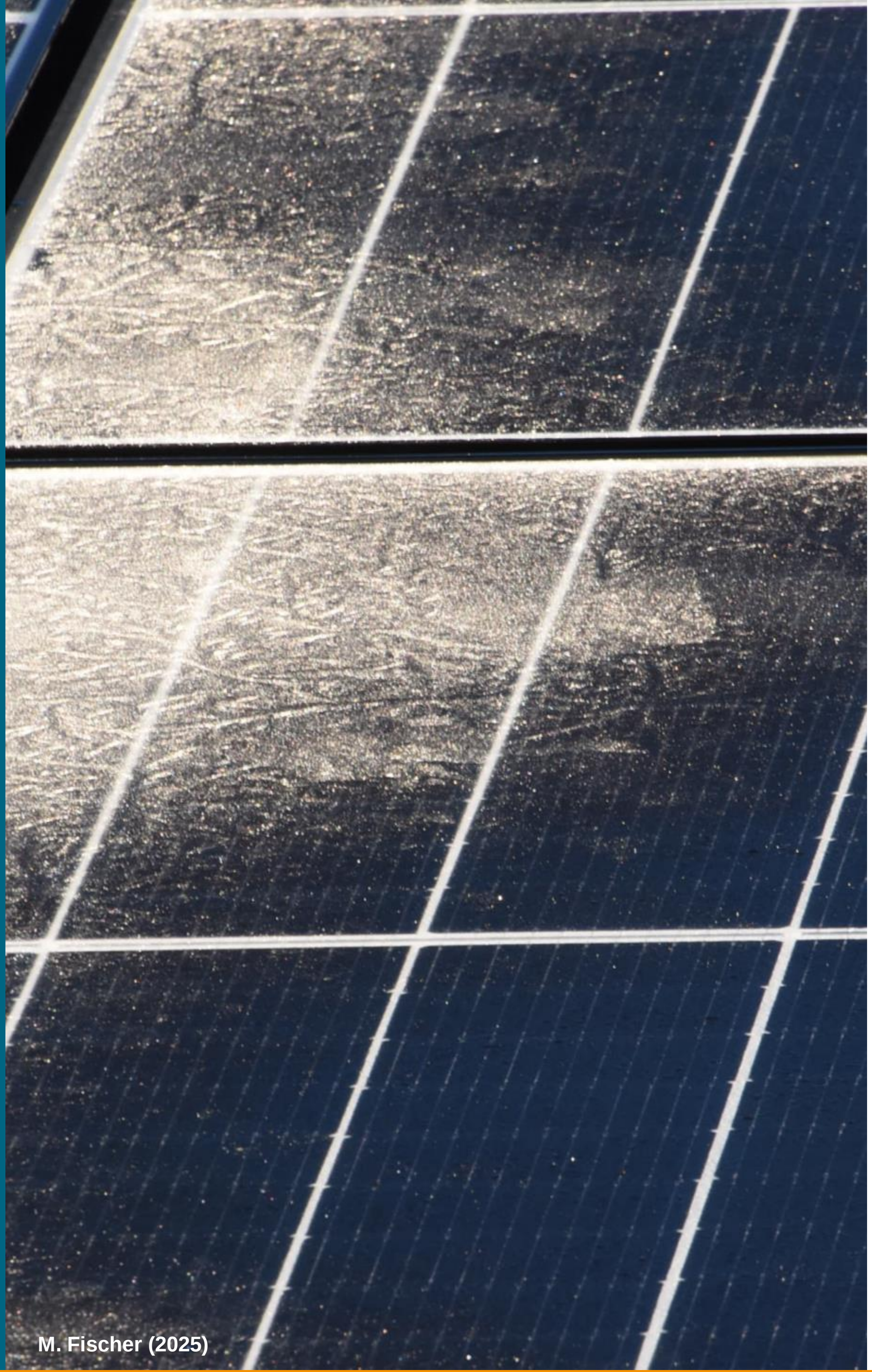

M. Fischer (2025)

Technology Trends and Insights from the International Technology Roadmap for PV (ITRPV)

VDMA, Sector Group Photovoltaics Equipment
Dr. Puzant Baliozian

TaiyangNews Event, New Delhi, India
11 April 2025

Future for upcoming generations
Renewable Energy Expansion Required

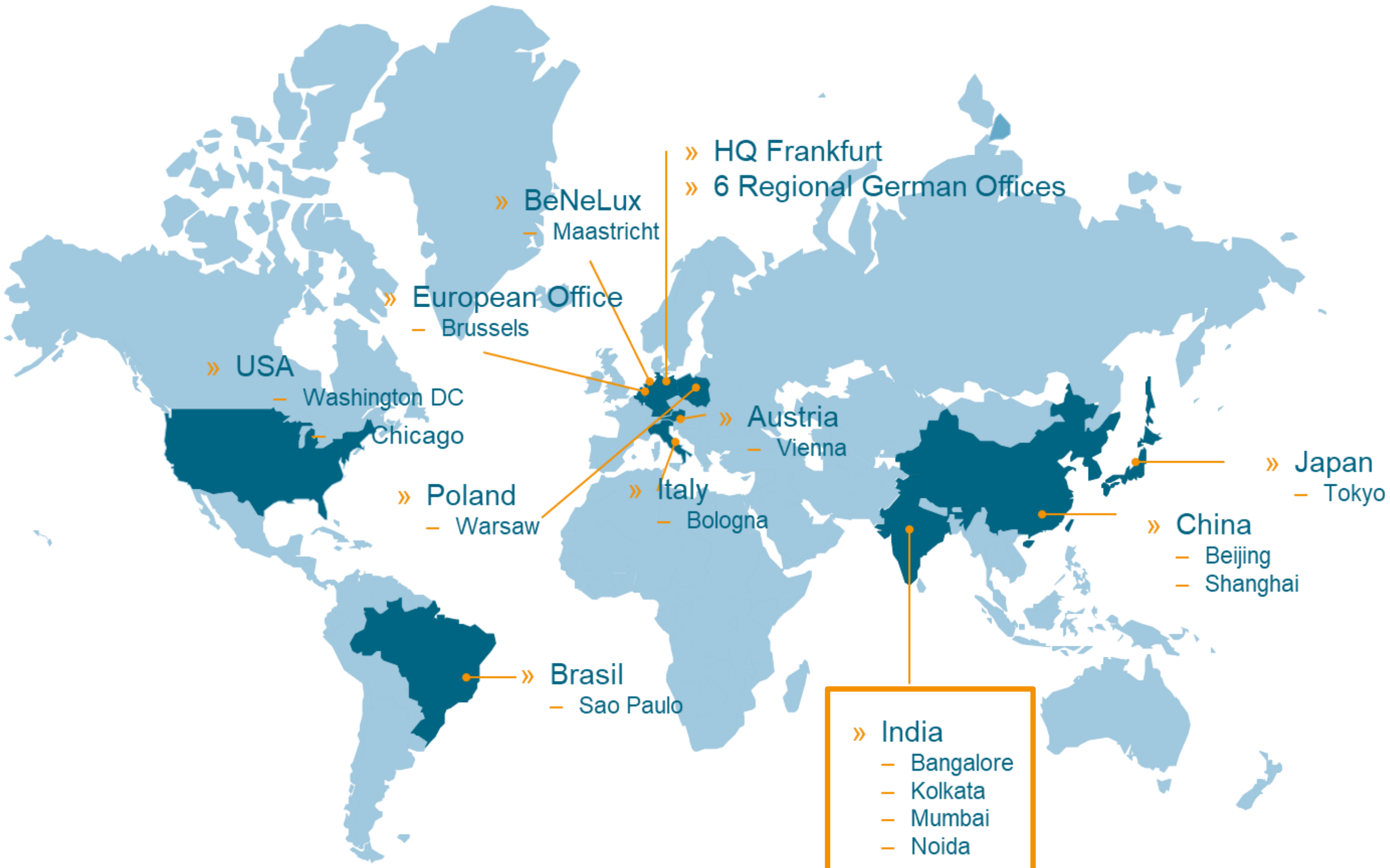
- **Commitment to limiting global warming to below 1.5°C**
- **Urgency to cut greenhouse gas emissions to prevent climate catastrophes**
- **Sustainable clean technologies to reducing CO_2 footprint, enhancing recyclability**
- **Growth of solar manufacturing of advanced PV technologies expected**
- **Machinery and equipment play an integral role in all energy transition technologies**

Source: shutterstock (2023)

VDMA

- **Machinery and Equipment Manufacturers Association**
- **Largest European network organization for the mechanical engineering industry (Around 3600 member companies)**
- **Representing the common techno-economic and scientific interest**
- **Headquarters in Frankfurt with offices across the globe**
  - Representation in Indian offices

"Shaping tomorrow's mechanical engineering together"



