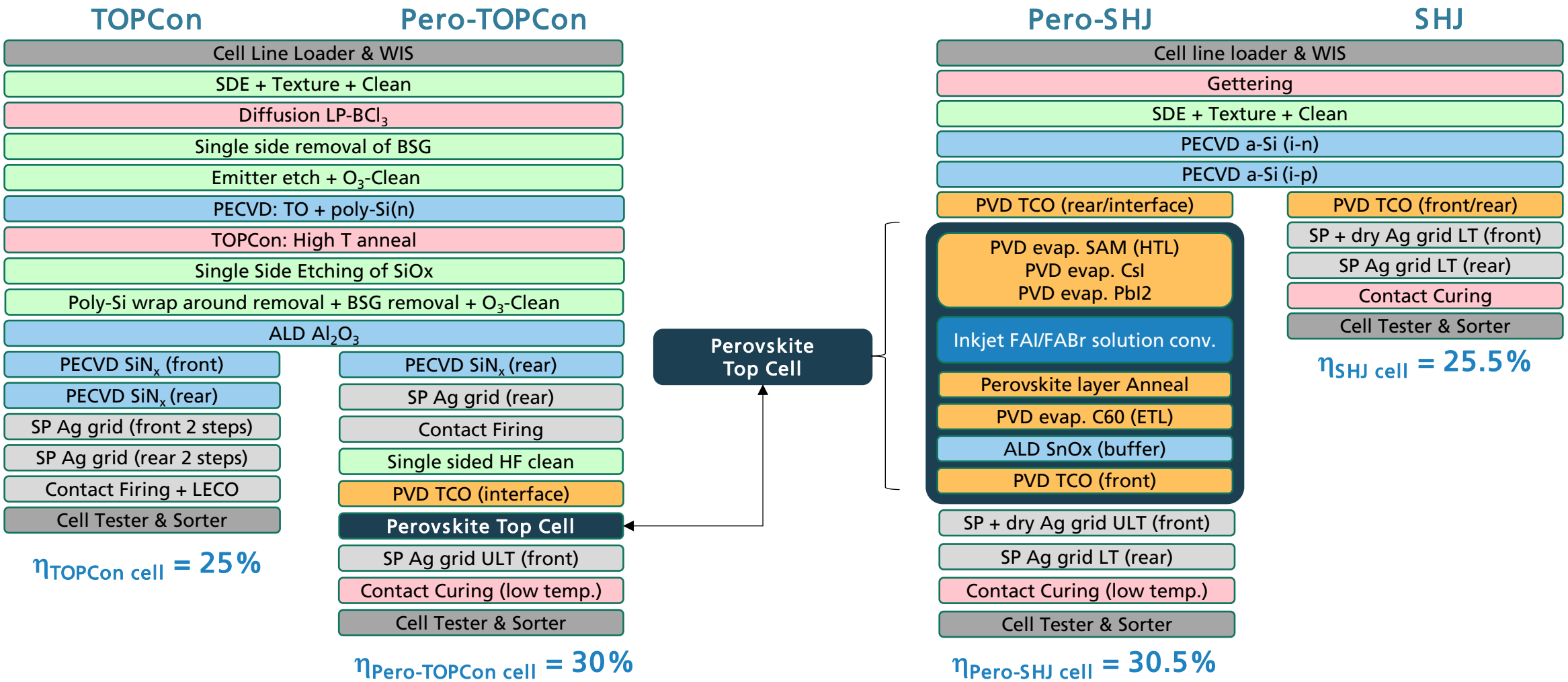


Location: Green field production site in Eastern Europe.
Annual output: Same number of modules produced per year (5.2 to 6.4 GWp/a)
n-Cz 130 µm M10 wafer price: 19 €ct/wafer[1]

1: OPIS avg. wafer price 2024

Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Analysed Cell Production Sequences



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Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Perovskite Top Cell Material Prices

Very high prices for perovskite materials currently used in research.

Perovskite Materials	Researched price for low volume orders	Price with 50% reduction	Price with 90% reduction	Unit
C60	**41,400**	**20,700**	**4,140**	€/kg
FAI	1,167	584	117	
FABr	1,460	730	146	
SAM 2-PACz	**470,000**	**235,000**	**47,000**	
CsI	**13,600**	**6800**	**1,360**	
PbI2	**3,500**	**1750**	**350**	

PbI_2, CsI, SAM 2-PACz and **C60** have the **largest material cost share**, based on their specific consumptions, of the perovskite top cell.

