



Renewable Technology
Solutions Partner

The Blueprint for GW-Scale Solar Manufacturing: Lessons in Design and Operations

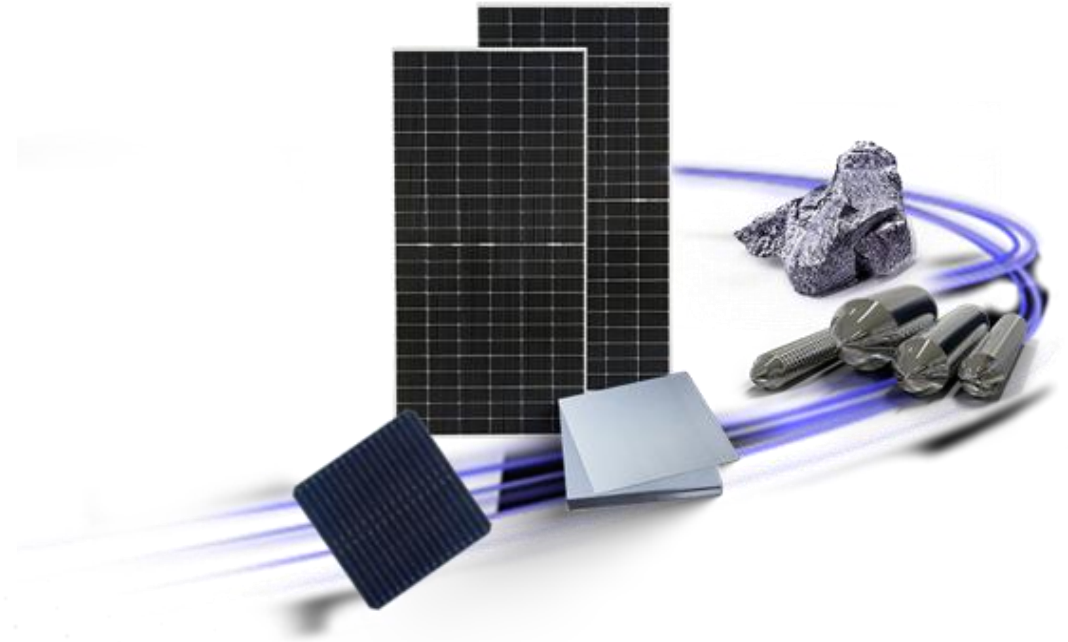
Markus E. Beck, Julian Reichle, Mehul Raval, Wolfgang Jooss, and Peter Fath
PV CellTech USA, San Francisco, CA, October 13&14, 2026
RCT Solutions GmbH



A member of



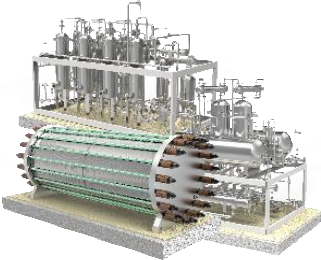
- ✦ About RCT Solutions
- ✦ 4 Lessons Learned
 - ✦ Utilities as Production-Critical Systems
 - ✦ Operational Excellence and Workforce Training
 - ✦ Supply Chain Localization and Optimization
 - ✦ TCO Leadership
- ✦ Case Studies & Execution Learnings
- ✦ Summary & Conclusions



RCT Group

A family of technology & manufacturing companies powering renewable energy value chains



RCT Solutions	OROS Energy	RCT Hydrogen	RCT Financial Advisory	RCT Space
 	 	 	 	 
2012 Founded	100% German Shareholding	>70 MW Globally Deployed	2025 Founded	LEO & MEO Solar Cell Production
29 Countries Worldwide	C&I and BESS Key know-how	>1.000 MW Manufacturing Capacity	ECA-Backed Financing Securing longer loans	Space Heritage Proven mission experience
100+ GW Total Integrated PV	European Focus	Modular Design 20 to 200 MW	Clean-Energy Mandate Solar, Storage, Hydrogen	Patented IP Technology