VDMA India – Overview

Head Office

Kolkata

Managing Director

Mr. Rajesh Nath

Regional Offices

Mumbai

Bangalore

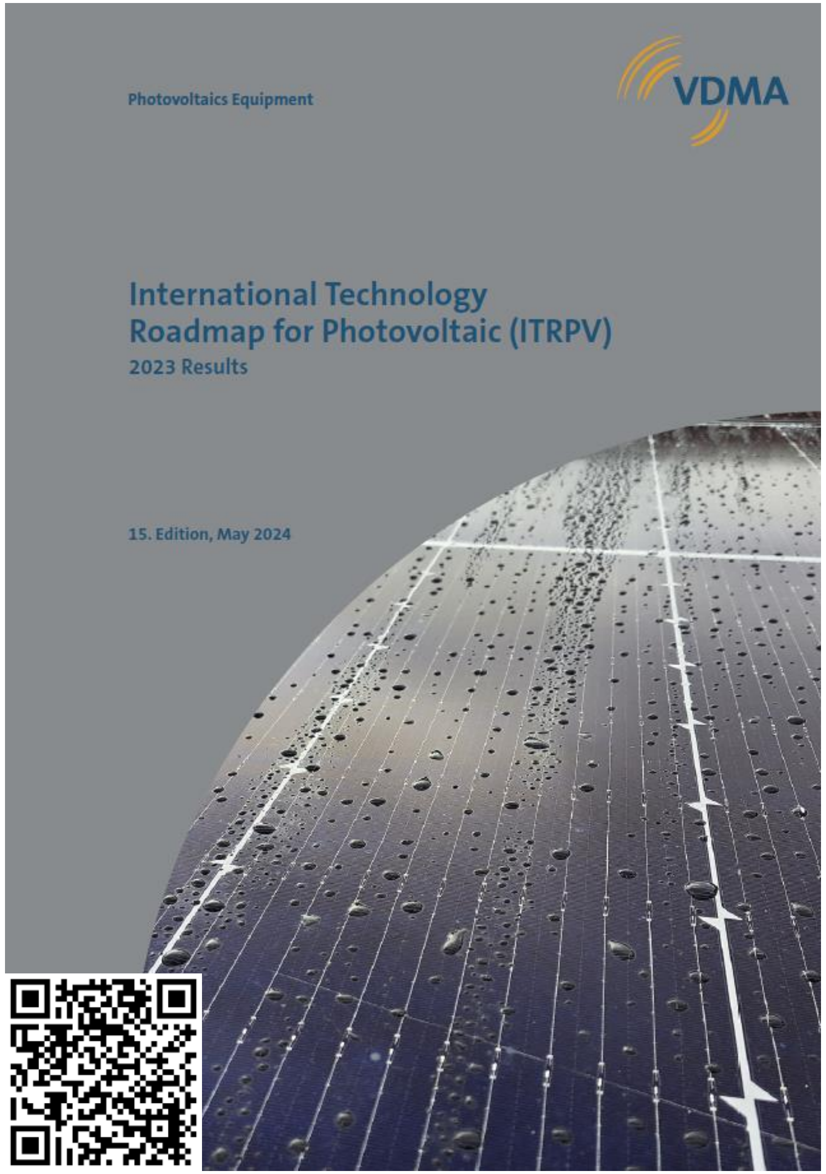
Delhi

Member Companies

Around 600

Active in various Specialized Sectors

The only association of its kind focusing on the Machinery and Equipment Industry



VDMA Sector Group
Photovoltaics Equipment

The voice of EU/German PV Equipment

- Representing equipment and machinery component manufacturers over the value chain
- Crystalline silicon and thin film technologies

- **Running the International Technology Roadmap for Photovoltaics (ITRPV)**
  - Latest PV production status
  - 10-year expert projections of tech topics
  - **One of the most cited PV technology roadmaps**

European PV equipment availability
Covering the PV value chain

- **Availability of high-quality machinery and equipment**
- **Ingot pullers for semiconductor industry can be developed for PV!**
- **European institutions offering entire factory consulting**
  - **Tens of GW-scale manufacturing experience globally**
- **Engineering, service, and operator training**
- **Top notch R&D institutes for the development of emerging tech**
- **Historically already active worldwide!**

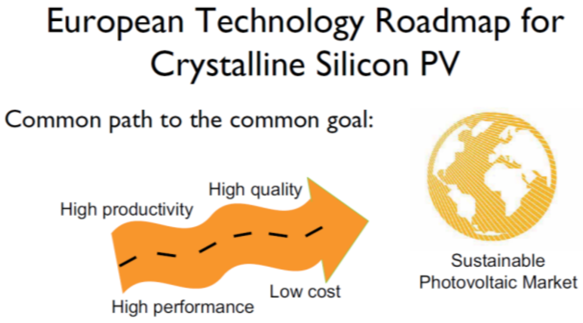
“Made in Germany/Europe“

Manufacturing steps: Wafer, Cell, Module

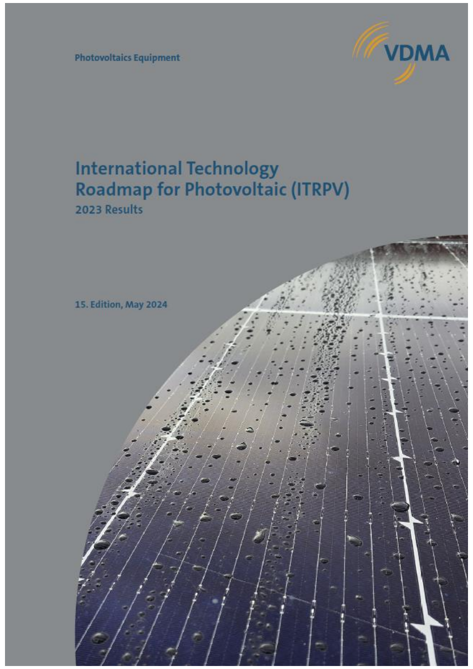
Key PV equipment	Availability in EU
Ingot Puller for PV Applications	✓
Cropping - Squaring - Polishing	✓✓
Diamond Wire Sawing	✓
Separation and cleaning	✓✓
Testing and Sorting	✓✓✓
Fab automation	✓✓
Wet Chemical tools (texture, etching, etc.)	✓✓✓
Thermal tools (diffusion, CVD, firing, etc.)	✓✓✓
Laser tools	✓✓✓
Printing	✓✓✓
IV Sorting, Insitu Quality Control	✓✓✓
Equipment + Fab Automation	✓✓✓
PERC, TOPCon, SHJ, New technologies	✓✓✓
Laser cutter	✓✓✓
Stringer	✓✓✓
Laminator	✓✓✓
IV Measuring – Inline Quality Control	✓✓✓
Fab automation	✓✓✓

ITRPV 16th Edition 2025

Accompanying PV tech development



itrpv.vdma.org



ITRPV 15th edition
Key findings

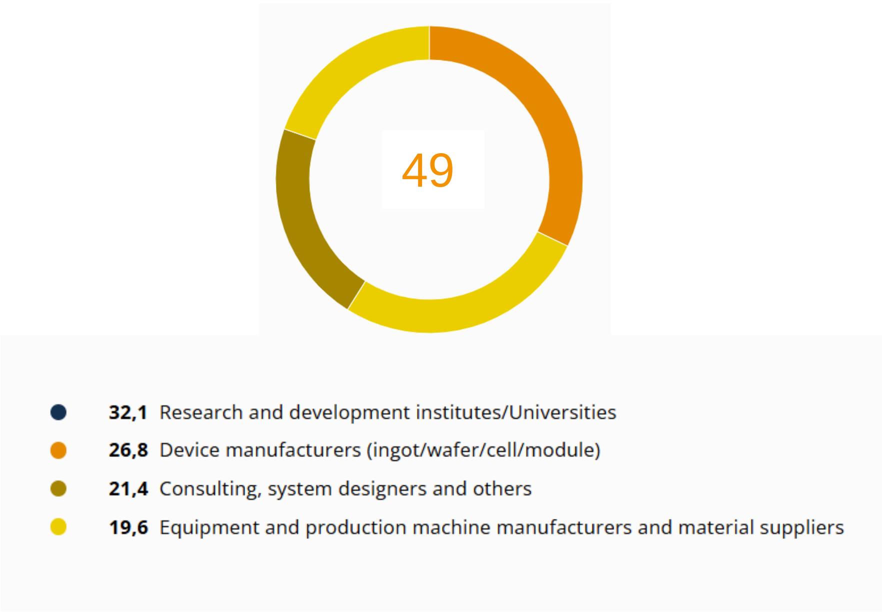
The International Technology Roadmap for PV
Methodology and Contributors

16th edition: 49 contributors from Asia, Europe, and US

Around 100 topics (materials, processes, products, results)

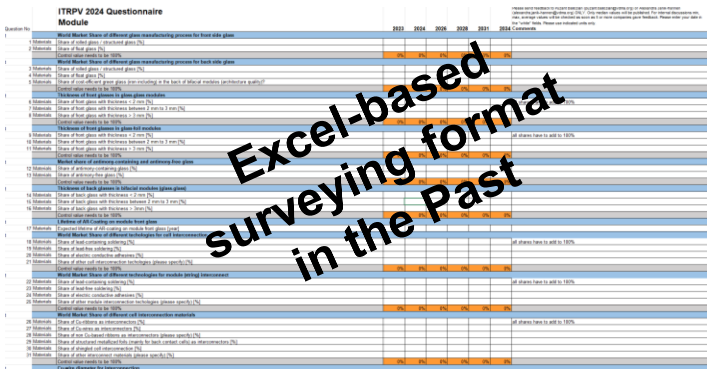
Participating companies → **Data collection and analysis (wafer, cell, module, system)** → **Next ITRPV edition**

Photovoltaics Equipment



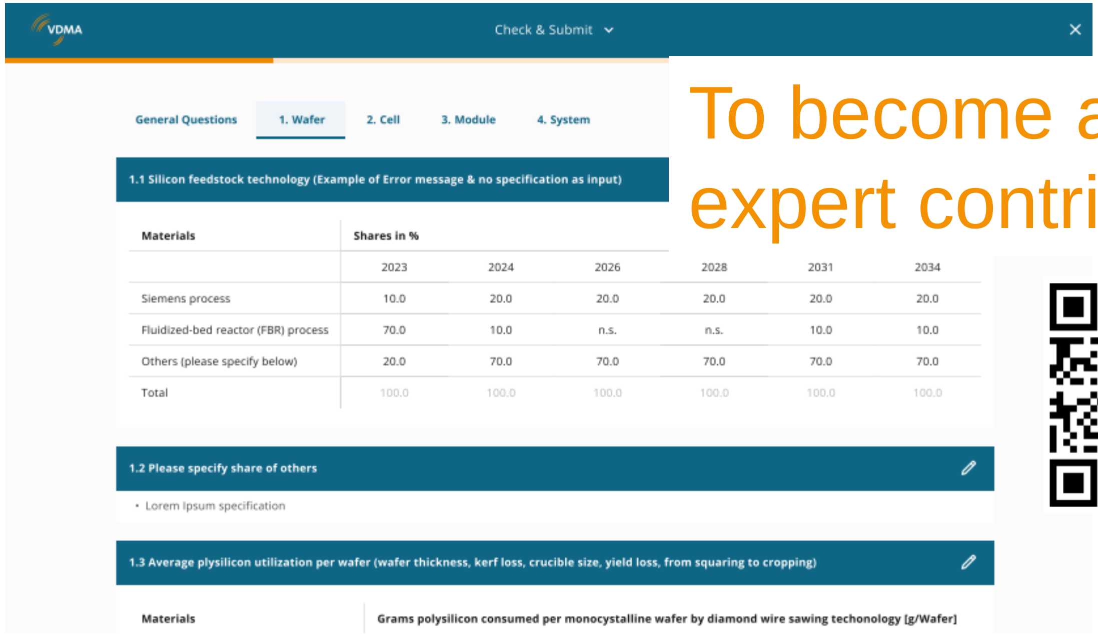
- Diagrams show median values
- Chairpersons discussing topics