- Low volume orders based on ISE orders, internet research and from contacting material suppliers.
- Not shown here are the solvents like butanol and ethanol which are bulk materials and will not be impacted by scaling.

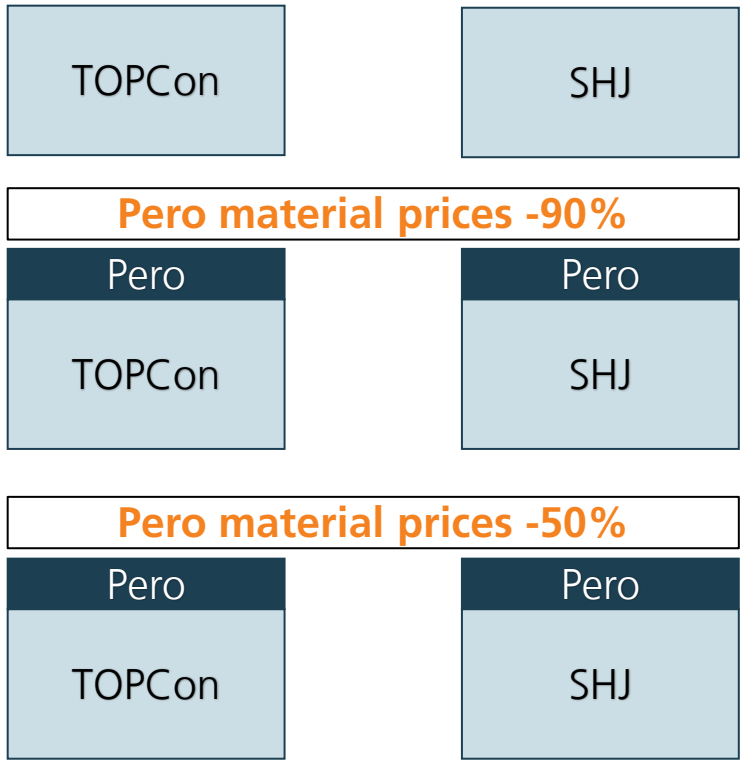
Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Analysed Technologies

4 technologies evaluated for cell (n-Cz 130µm M10 wafer) and module (72 cell glass-glass) production:

- **2 single junction crystalline-Silicon based:**
- **2 fully textured 2-Terminal tandems:**

2 further scenarios for non-optimized tandems with:



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Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

Analysed Module Production Sequence

72 cell Glass-Glass module
2 mm Glass loader1
Lay-up POE1
Combined tabber stringer + Auto bussing
Lay-up Cells / POE2 / 2mm 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

Materials (e.g. glass, POE, Al-frame, etc.) **account for ~80%** of module production costs for the single junction modules.

Butyl edge sealant for tandems increases module production costs by **~20%** vs. single junction modules.

Cell-type	Eta cell	Eta module / P_{mpp} (72 cells/mod)
TOPCon	25.0 %	23.0 % / 593 Wp
Pero-TOPCon	30.0 %	27.3 % / 705 Wp
SHJ	25.5 %	23.4 % / 605 Wp
Pero-SHJ	30.5 %	27.8 % / 717 Wp

- Module dimensions: 2278 x 1134 mm
- CTM (power loss) considered as -0.21% & -1.11% absolute for the SJ and tandems respectively.