RCT Future



Investing Ideas

Stable Growth

Centralized

Venture Markets

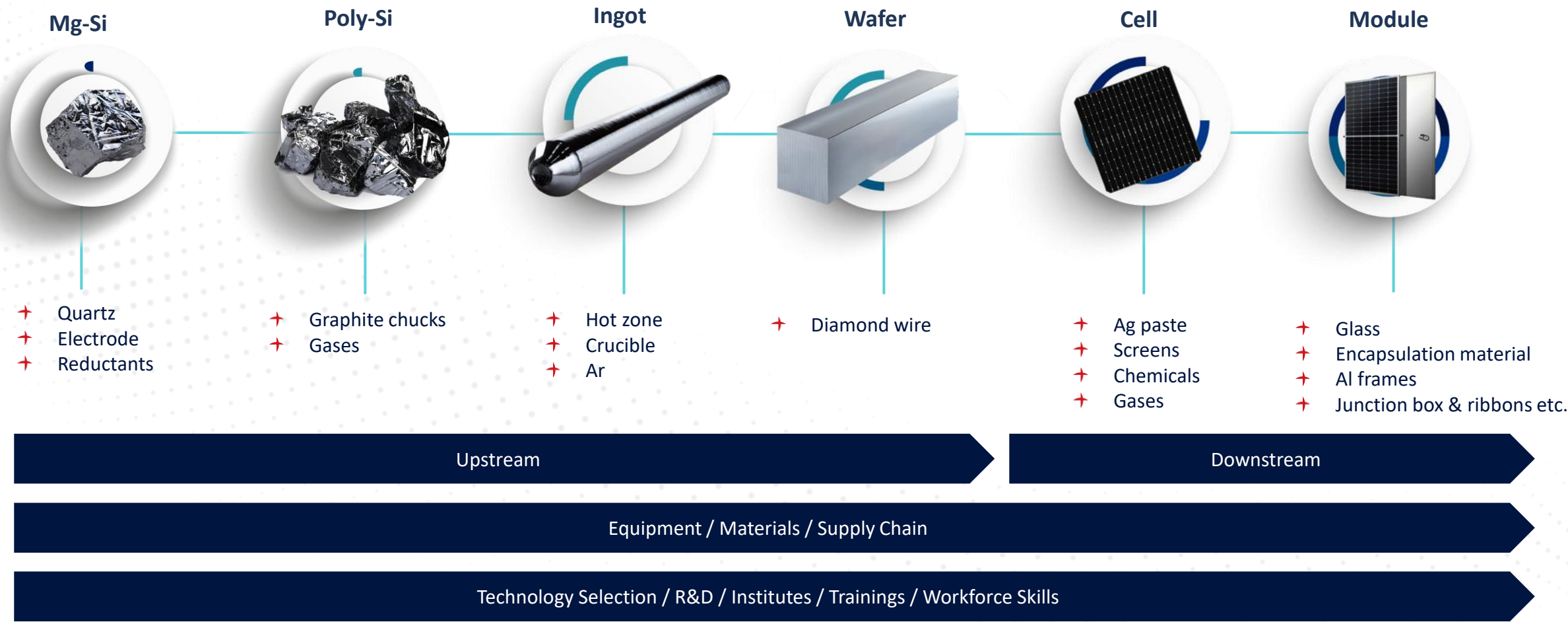
Stable

Investment Structure

Where we work as RCT Solutions



We execute both vertical (end-to-end from ingot/wafer to cell and module) and horizontal (targeted line upgrades, supply chain, consumables, debottlenecking, and ramp support) manufacturing programs.



Services

RCT Solutions GmbH—founding member of RCT Group—is an independent engineering house dedicated exclusively to photovoltaic manufacturing.

01



Feasibility Studies

Decision-ready feasibility that turns intent into an actionable PV factory plan

03



Lenders' Engineering

Independent technical assurance for PV factory financing and delivery

05



Commissioning & Ramp-up

Installation and ramp-up—until acceptance and output targets are met

02



Owner's Engineering

Execution-ready owner representation for PV factory programs

04



Basic Engineering

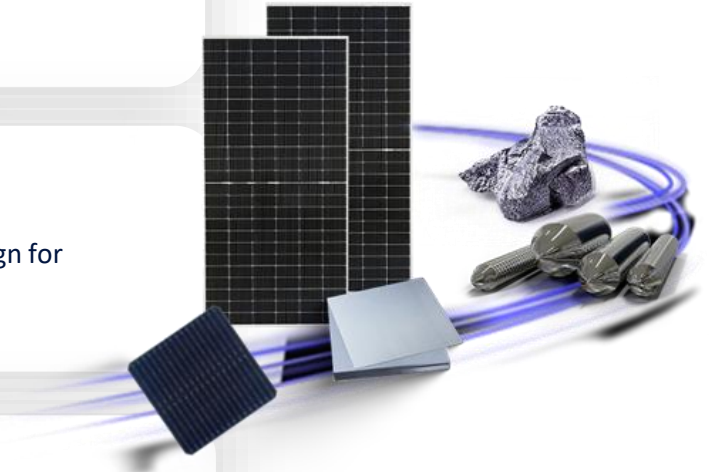
Approval-ready front-end design for gigawatt-scale PV factories