ITRPV Digitalization Project
Questionnaire - Results

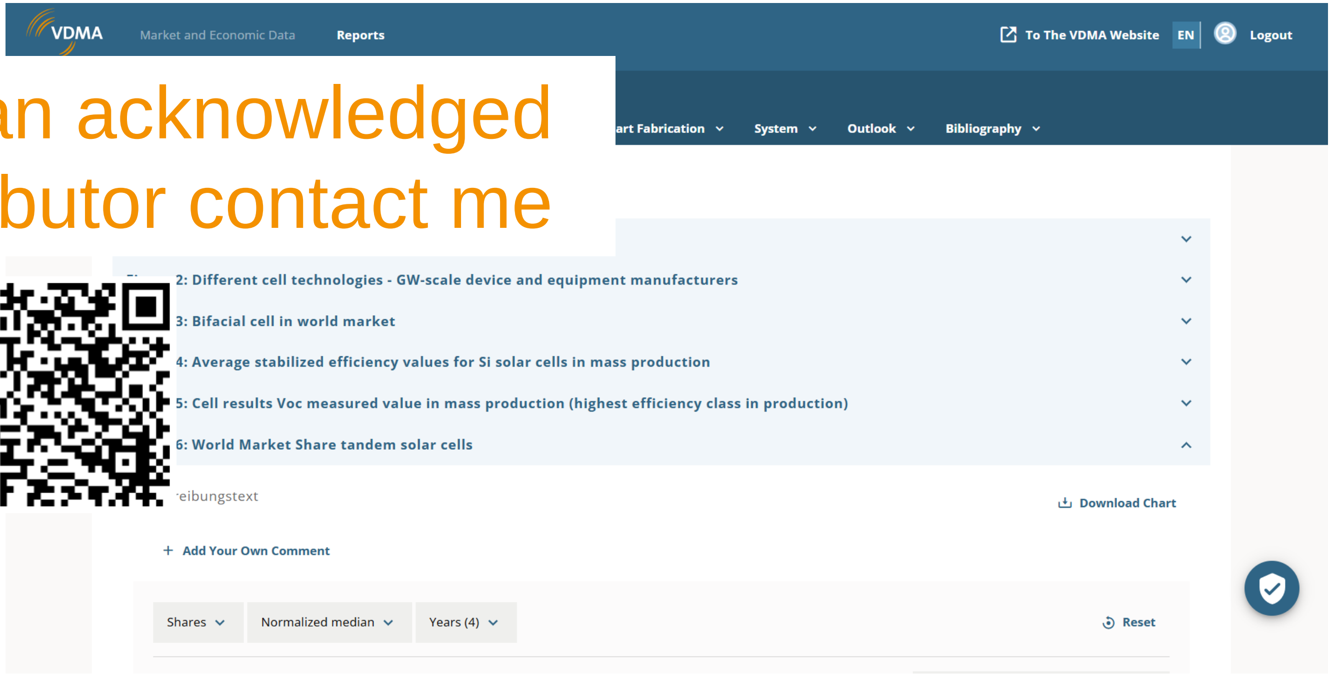


Digital product platform with exclusive features for VDMA members and contributors

Surveying

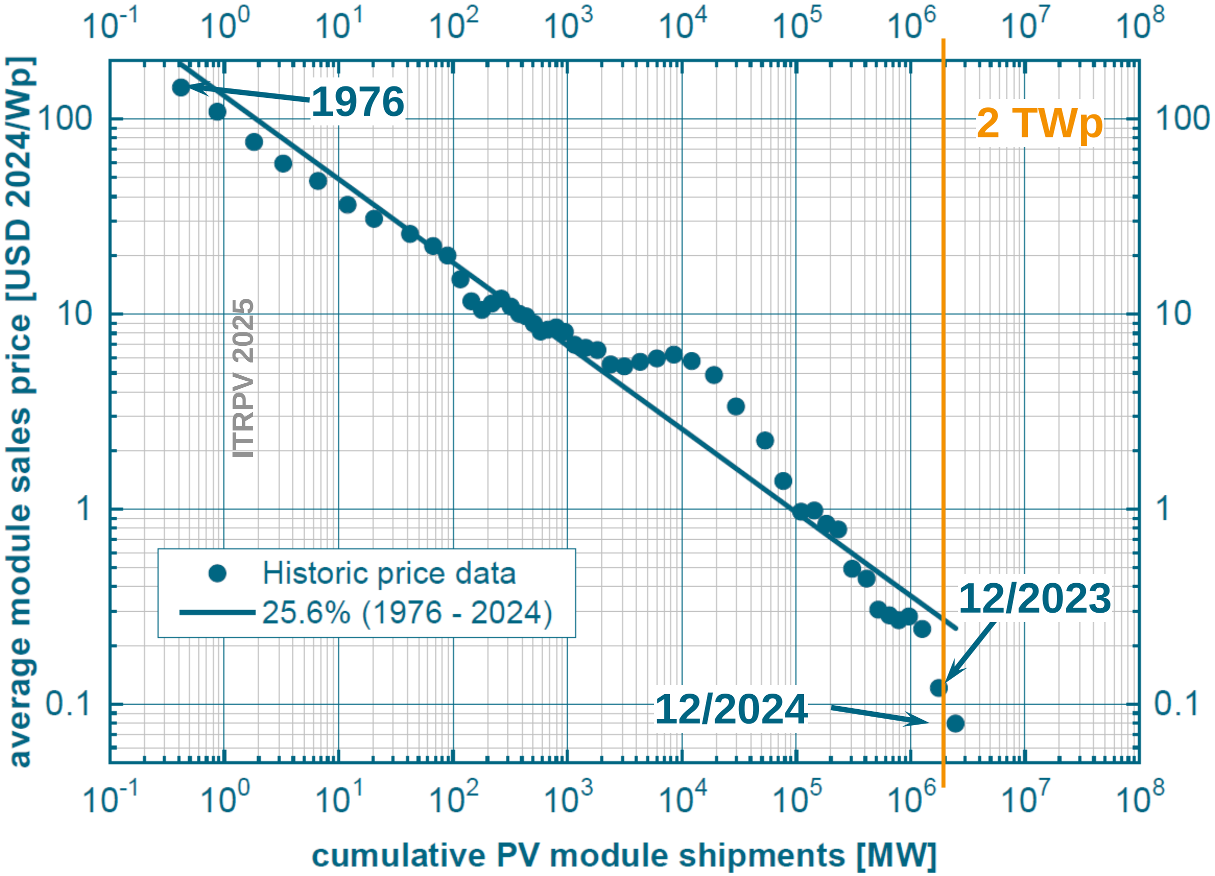


Results



To become an acknowledged expert contributor contact me

Photovoltaics learning curve
Tracking technology and market



Shipments /avg. module spot market price at year end:

2023: 502 GWp / 0.12 US$/Wp
2024: 703 GWp / 0.08 US$/Wp

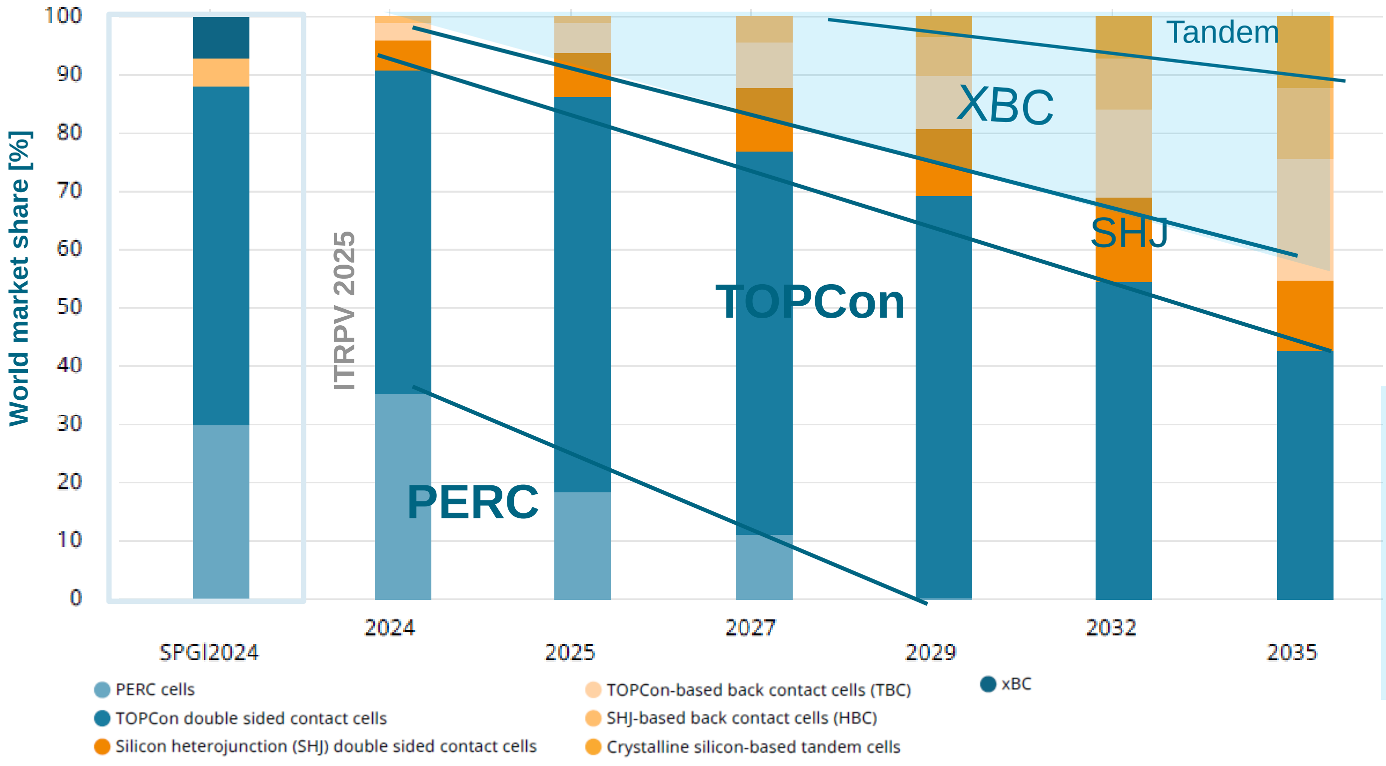
Overall shipment: ≈ 2.472 TWp
Installation 2024: ≈ 566 GWp
Overall installation: ≈ 2.176 TWp