Total Cost of Ownership (TCO) of Pero-Si Tandems vs. SJ c-Si PV Technologies

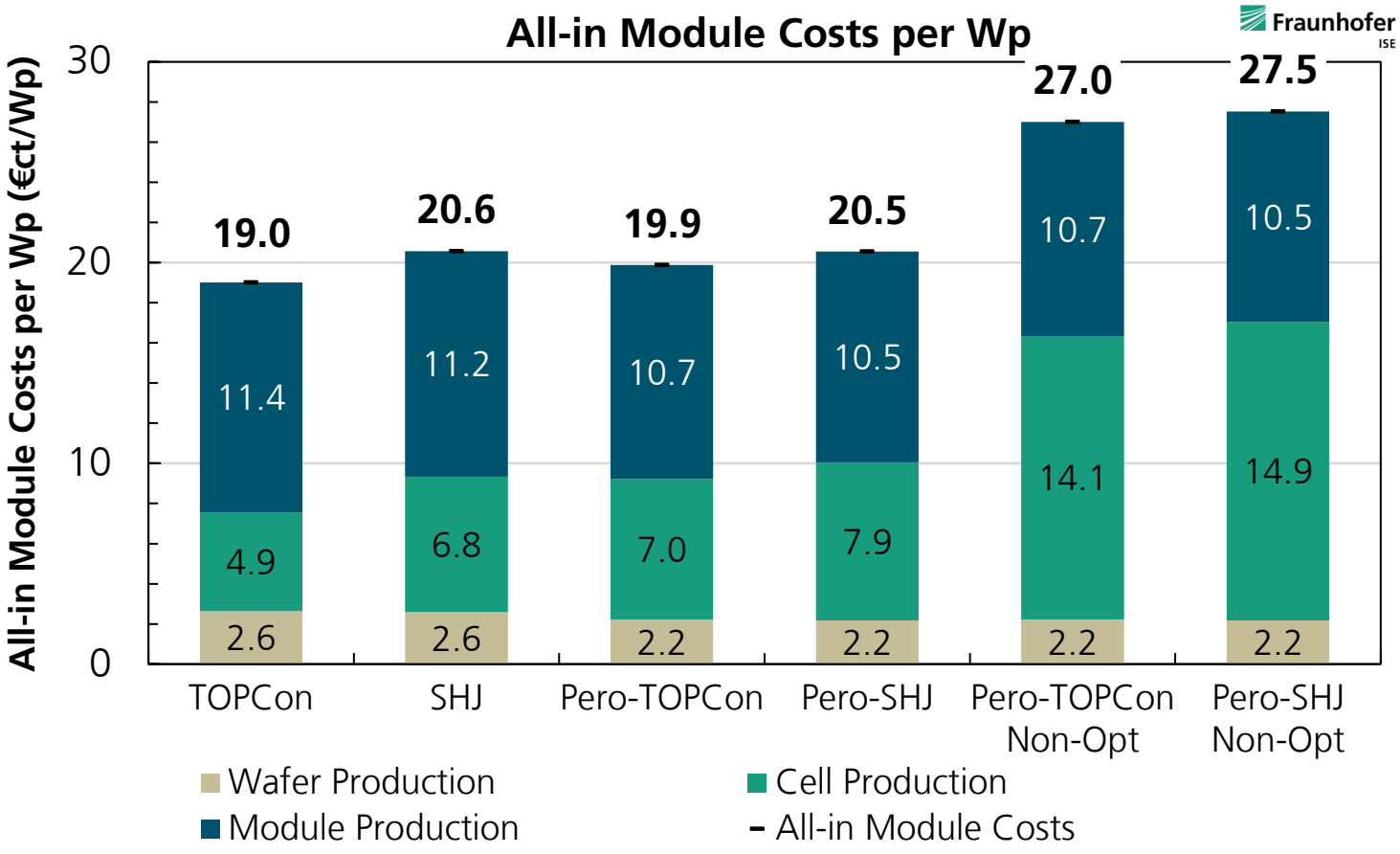
All-in Module Cost Comparison for all Technologies

All-in-module costs (Wp) for:

- Pero-TOPCon tandems vs. TOPCon:
  + 5% to + 42%
- Pero-SHJ tandems vs. SHJ:
  -0.1% to +34%

Pero-Si tandems can provide competitive all-in module costs to established & mature SJ technologies.

Focus on reducing perovskite material prices!



Note: All-in Module costs include SG&A / R&D costs and cost of capital on top of production costs.
Module efficiency: TOPCon - 23%, SHJ - 23.4%, Pero-TOPCon - 27.3%, Pero-SHJ - 27.8%

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LCOE Analysis of Pero-Si Tandems vs. SJ c-Si PV Technologies

General Assumptions and Key Inputs

LCOE evaluation for:

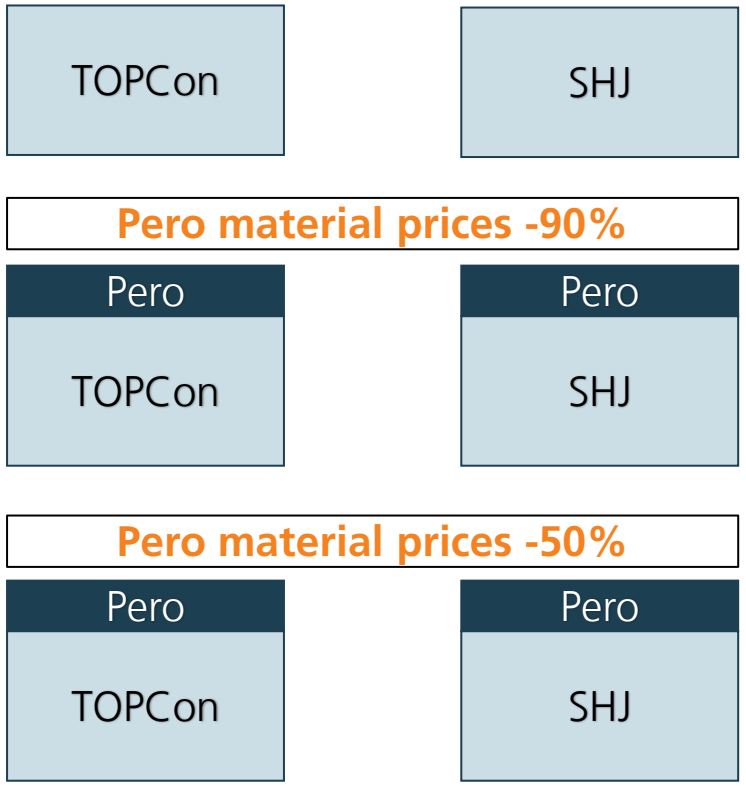
- 10 kWp residential rooftop system
- Location: Southern Germany (GHI: 1300 kWh/m²a)
- Assumed same annual specific PV energy yield for:
  - TOPCon and Pero-TOPCon of 1256 kWh/kWp/a
  - SHJ and Pero-SHJ of 1268 kWh/kWp/a

For TOPCon, SHJ, Pero-TOPCon and Pero-SHJ:

- Degradation rate (1st year/2nd year on): 1 / 0.5 %/year
- System life: 30 years

For non-optimized Pero-Si tandems:

- Degradation rate (1st year/2nd year on): 1 / 1 %/year
- System life: 20 years



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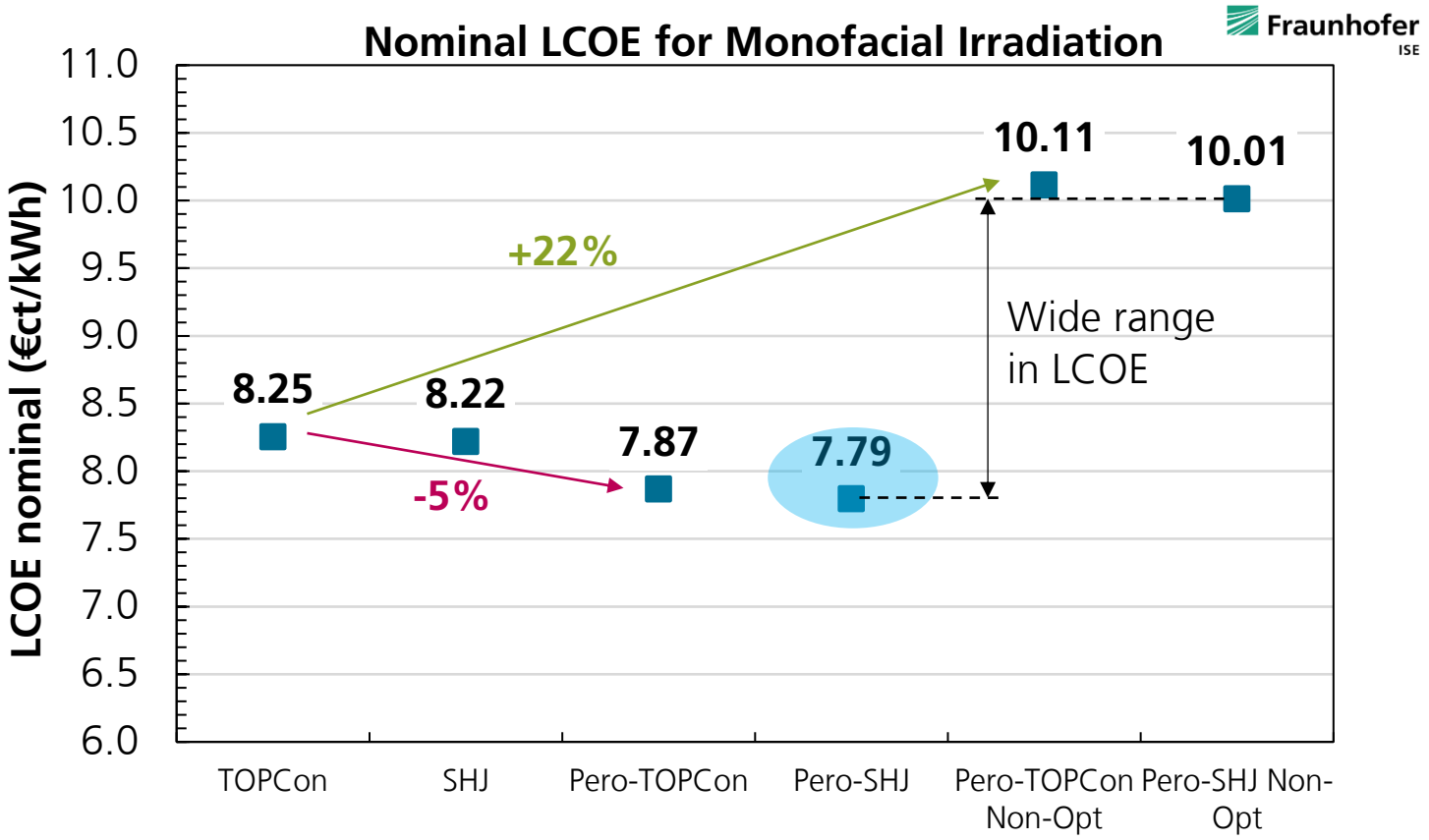
LCOE Analysis of Pero-Si Tandems vs. SJ c-Si PV Technologies