06



Solar Academy Training

PV Manufacturing Workforce Training & Education for operational readiness



Track record of RCT Solutions projects

Completed & Under Execution (2022-2026)



Projects
93
Total Capacity
109 GW

Today's four lessons learned for U.S. solar manufacturers

Based on RCT Solutions project experiences



Production-critical utilities

Design utilities to keep production running

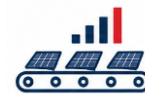
01



Operational excellence & workforce training

Build workforce skills and consistent operating practices

02



Supply chain localization & optimization

Strengthen local sourcing and supply performance

03



TCO leadership

Optimize for total cost of ownership not just CAPEX

04



1. Production Critical Utilities:

RCT re assessed design assumptions and simplified oversized system resulting in \$18.5M savings

The project utilities were overengineered by 25%, contributing to cost overruns and delays

Civil / structural

≈ **\$12.5M**

- ✦ Reassessed equipment loads
- ✦ Reduced excessive safety margins

Electrical systems

≈ **\$5M**

- ✦ Reassessed power demand for high-load equipment
- ✦ Optimized electrical infrastructure and power distribution

Mechanical / utilities

≈ **\$1M**

- ✦ Optimized PCW, vacuum and exhaust for Cz furnaces
- ✦ Reduced system complexity and overdesign



Project outcome:

RCT established the engineering basis, aligned the customer, OEM, DEC and EPC teams, and prepared the engineering for construction and execution.

2. Operational excellence & workforce training

U.S. Solely relying on the equipment vendor tends to result in significant delays and operational losses



9.4%

Manufacturing share
of U.S. GDP

≈ \$3T contribution to GDP

27,000

Direct PV
manufacturing jobs⁽¹⁾

< 0.01% of US population

≈ 16,000

Additional jobs projected
over the next 1-2 years⁽¹⁾

Majority in more challenging cell
and ingot/wafer manufacturing



(1) [American Clean Power: America Builds Power: The State of Clean Energy Manufacturing 2026](#)

2. Operational excellence & workforce training

Strong equipment needs a stronger team

Ramp-up performance

≈ **97–99%**

A-grade yield

Yield measures product quality



Train the team

Workforce and
maintenance capability

≈ **60–65%**

Utilization

Utilization measures equipment availability



Stabilize operations

Procedures, automation
and clear ownership

85%

Peak utilization



Align quality data

Inspection grades and
MES classifications

Operational excellence is a designed outcome

Ramp-up performance limited by workforce maturity not equipment capability

2. Operational excellence & workforce training

Account for workforce access as part of site selection & invest in workforce training early and continuously

- + Essential throughout the entire organization
- + Annual workforce attrition in U.S. PV module assembly as high as 30%
 - + Night, weekend, holiday shift coverage difficult to staff
 - + Competing with other, more attractive sectors/job types
 - + Lack of career perspective
 - + Limited talent pool inside locally-accepted commute range
 - + Community unattractive to relocate or attract top talent



Managers



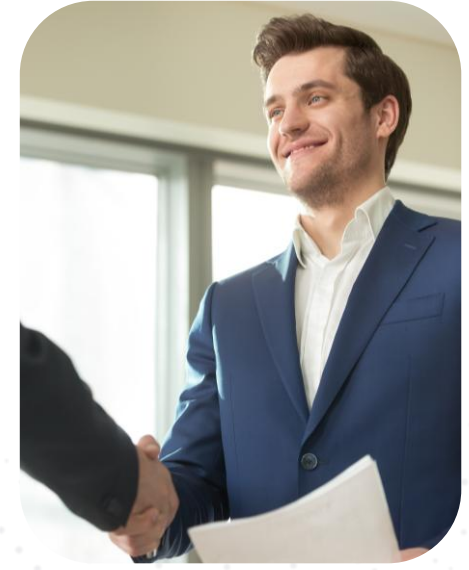
Engineers



Technicians & Operators



R&D



SG&A

2. Operational excellence & workforce training

Different delivery formats: combining traditional, face-to-face and hands-on instructions with digital, self-paced online learning.