≈ 98% is crystalline silicon 2% thin film

Learning rate ≈ 25.8 % (1976 …. 2024) depends on technological advancements but also price drops due to oversupply

Market share of c-Si PV cell technologies
Product Forecast

TOPCon replaced PERC as PV Tech workhorse in 2024



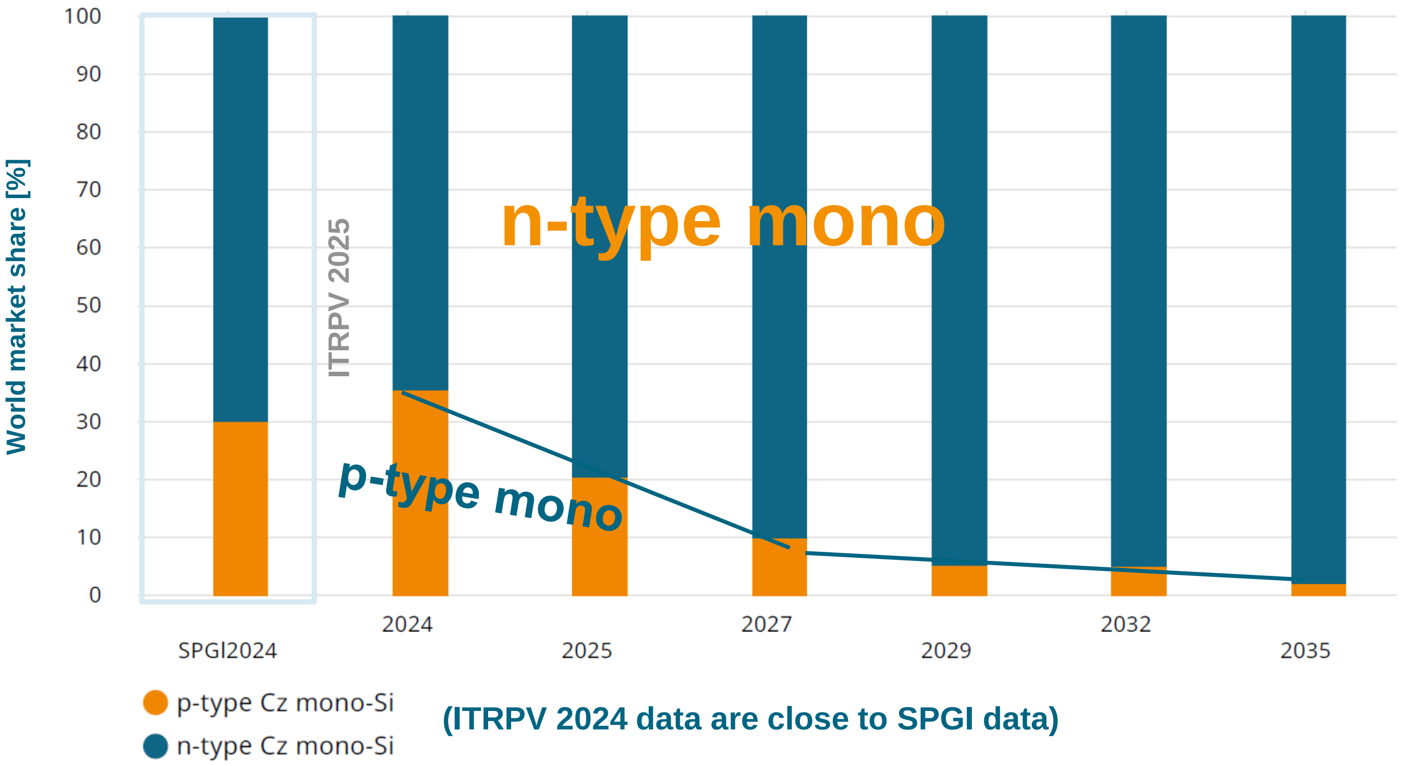
(ITRPV 2024 data are close to SPGI data)

- **TOPCon on n- type 68% share in 2025**
- **PERC on p-type 18% in 2025 phase out ongoing**
- **Si- heterojunction (SHJ)** ≈ 8% in 2024 → ≈12% in 2035
- **Back contact concepts (SHJ/TOPCon-based)** ≈6 % in 2025 → **≈33% in 2035 "XBC"**
- **Si-Tandem** expected after 2026 ≈3 % in 2029 → 12% in 2035

Products Wafer
Market share of wafer types

- Silicon PV goes n-type mono
  - 100% mono-Si → 65% n-type
- n-type material leading in 2024
  - Continued transition expected
- P-type shares fades away coupled with the reduction of PERC share
- Aggregated GW-scale manufactures' data show even faster transition
- Recharged Czochralski-grown process dominates crystallization

Share of c-Si material types

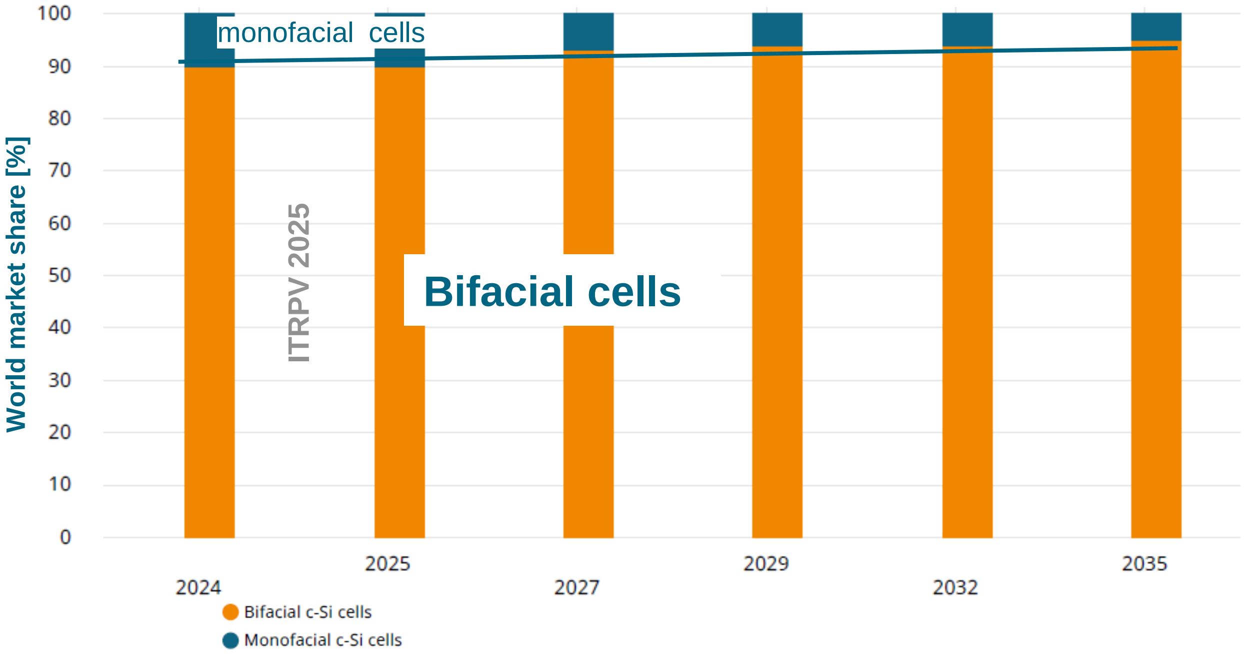


(ITRPV 2024 data are close to SPGI data)

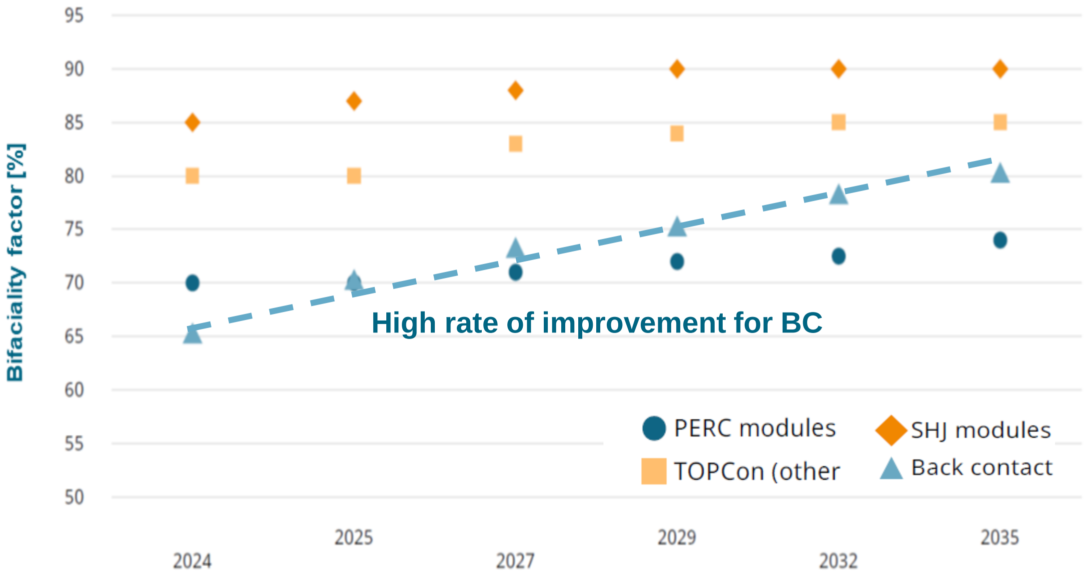
Bifacial products
Market dominance of cells and module bifaciality improvement