Nominal LCOE for Residential Rooftop Systems

LCOE Results

- Pero-Si tandems can provide lower LCOE than the SJ counterparts.
- Non-optimized Pero-Si tandems show substantially higher LCOE than SJ counterparts.

Low perovskite material prices, high reliability and stability are key for Pero-Si tandems to provide a competitive LCOE!



LCOE parameters: System size: 10 kWp (pitched roof); GHI: 1300 kWh/m²a; Degradation (1st year/2nd year on): 1/(0.5/1) %/a; Temp. coeff.: -0.27/-0.32 %/K; System life: 30/20 years; WACC: 5%
BOS costs: Inverter 10 €ct/Wp; Area proportional BOS costs: 103 €/m²; Power proportional BOS costs: 22 €ct/Wp; Soft BOS costs: 23 €ct/Wp; Annual costs: 1 €ct/Wp; Margin: 15% on total PV system costs.

LCOE Analysis of Pero-Si Tandems vs. SJ c-Si PV Technologies

LCOE Residential Rooftop – Sensitivity Analysis

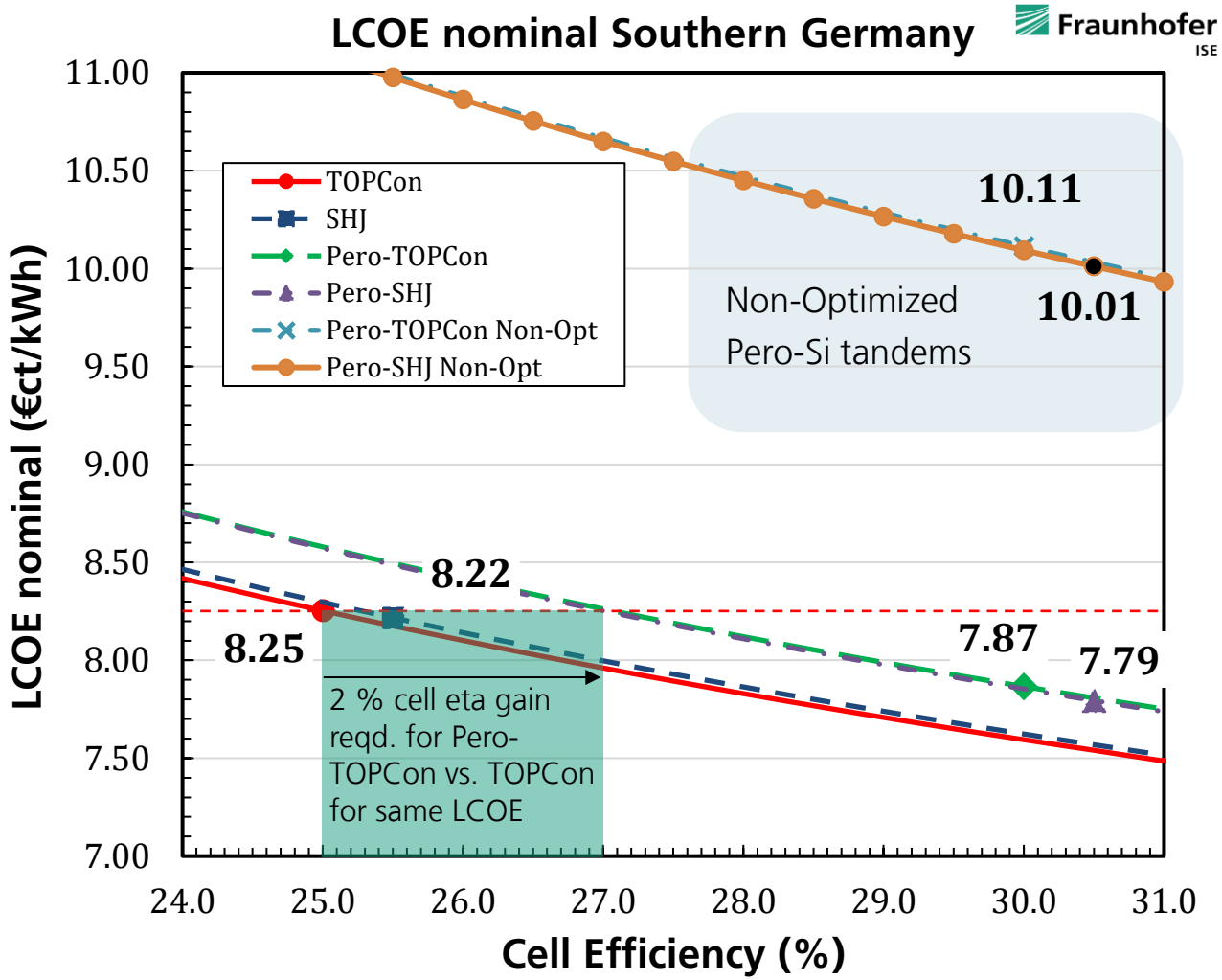