Fundamentals via
E-Learning & Live Courses



Blended Options



Hands-on Training



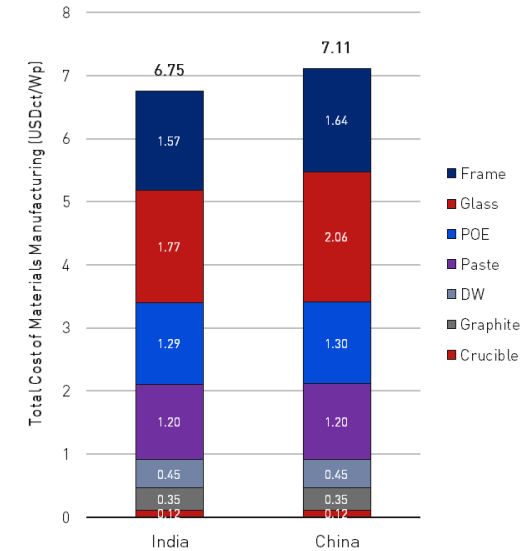
Laboratory

3. Supply chain localization & optimization

FEOC-compliant supply chain diversification

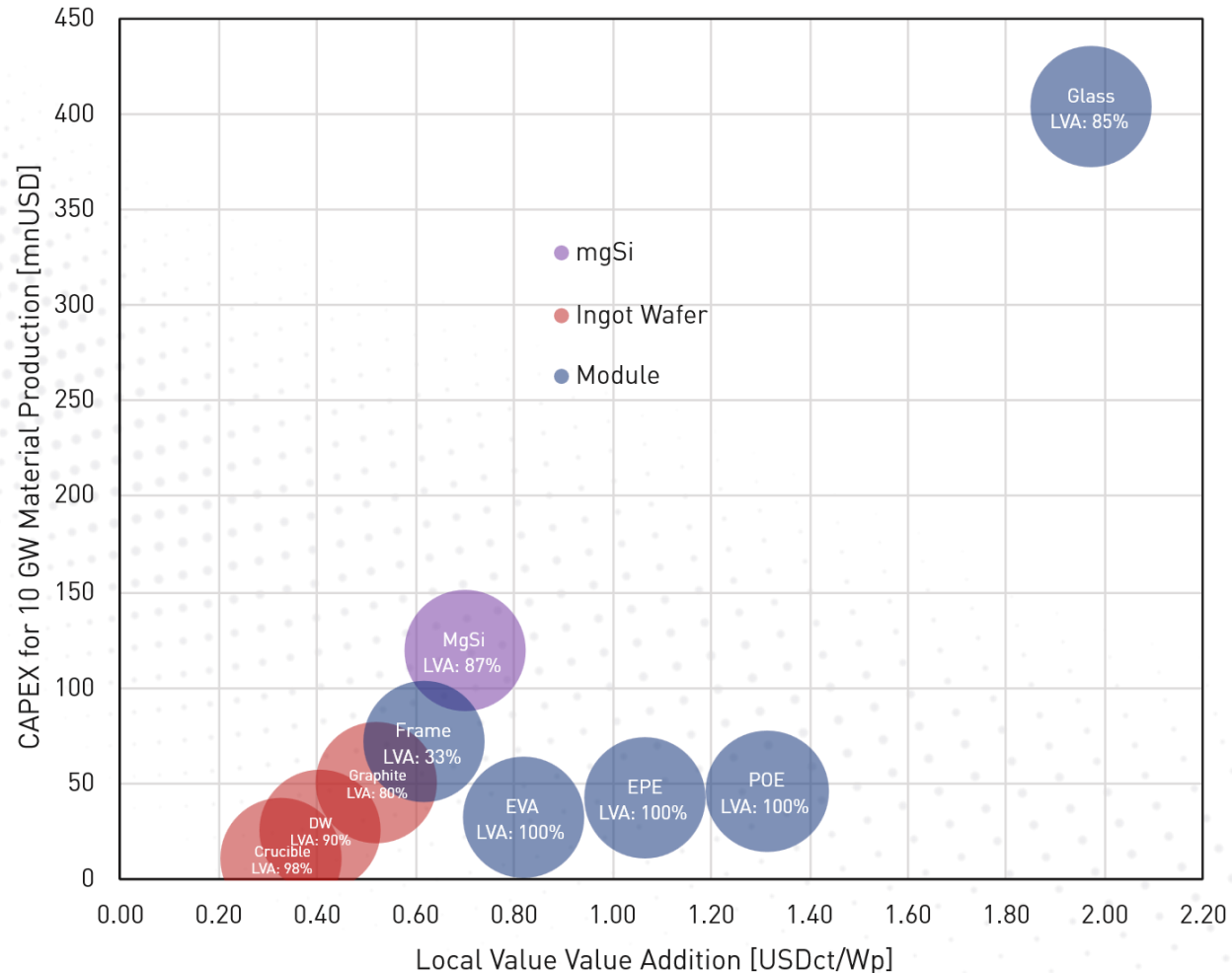
Stage	Raw Material	Demand for 10 GW	Key Raw Materials	Manufacturing Challenges	CAPEX [\$M/GW]	Setup Time
Polysilicon	mg-Silicon	21,810 MT	- Quartz - Coal - Prebaked Electrodes - Wood logs	- Energy intensive - Quartz quality	10.0 – 14.0	5 years
Ingot	Crucible	8,000 pcs	- Quartz Sand - Electrodes	- Energy intensive - Quartz quality	0.6 – 1.0	4 years
Ingot	Graphite Parts	1,300 sets	- Coke - Graphite	- Energy intensive - High CCC	4.0 - 6.0	5 years
Wafer	Diamond Wire	3,750,000 km	- Steel wire - NaOH - Nickel Sulfamate - Nickel Chloride - Nickel Pellets - Diamond particles	- Process - Diamond supply	2.0 – 3.0	3 years
Cell	Silver Paste	120,000 kg	- Silver Powder - Glass frits - Additives - Solvents	- Technology and process	N/A	2 years
Module	Encapsulant EVA/POE	83,333,400 m ²	- EVA 28% vinyl acetate content - POE (ethylene based C8)	- Process & material quality	2.5 – 3.6	2 years
Module	Glass	83,333,400 m ²	- Silica sand - Limestone - Dolomite - Grinding disks and tools	- High invest - Shipping - Material quality	30.0 – 40.0	4 years
Module	Al-Frame	17,241,379 pcs	- Aluminum billets - Dies/tooling steel - Sulfuric acid - Nickel acetate	- Energy intensive - Low value add	4.0 – 5.5	3 years