Light capture from front and rear sides for energy yield boost

Bifacial cells in "dual" use



Bifaciality factor



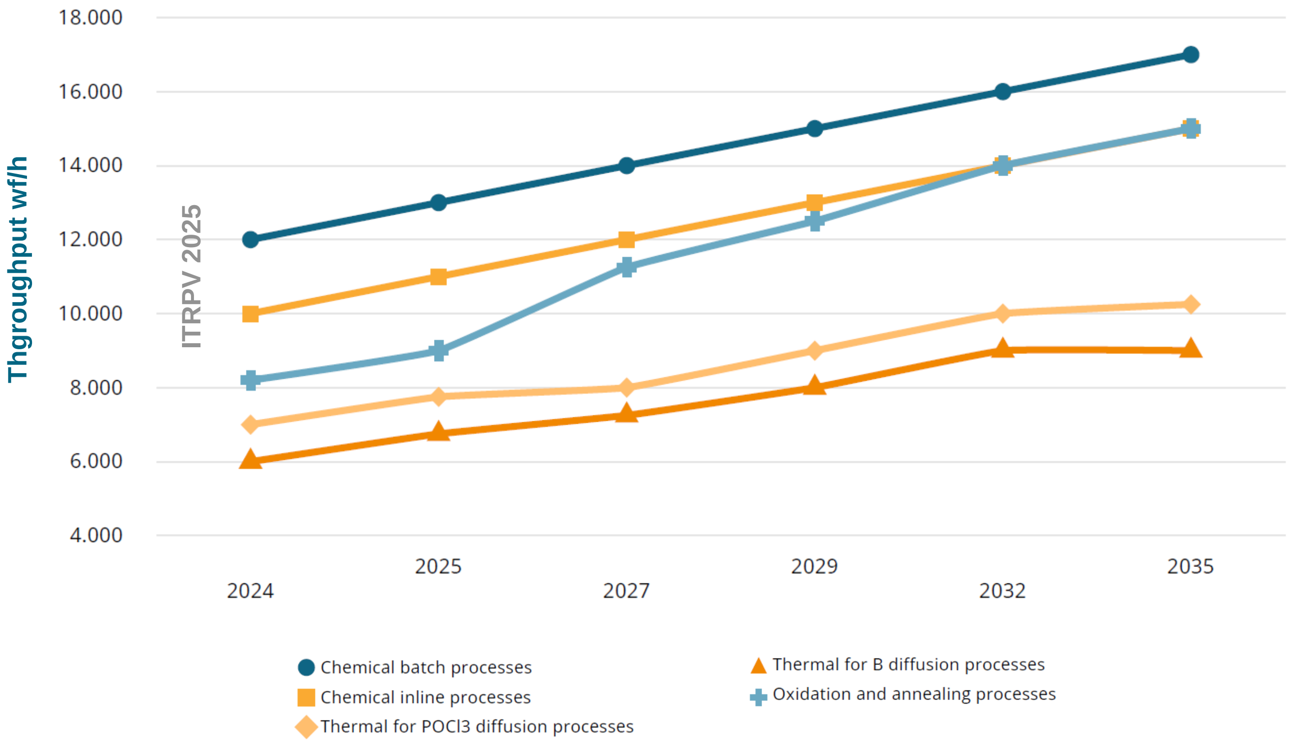
- Bifacial cells are standard today used in mono- and bifacial modules
- Bifaciality (% ratio: rear side efficiency over front side): SHJ leads (87%), TOPCon (80%), PERC (70%) IBC (70%) 2025

Cell production tool throughput

Expected continuous improvement in wafers/hour

- **Batch wet processing stays throughput leader: 12,000 → 17,000 wafers/hour**
- **Boron-diffusion has lowest throughput**
- **Atomic Layer Deposition (ALD) leading deposition process throughput 12,000 → 18,000 wafers/hour**
- **Full report includes backend processes laser, metallization and classification**

Process throughput for new cell tools



Cell metallization trends
Silver (Ag) consumption reduction ongoing

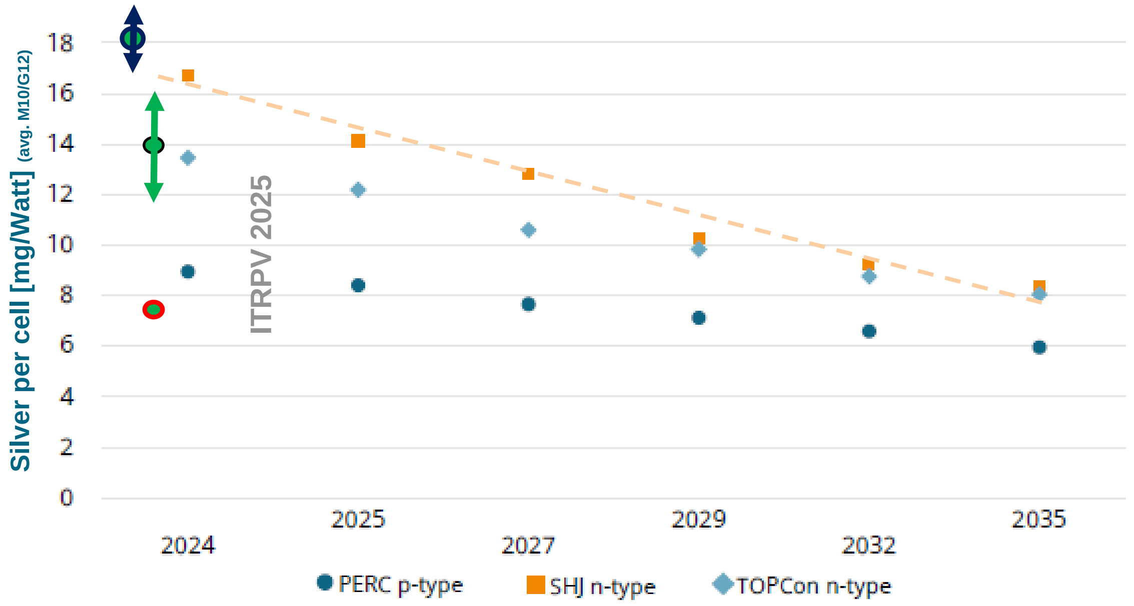
- **M10 Format 2024 results:**
  - p-type PERC ≈ 70 mg/cell
  - n-type TOPCon ≈ 111 mg/cell
  - n-type SHJ ≈ 140 mg/cell

- **Per cell performance average values (mg/Watt)**
  - PERC: 9 mg/Watt
  - TOPCon: 13.5 mg/Watt
  - SHJ: 16.7 mg/Watt

- **Sub < 10 mg/Watt levels in a decade**

- Finger width reduction, multibusbar/busbarless formats etc… in full report

Silver consumption (mg/Watts) or avg. t/GW



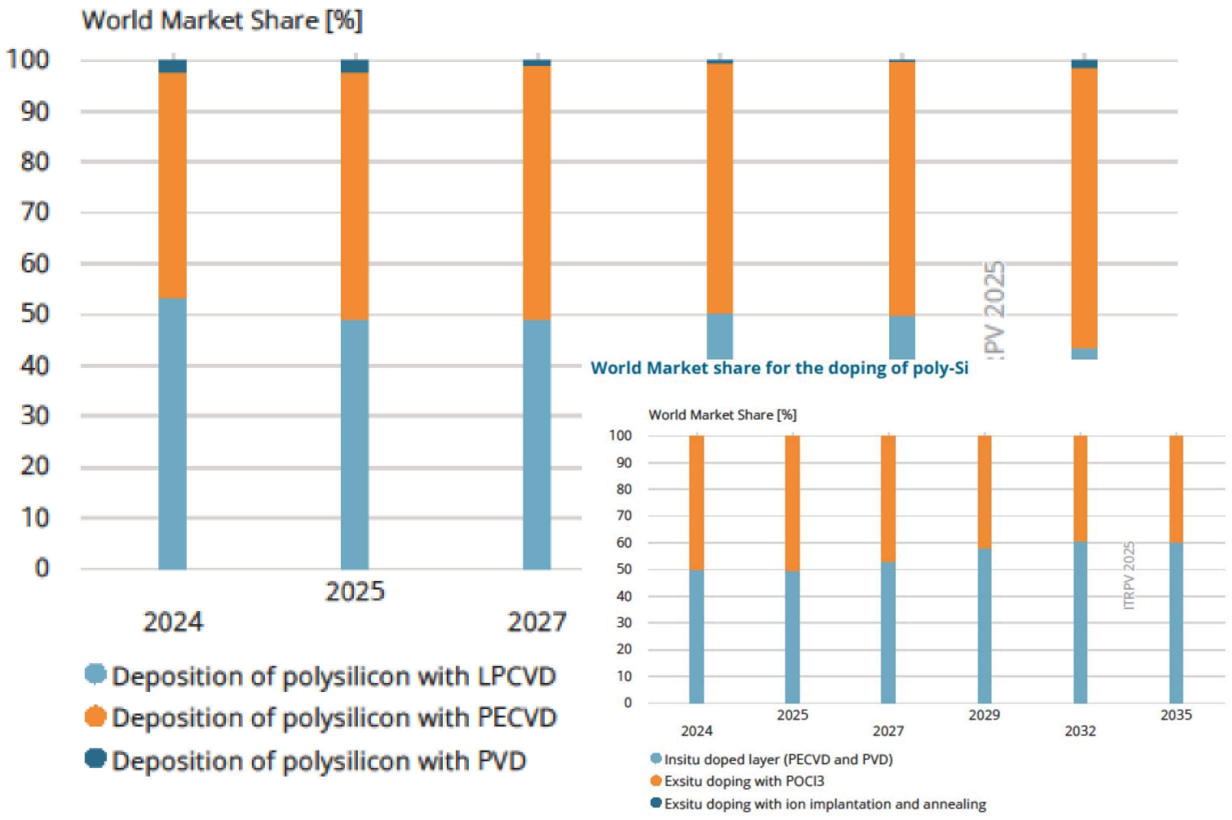
Reported Tier 1 cell manufacturers confirm results

TIER1 mg/W: PERC: 7…8 ✓ - HJT: 17 …20 ✓ - TOPCon: 12 ..16 mg

Cell Processes
TOPCon polysilicon

- **LPCVD and PECVD have similar projected shares**
- **Some market share of PVD expected**
- **Doping technology market share complementing the results of deposition technology**
  - **insitu and exsitu (POCl3) have similar shares**
- **A clear trend is not predicted**
- **Polysilicon thickness expected to reduce from 115 nm down to 70 nm**