Iso-LCOE curves for all assessed technologies.

To achieve the same LCOE:

~2% higher cell efficiency required for Pero-Si tandems compared to SJ technologies.

For the non-optimized Pero-Si tandems, a **cell efficiency gain of >10%** required.

Focus on reducing perovskite material prices, improving reliability and stability of Pero-Si tandems!



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Life Cycle Assessment (LCA) of Pero-Si Tandems vs. SJ c-Si PV Technologies

General Assumptions and Key Inputs

Focus on Carbon Footprint in g CO_2-eq/kWh or the Global Warming Potential (GWP)

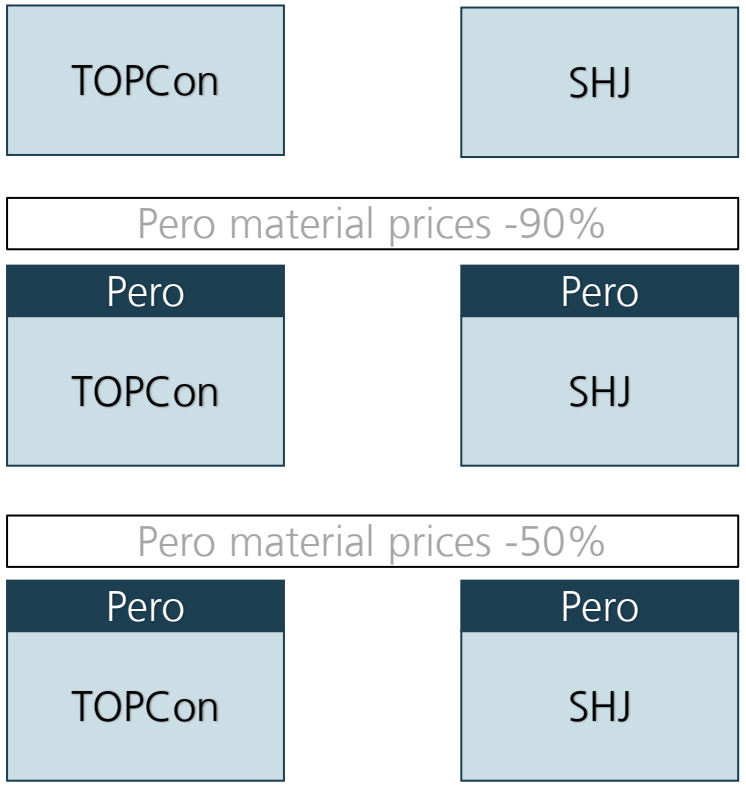
- Residential rooftop system, functional unit 1 kWh
- Wafers are assumed to be supplied from China.
- Cells and modules are assumed to be produced in Germany.
- Proxy consumables are used for materials not available in the Life Cycle Inventory.