TOP 7 Materials Cost



3. Supply chain localization & optimization

Local Value Addition (LVA): the key to domestic content



- Glass manufacturing requires significant investment but adds a high local value. Government incentives necessary to drive investment.
- mgSi requires a medium CAPEX while LVA is relatively modest. Emphasizes the need for government incentives or partnerships to reduce barriers to entry for high-CAPEX segments.
- Frame and encapsulants show a relatively balanced CAPEX and medium LVA. These components offer strategic opportunities to localize manufacturing as they combine low investment requirements with significant value addition potential.
- Crucible, graphite, and diamond wire require lower CAPEX and contribute less to local value addition. These components can be easily localized due to lower barriers to entry, providing a pathway to bridge supply chain gaps and increase domestic production.
- While onshoring PV manufacturing in the U.S. is challenged by CAPEX for certain components and materials in the vertical supply chain, it offers substantial opportunities.
- A strategic focus on materials with favorable investment to LVA ratios, combined with robust policy support for those with a lower ratio, can accelerate domestic production, add supply chain resilience, and drive job creation.

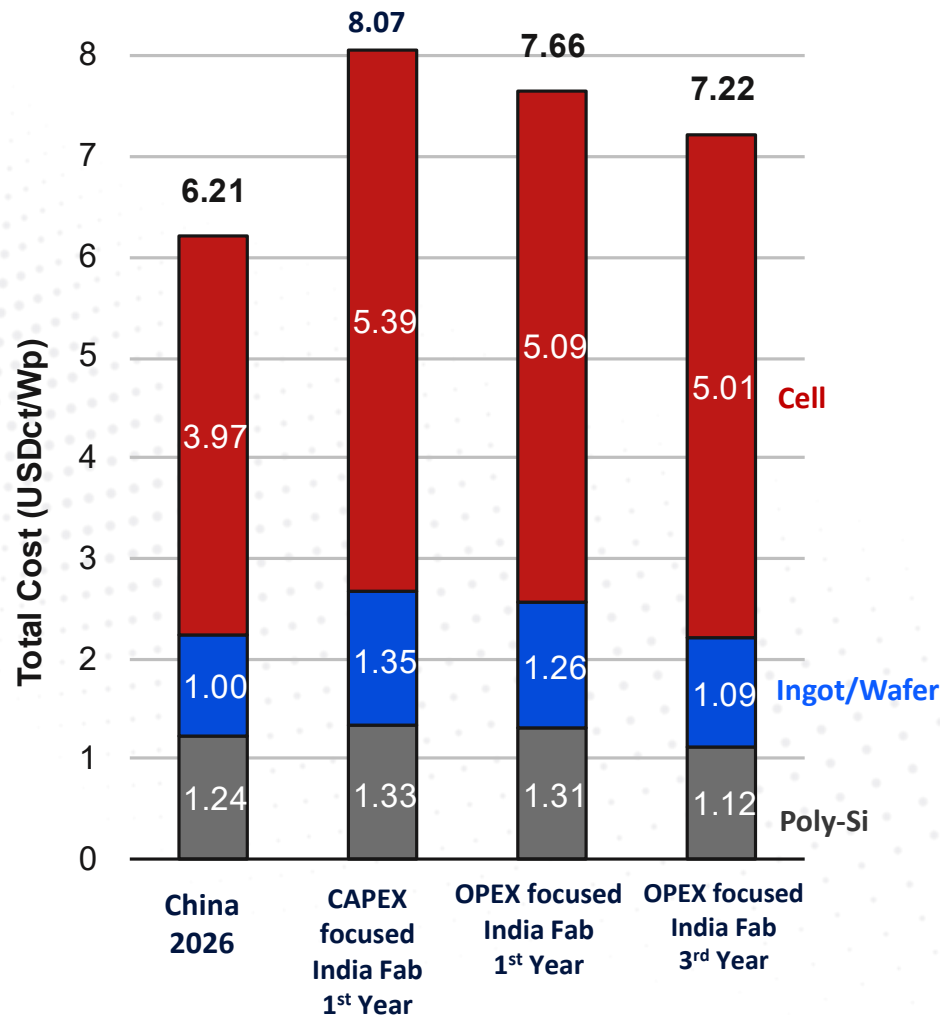
4. TCO leadership

Optimization for CAPEX: An impediment to long-term, sustainable operations

- CAPEX-driven decisions reduce initial investment but create structural inefficiencies in operation
 - increased OPEX—reduced yield, higher utility & consumables costs, increased maintenance burden
- Typically driven by
 - financing constraints,
 - pressure to minimize upfront investment, and
 - difficulty of quantifying operational risks in early project development
- Often appears as
 - underinvestment in critical infrastructure,
 - conservative equipment sizing, or
 - lower-cost choices in utilities, automation, and process integration, and
 - lack of investment in workforce training
- Often reinforced by benchmark assumptions or vendor-driven input instead of integrated bottom-up modelling and an honest assessment of the company skills
- Results in underestimating the economic impact of reliability, uptime, and process stability, ultimately weakening long-term competitiveness

4. TCO leadership

Enables complete operations to Tier-1 manufacturers at a better margin profile



Basic illustration for wafer-cell cost reduction

2 Approaches

- ✦ OPEX-driven model: productivity, yield, uptime
- ✦ CAPEX-driven model: lower investment cost per GW, deploy more capacity

Cost of Production–Wafer (USDct/Wp)

- ✦ Chinese Tier-1 peers: 2.24
- ✦ CAPEX-focused India fab: 2.68
- ✦ OPEX-focused India Yr.1: **2.57**
- ✦ OPEX-focused India Yr.3: **2.21**

Trajectory (Wafer)

- ✦ **14% drop** from Yr.1 to Yr.3
- ✦ **17% lower** vs. Tier-1 peers by Yr.3

Key Drivers for improvement

- ✦ Productivity improvements: uptime, yield, and throughput
- ✦ Process improvements

Conclusion

- ✦ Cost in China is currently higher than price
- ✦ Manufacturing cost in India higher than in China
- ✦ TCO can be reduced sustainably via OPEX-focused approach
- ✦ Cost leadership via process & productivity improvements