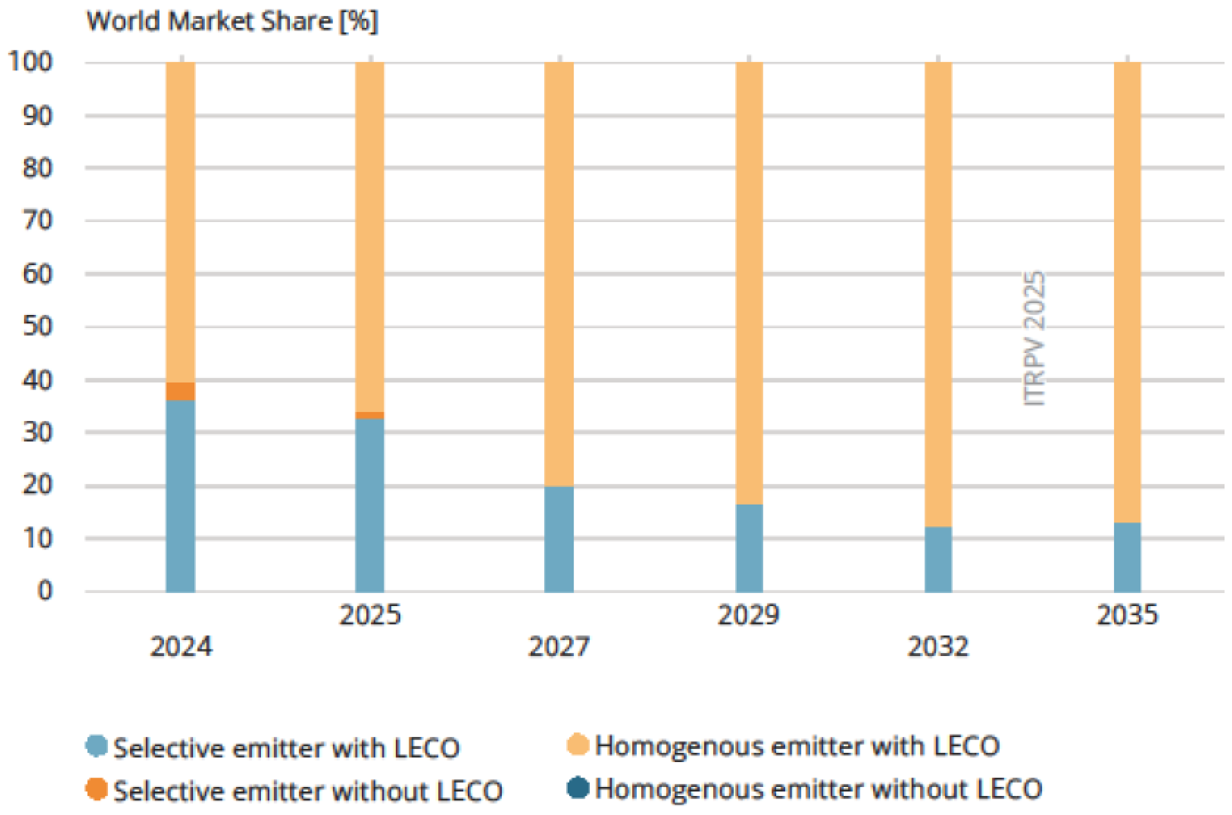
Different deposition technologies for TOPCon polysilicon



Cell Processes
TOPCon emitter

- **Homogeneous emitter with laser enhanced contact optimization (LECO) dominating**
- **Market share of selective emitter is project to decrease**
- **LECO is standard for n-type TOPCon**

Market share of emitter for n-type TOPCon



Cell Processes
Edge passivation of separated cells by deposition

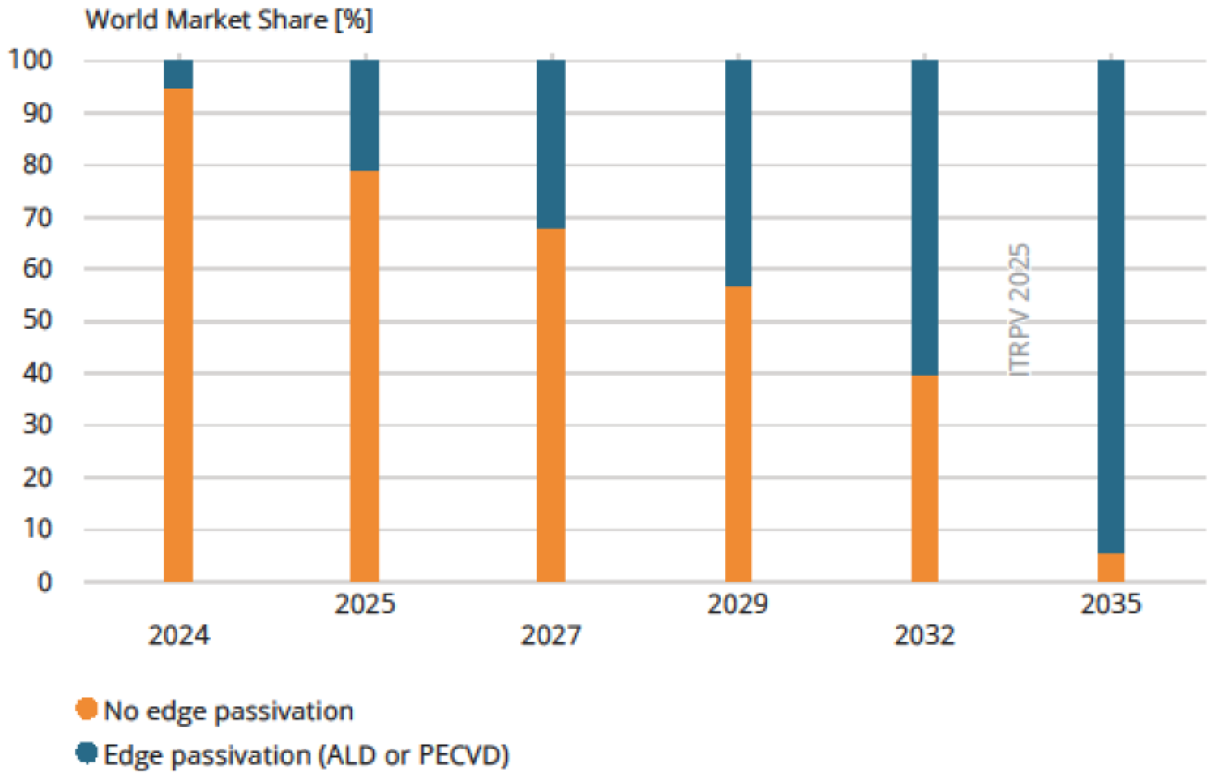
- **Post-metallization separation process leads to newly formed edges**
  - **Leading to losses in efficiency**
  - **Lower pseudo-Fill Factors and Open cicuit voltage V_{OC}**

- **Edge passivation by post-separation deposition of dielectric materials by ALD* or PECVD**

  → to regain efficiency loss

- Gaining market share in the upcoming years

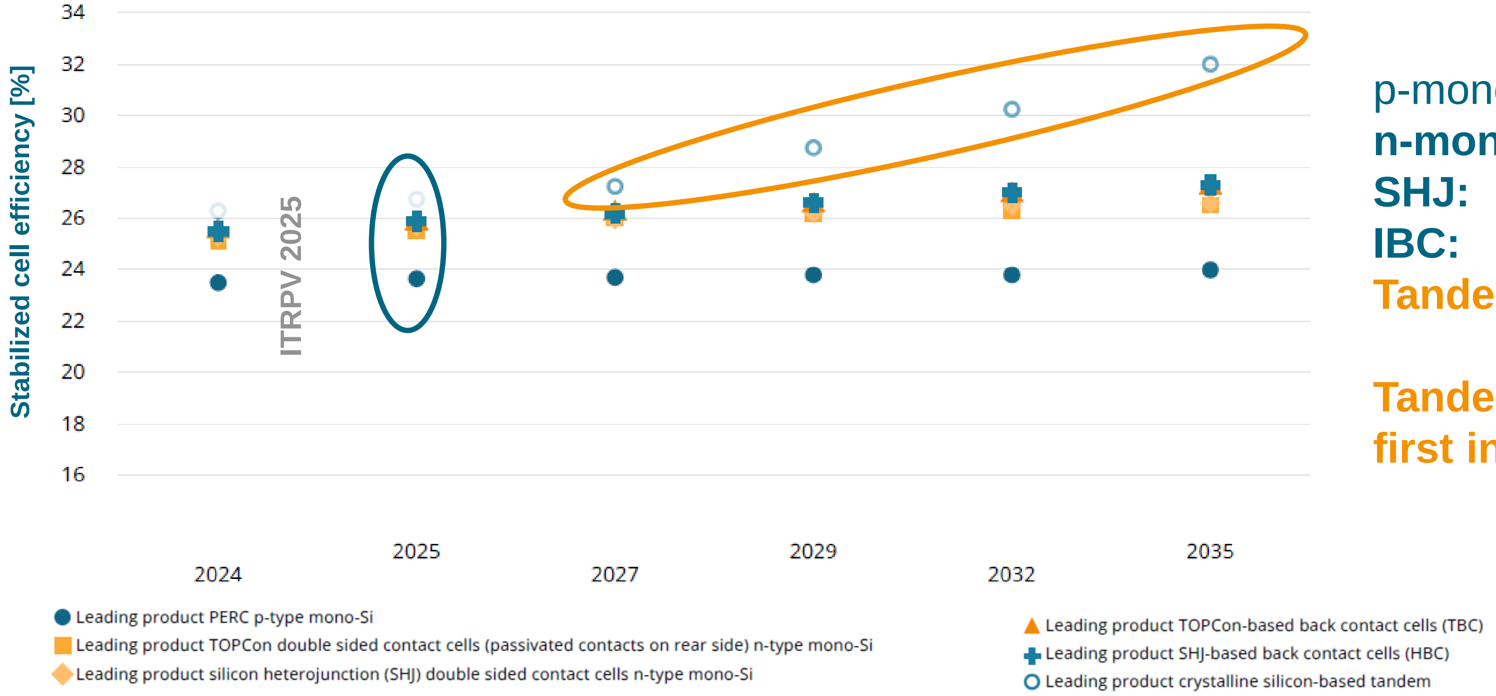
Edge passivation technology for separated cells smaller than half cells



*P. Baliozian *et al.*, "Postmetallization "Passivated Edge Technology" for Separated Silicon Solar Cells," in *IEEE Journal of Photovoltaics* (2020)

Cell Products
Stabilized efficiency in mass production

Leading cell efficiencies in production
n-type leads in efficiency with IBC, SHJ, TOPCon



	2025	2027	2035
p-mono PERC:	23.5%	23.8%	24.0%
n-mono TOPCon:	**25.5%**	**26.0%**	**26.5%**
SHJ:	**25.7%**	**25.9%**	**26.6%**
IBC:	**25.9%**	**26.2%**	**27.3%**
Tandem:		**(27.3%**	**32.0%)**