For TOPCon, SHJ, Pero-TOPCon and Pero-SHJ:

- Degradation rate (1st year/2nd year on): 1 / 0.5 %/year
- System life: 30 years

For non-optimized Pero-Si tandems:

- Degradation rate (1st year/2nd year on): 1 / 1 %/year
- System life: 20 years



Climate change within Environmental Footprint 3.0 impact assessment method, the Ecoinvent 3.11 database, allocation cut-off by classification used and the LCA Software SimaPro.

Life Cycle Assessment (LCA) of Pero-Si Tandems vs. SJ c-Si PV Technologies

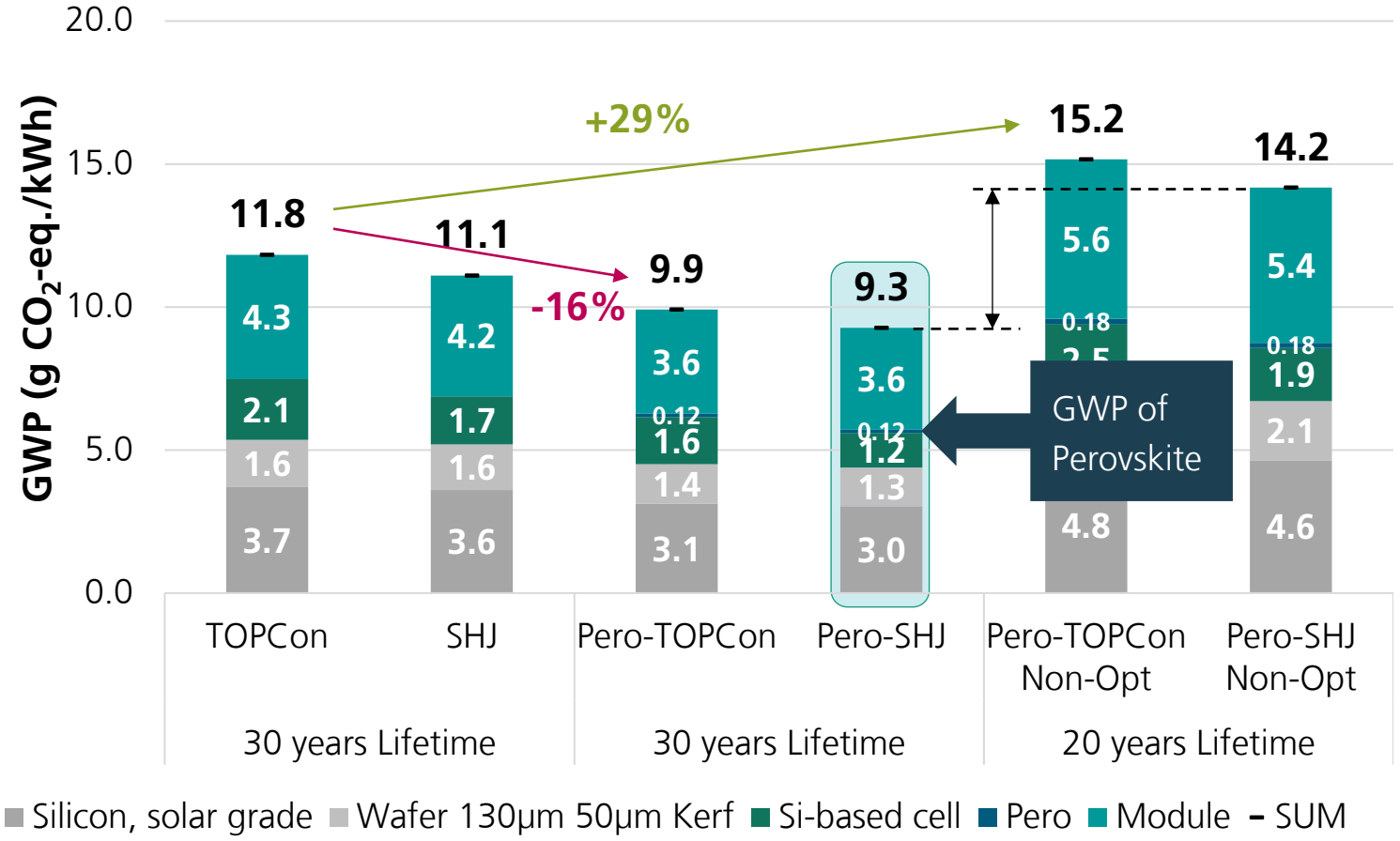
Carbon Footprint or Global Warming Potential (GWP) Assessment