**Renewable Technology
Solutions Partner**

Case Studies & Execution Learnings



World's First Integrated Factory outside China: Kalyon PV Ankara

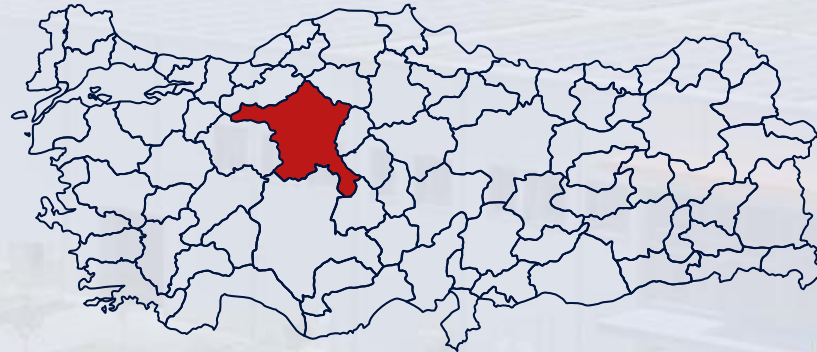
Scope: Owner's Engineering, Value Chain, Conceptual Design, Solar Academy

Location: Ankara, Türkiye

Capacity: 2.2 GW, TOPCon

Production: Ingot, wafer, cell, module in full production

Section	Phase I (MW)	Phase II (MW)	Phase III (MW)	TOTAL (MW)
Ingot	585	160		745
Wafer	616	150		766
Cell	546	673	1.000	2,219
Module	570	519	1.000	2,089



Kalyon PV Factory Present Day



An integrated facility full operational with an R&D Center



Ingot Factory



R&D Center



M10 Module Factory



TOPCon Cell Factory



G12R Module Factory

A successful adaptation for U.S. market

Indosol Solar's journey to high functioning operation excellence



Integrated photovoltaic manufacturing in Andhra Pradesh, India



Indosol’s adaptation for U.S. market



NAME SERIES	PRODUCT	MARKET
	G12R N-Type Monocrystalline Wafer	United States + India 
	G12R TOPCon Cell	India
	G12R Bifacial Glass-Glass Module	India

QUALIFICATION & TRACEABILITY

- November 2026, Indosol Solar will produce G12R N-Type wafers using Western polysilicon.
- Material provenance and product performance can be independently assessed.

OWNERSHIP & CONTROL

- Indian Ownership. Transparent Control.
- Indosol Solar is backed by an Indian promoter group, with no Chinese equity ownership and no Chinese control.
- Clear ownership. Clear governance. Transparent manufacturing.

45X Credits

- Certification supporting MACR (Material Assistance Cost Ratio)
- Documented Polysilicon → Ingot → Wafer chain of custody

Indosol Solar will be expanding its capacity to 10GW by 2028

Lessons Learned – U.S. GW-Scale PV Manufacturing



Compared to China and India, U.S. projects require a different development and execution strategy for both project owners and lenders.