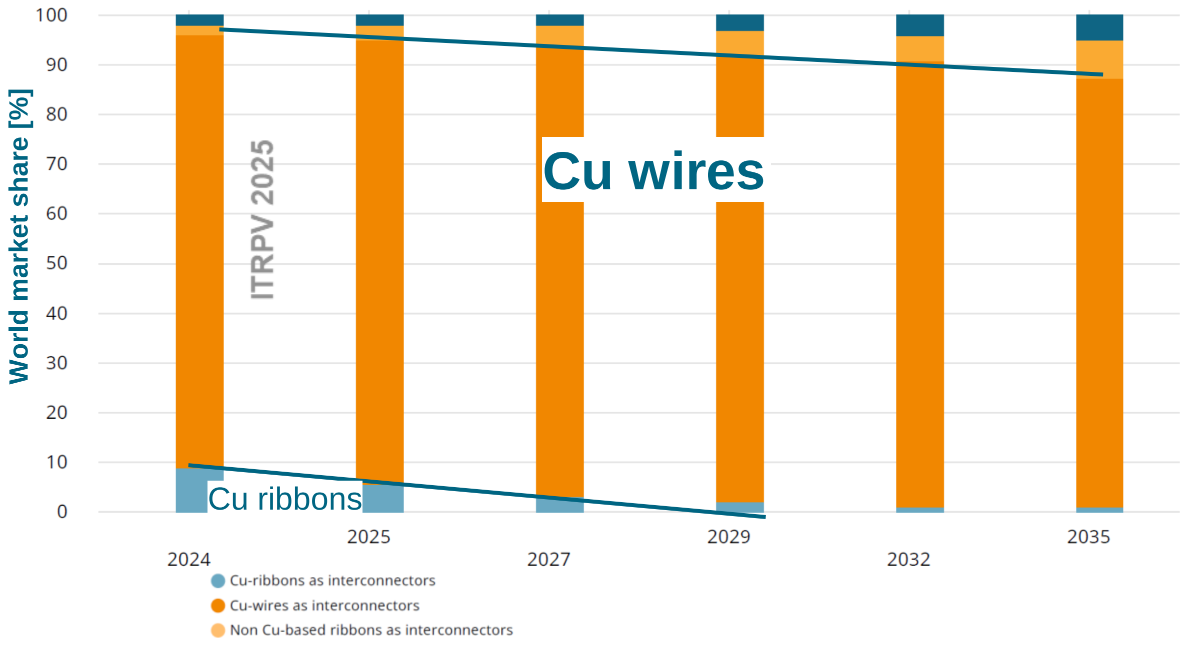
Tandem still expected in mass production first in the form of silicon-perovskite

Module Materials

Cell interconnection material copper (Cu) dominance

- **Cu remains key base for cell and string interconnection**
- **Cu wires are mainstream with expected diameter reduction: 260 µm → 200 µm**
- **Lead-containing soldering dominates gradual share increase of lead-free solder**
- **Electrically conductive adhesives (ECAs), gaining share (graph in full report)**

Cell to cell interconnection and soldering



Module Product
Module size and Weight

All applications size and weight are increasing

Residential
Size is increasing due to new cell formats…

Power plant
<2m² disappeared, >3m² will gain share

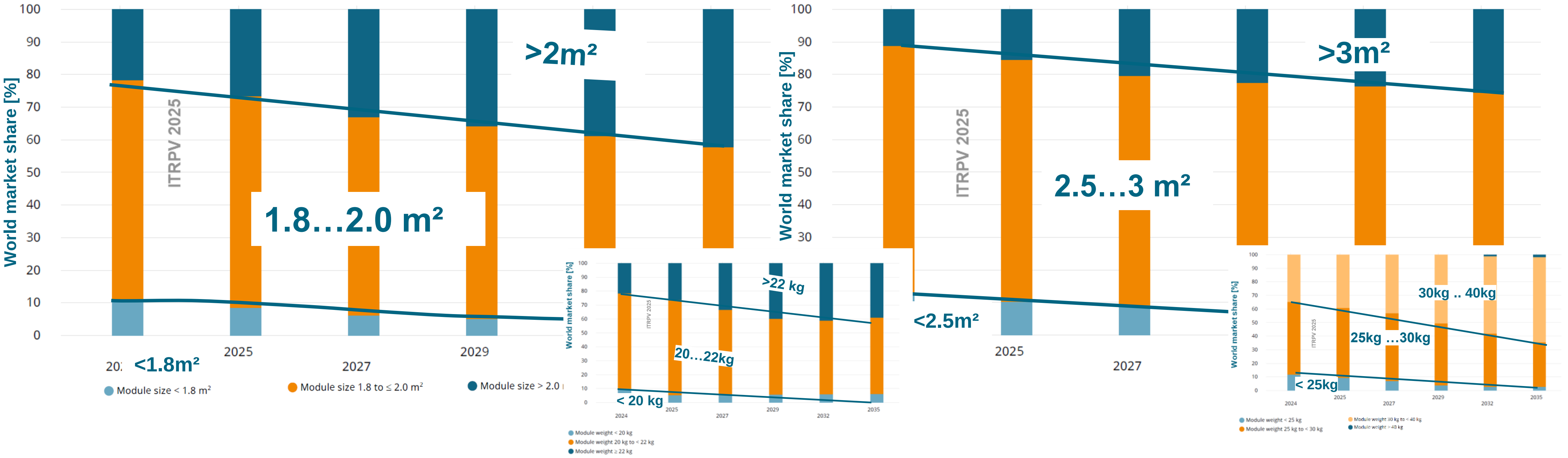



Photo: M. Fischer (2023)

Side event of

📢 Join Us at: Advances in Solar PV Production Technologies – Key Findings from ITRPV 2025

Photovoltaics Equipment

📅 May 8, 2025, time: and venue: | 📍 The Smarter E / Intersolar Europe

Agenda:

- **Dr. Puzant Baliozian (VDMA PV)**
  Unveiling of the New ITRPV Digital Product

- **Dr. Markus Fischer (Hanwha QCells)**
  Presentation of the 16th Edition results

By invitation and registration only

For registrations please contact:
Alexandra Janik-Hannen
(alexandra.janik-hannen@vdma.org).

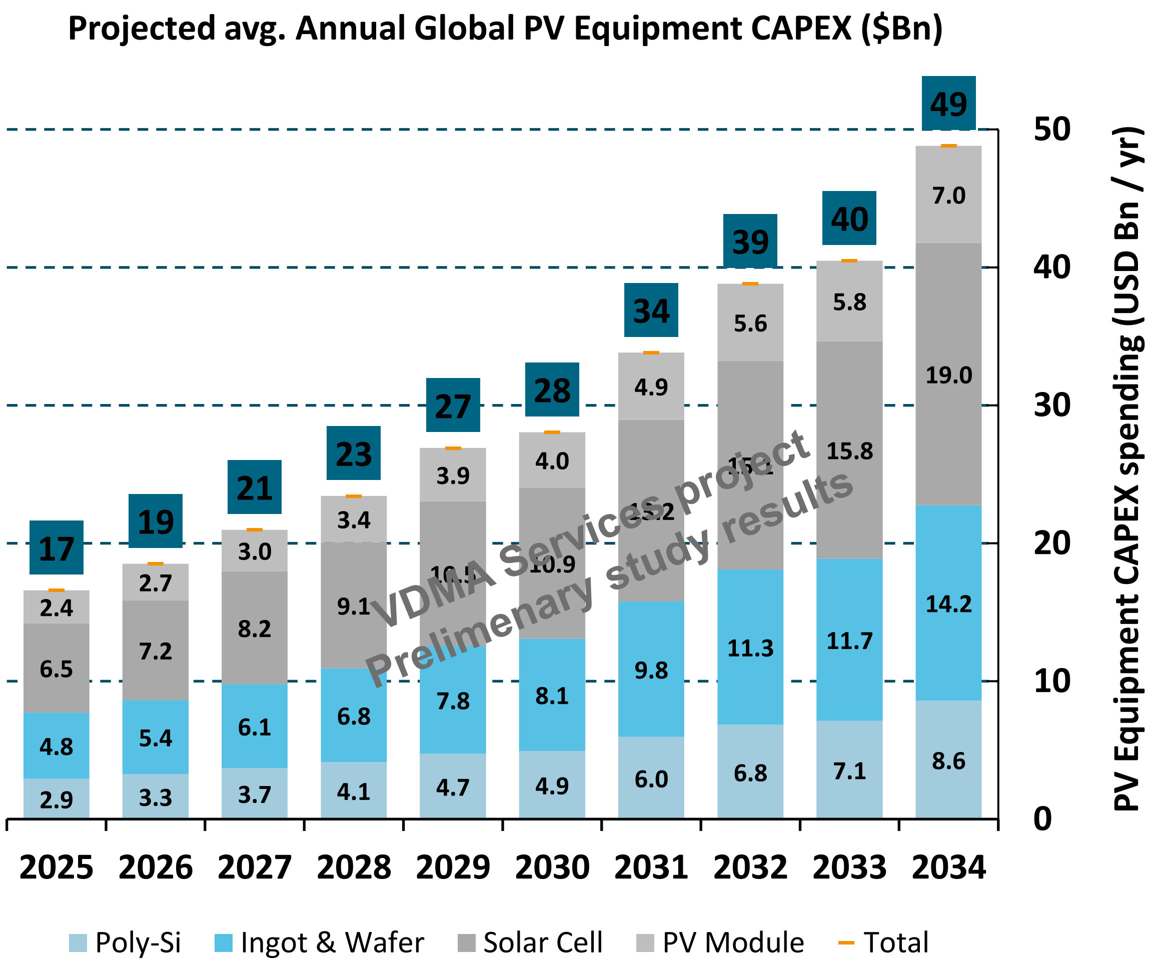
https://www.vdma.org/photovoltaik-produktionsmittel

Projected average Annual Global PV Equipment CAPEX
Preliminary Result PV Machinery Study

- **Only solar PV production equipment market potential forecast**
- **Calculation based on assumptions and third-party references**
- **Expected to add more CAPEX if utility and components included**
- **Assumption considers TOPCon lines**
- **Further analysis details in the final study**

VDMA Services GmbH Study conducted by

ISC research for a sunny future — Fraunhofer ISE



Source based on: S. Nold, B.S. Goraya, R. Preu, J. Rentsch, J. Reichle, W. Jooß, P. Fath, M. Woodhouse, Comparative Global PV Manufacturing Cost and Sustainable Pricing Assessment: China, Southeast Asia, India, USA, and Europe, EU PVSEC 2024,
- Market development until 2030 based on Solar Power Europe (SPE) Global Market Outlook (until 2028). The PV production Capacities for 2029 - 2034 were extrapolated with an annual increase of 13% (same as for last year 2028 in SPE Global Market Ourlook).