Pero-Si tandems show **lower GWP** than the SJ counterparts.

Non-optimized Pero-Si tandems show **substantially higher GWP** than SJ counterparts.

Perovskite materials and perovskite top cell production only **contributes ~1%** to the GWP of Pero-Si tandems.

Focus on improving reliability and stability of tandems!



Climate change within Environmental Footprint 3.0 impact assessment method, the Ecoinvent 3.11 database, allocation cut-off by classification used and the LCA Software SimaPro.

A.A. Khan et al, Environmental Profile of Scalable Perovskite Silicon Tandem vs. Silicon Heterojunction Technology, tandemPV workshop 2023, Fraunhofer Lighthouse project MaNiTU.

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TCO, LCA and LCOE Analysis of Pero-Si Tandems vs. SJ c-Si PV Technologies

Summary & Takeaways

TCO analysis shows that **Pero-Si tandems can provide competitive all-in module costs** to established & mature single junction technologies.

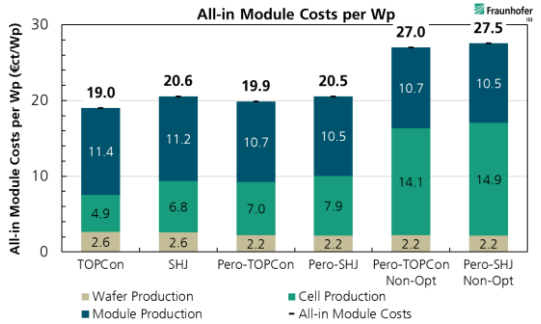
- **Focus on reducing perovskite material prices!**

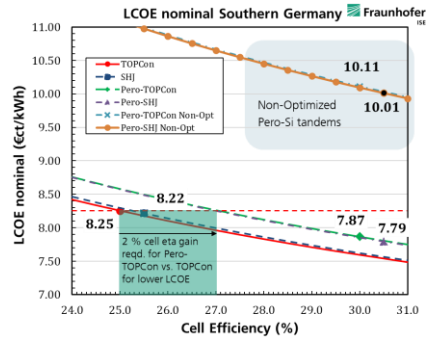
LCOE analysis shows that **~2% higher cell efficiency required for Pero-Si tandems** (-90% perovskite material price, -0.5%/a degradation rate & 30-year lifetime) compared to single junction technologies to achieve the same LCOE.

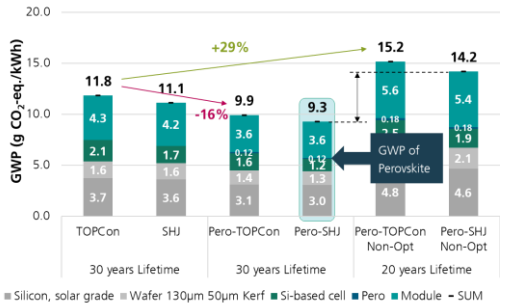
- **Focus on reducing perovskite material prices and improving reliability and stability!**

LCA shows **that Pero-Si tandems can provide the lowest carbon footprint / GWP** from all assessed technologies.

- **Focus on improving reliability and stability!**







Thank You for Your Attention!

Contact

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Link to Fraunhofer ISE contributions of the 42nd EU PVSEC:
https://ise.link/eupvsec2025
available as of 26.09.2025