Key Lesson

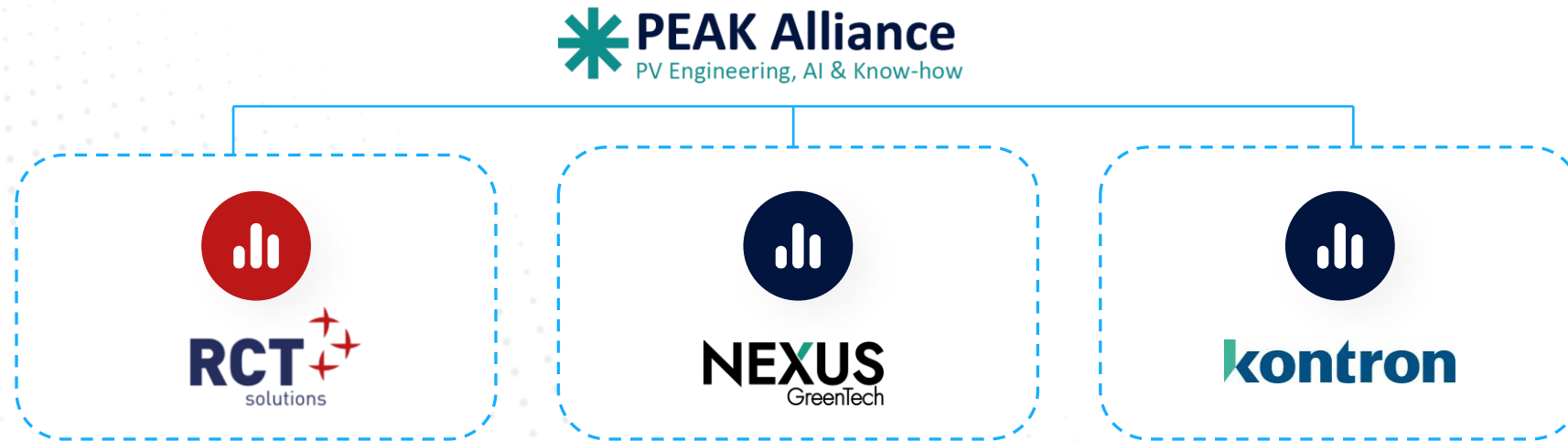
Observation

IP Strategy	IP disputes can influence technology selection and financing, regardless of their commercial or legal outcome. Early IP/FTO assessment is essential.
Permitting	Environmental and construction approvals require significantly longer lead times and must be reflected in the project schedule.
Realistic CAPEX	Actual building, utility and EPC costs are often 30–50% higher than early estimates due to limited local PV manufacturing experience.
Owner's Engineering	Strong Owner's Engineering is critical to manage interfaces between OEMs, EPCs, and contractors and reduce execution risk.
Workforce	Limited availability of experienced PV manufacturing personnel requires early recruitment and structured training.
Supply Chain	FEOC, domestic content, and localization requirements directly impact technology selection, sourcing and project economics.
Lender Expectations	U.S. lenders place greater emphasis on execution risk, schedule certainty, IP and documentation maturity.

A joint force for German PV technology, engineering and Industry 4.0

PEAK Alliance

- ✦ CAPEX-driven decisions reduce initial investment but create structural inefficiencies in operation
- ✦ Often reinforced by generic benchmark assumptions or equipment vendor-driven input instead of integrated, project-specific bottom-up modelling and an honest assessment of the internal skills
- ✦ Results in underestimating the economic impact of reliability, uptime, and process stability, ultimately weakening long-term competitiveness



PEAK coordinates the project-specific engineering, digitalization, and operational layers around the equipment scope



**Renewable Technology
Solutions Partner**

Summary & Conclusions



Summary & Conclusions

Key challenges for U.S. projects identified and align with several services RCT Solutions is offering

+ **GW-scale c-Si manufacturing projects often underperform**

- + This is not due to lack of best-in-class equipment, but because the transition from design assumptions to operational reality is not sufficiently resourced

+ **Utility systems must be treated as production-critical systems rather than auxiliary infrastructure**

- + Process-related utilities (e.g., DIW, CDA, PCW, chemicals/gases, exhaust & WW treatment) require the same robustness as production tools since failures can disrupt production resulting in performance, yield, throughput, and uptime losses

+ **Operational excellence often taken for granted despite lack of direct in-house experience and access to a skilled workforce**

- + Stabilized performance depends on line automation, extensive workforce training, adequate SOPs, disciplined SOP reinforcement, maintenance maturity, and transparent quality governance

+ **Supply Chain Localization and Optimization**

- + Supply chain strategy and upstream integration are often undervalued despite their importance for both cost optimization and resilience

+ **TCO Leadership**

- + CAPEX-driven decisions reduce initial investment but create structural inefficiencies in operation
- + Underestimating the economic impact of reliability, uptime, and process stability ultimately weakening long-term competitiveness

An integrated approach reduces execution risk, supports more reliable project planning and financing, shortens implementation schedules, and provides the basis for a long-term profitable PV manufacturing business



**Renewable Technology
Solutions Partner**

Thank You

Markus.Beck@RCT-Solutions.com



Solar Academy & Training



RCT Solutions offers a complete training portfolio to enable our customers to achieve operational excellence resulting in reduced opex, outstanding product quality, and higher workforce retention.



Outputs of Workforce Training*

- + Fundamental training
- + Process-specific training
- + Upskilling and reskilling
- + Classroom, virtual, hands-on
- + Customized (incl. Spanish)
- + Documentation
- + Managers
- + Engineers
- + Technicians
- + Operators

**varies depending on package and scope of customer selection*