PV-Pilot project
Feasibility study

Based on project 2023:

LIBERTAS
PV Feasibility Study

Techno-economic assessment: building a complete value chain in Germany/EU to secure technology sovereignty

Duration: 01.10.2024 - 30.04.2025

Research and pilot environment to support resilient European/German PV production

BMWK – PtJ Project


Source: Shutterstock

Side event of

THE smarter E EUROPE

intersolar | EUROPE
connecting solar business

European/German PV Production Technologies Equipment and Technology Transfer for Global Manufacturing

📅 **Date & Time:** May 6, 2025 | 1:00 pm – 6:00 pm
📍 **Venue:** Messe München, Room B51/B52

🎯 **Side Event of The smarter E – Intersolar**

Agenda Highlights:

- **Key Findings from the PV-Pilot Project**
- **PV Machinery and Equipment Study**
- **Panel Discussions & Networking**

By invitation and registration only, for an official invitation with registration link
Alexandra Janik-Hannen (alexandra.janik-hannen@vdma.org)

PV-Pilot project partners:

VDMA Services GmbH event

RCT solutions · ISC research for a sunny future · Fraunhofer ISE · ISFH · HZB Helmholtz Zentrum Berlin · VDMA Photovoltaik-Produktionsmittel

Join our ONLINE Kick-off Event on 30th April 2025:

VDMA European Photovoltaics Equipment Incoming Orders and Sales Report

Gain access to exclusive insights

Requirements for Participation**:**

- **European Machinery and Equipment Companies**
- Members and non-members can participate

Your **Benefits**:

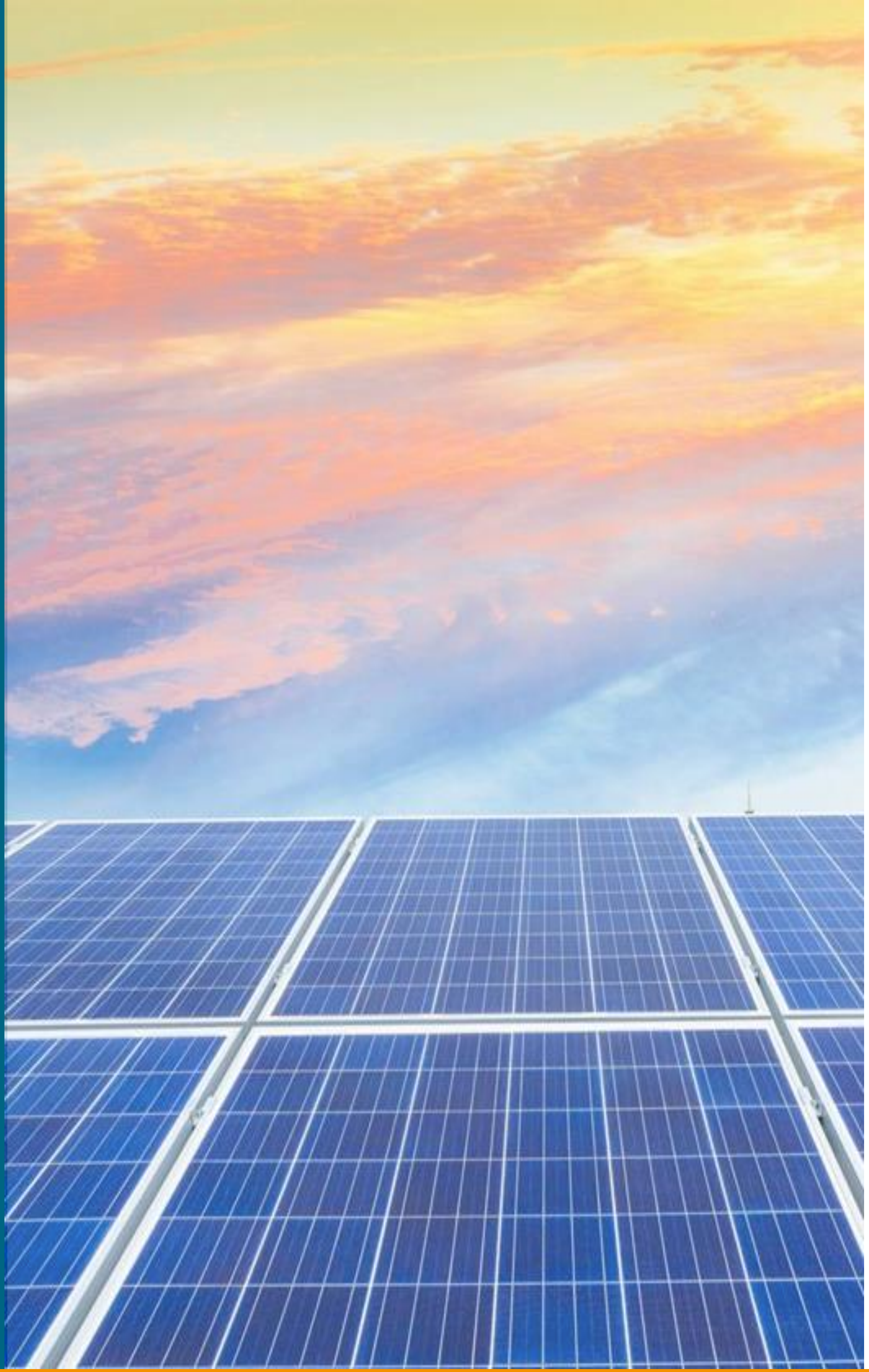
- Earliest access to **data trends**
- Access to **result reports & insights**
- **Market awareness**
- Building a **network**
- **Exchange** through collaboration

VDMA

Photovoltaics Equipment

Email us to sign up now

Fatemeh.Abbasi@vdma.org



Acknowledgements:

- VDMA member companies
- VDMA PV Equipment executive board
- ITRPV Steering Committee
- Event organizers
- Thank you for your presence!

VDMA PV Equipment Contacts

Photo: M. Fischer (2023)

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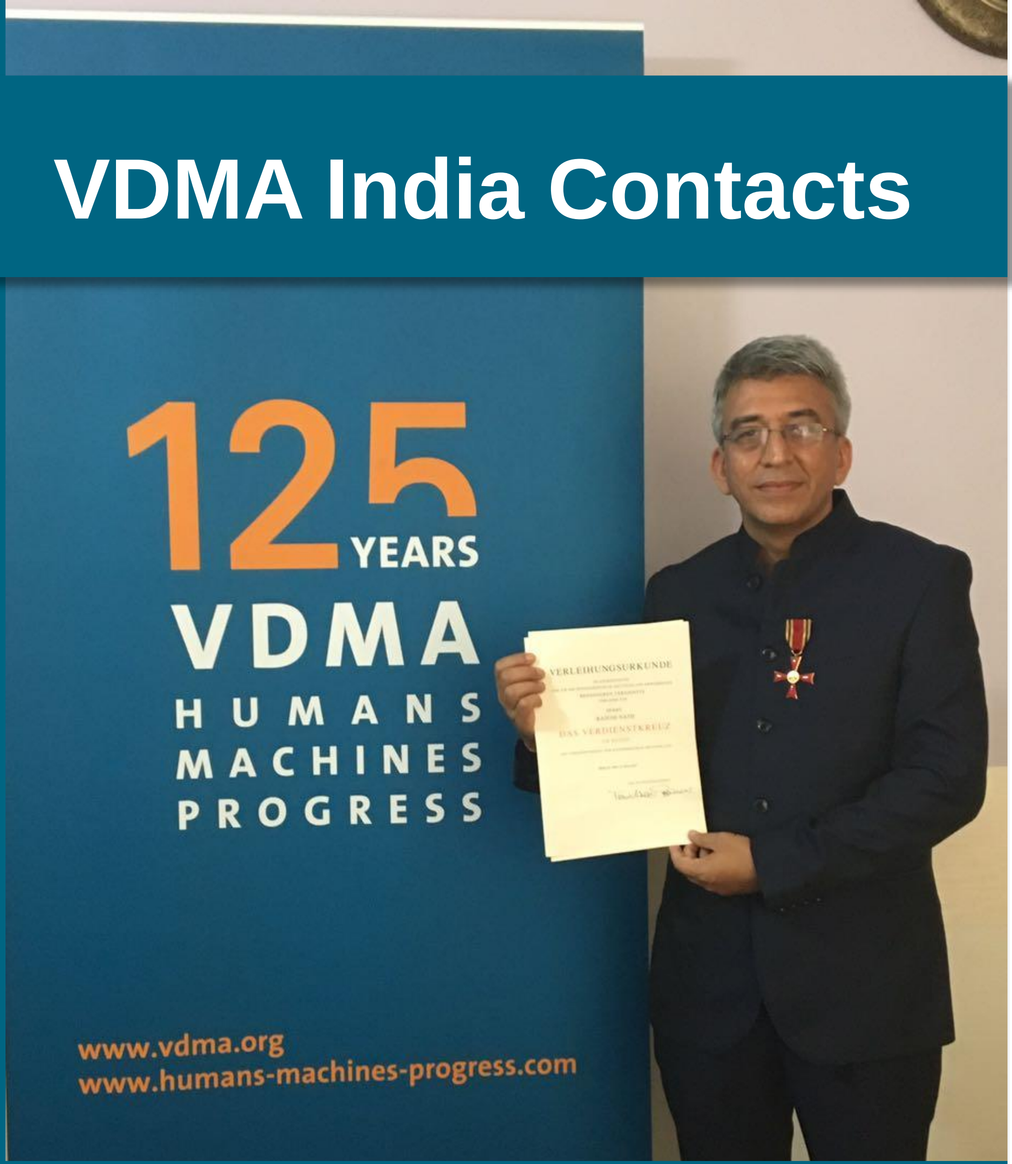

Mr. Rajesh Nath-Felicitated with **“Cross of the Order of Merit”**- Highest Civilian honour by German Government

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