BOOK II

PV Development

Methods, Manufacturing Processes and Companies

Publication information and a note to the reader.

Alper Ferudun · Mercury Software GmbH

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This book is designed to guide readers with no prior knowledge of photovoltaics from basic concepts to research questions. In historical experiments, the setup and observations are explained, and in technical subjects, the mechanism, unit, example, and model limits are explained together. After the introductory explanations, the text moves on to more advanced details.

Editorial guidance and publication: Alper Ferudun. OpenAI tools were used in the preparation of the text and visuals. Conceptual illustrations are not actual sample photographs; numerical examples are synthetic unless otherwise specified. This work does not claim to be a peer-reviewed publication or to present experimental validation. It is not claimed that all literature has been reviewed; the limitations of access to sources are explained in the records.

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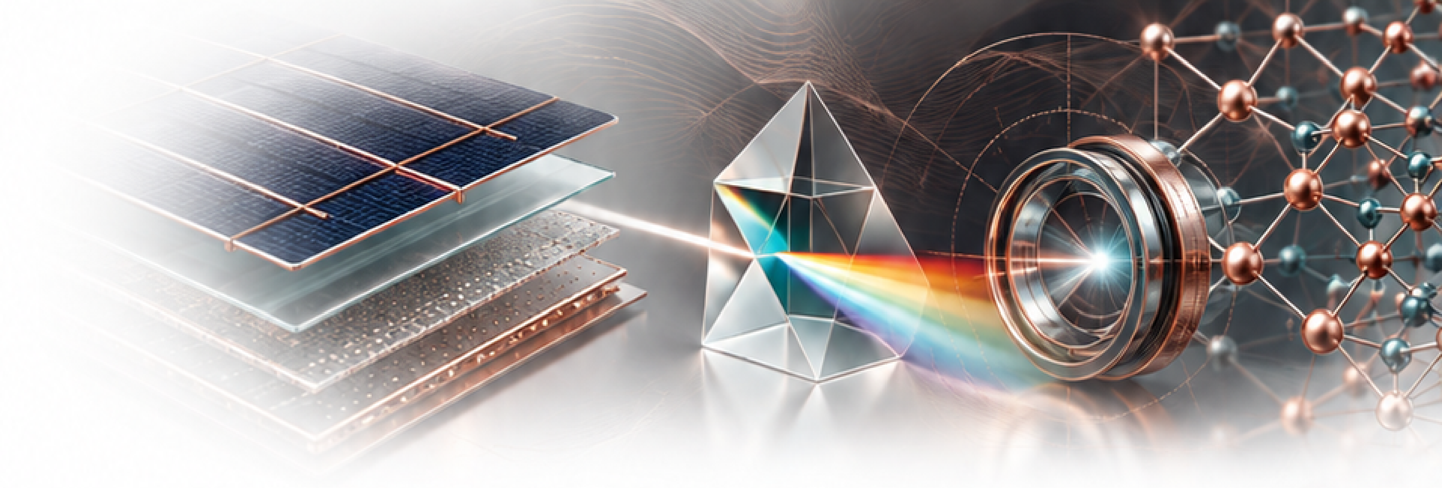
Contents

Chapter titles and page numbers are clickable. This volume is a standalone book in a two-book series.



List of figures

Figures and calculated plots in the text. Each caption identifies the conceptual explanation, model or data source.

How to use this book

The first book establishes the physical foundation. This book addresses the selection of methods, the design of controlled experiments, the diagnosis of process losses, and the transfer of the results to production. All numerical teaching examples are identified in the text as synthetic or hypothetical.

Scope of the sources

This work brings together selected foundational papers, methodological studies, official research resources, standards catalogues and dated company statements. It does not claim to cover the entire PV literature exhaustively. Company and process sources were last accessed on 8 September 2026. Where only the abstract of a primary text was accessible, this is stated in the references.

Reading pathways

Need	Priority chapters
Silicon cell development	II.01-06, II.10-14
Perovskite and tandem	II.01-02, II.07-08, II.11-15
Alternative technologies	II.09-10, II.12-15
Companies and research planning	II.16-18; the relevant manufacturing-method chapter

BOOK II · CHAPTER 01 / FOUNDATIONS OF DEVELOPMENT

Developing PV technology: bringing the target, the loss, and the proof together

The question of this volume: what do we change, and what do we gain?

Developing a solar cell is a broader undertaking than simply trying out new material names. The **product** is the object that, in the end, we want to perform a specific task: a small sensor supply, a rooftop module, or a space cell are all different targets. The **process** is the sequence of operations applied as we move from raw materials to the device. The **recipe** defines the settings of a process, such as material, device, duration, temperature, and the like. The **process window** is the range of conditions within which an acceptable product is obtained, despite minor deviations. The goal of development is to progress from a single, good sample to this reliable range.

For the reader starting with this volume, let's briefly establish the physical chain. Light creates mobile electrons and holes in a suitable semiconductor. A hole is the state of electron deficiency, which we track as a positive charge carrier. Selective contacts direct these two charge carriers to the appropriate terminals. Charge transfers energy in the external circuit. Production must successfully involve generation, collection without loss, and electrical connection. Detailed band and transport descriptions can be found in the first nine chapters of the first volume.

The loss budget is a cause-and-effect diagram

The **loss budget** breaks down the difference between the ideal or reference case and the actual output into its components. Optical losses are due to light reflection; recombination losses are due to the premature loss of generated charge carriers; electrical losses are due to resistance in the conduction path; and process losses are due to defective products during manufacturing. The same "low efficiency" symptom can arise from very different causes. The correct development method is chosen by identifying where the dominant loss occurs.

Synthetic example: Let the cell powers accepted in the two processes be 5 W and 5.2 W, respectively. In the first process, 95 out of 100 cells are accepted, and in the second process, 80 are accepted. The total accepted power produced is 475 W and 416 W. Although the best cell power has increased, the good yield per initial quantity has decreased. Here, the **acceptance rate** is the ratio of products that meet the specifications to the total number of products; it is different from the energy conversion efficiency.

A **hypothesis** is an explanation that predicts a measurable outcome: “Recombination at the back surface limits the voltage; this process will reduce it.” The **control** is a sample that does not undergo this process but has otherwise matching characteristics. The **decision criterion** is which change is sufficient to justify switching to the new method. The following development steps place these concepts in the actual order of operations.

Comprehension check: which efficiency increased?

Before accepting the statement “Efficiency 4% has increased,” ask whether it refers to the energy conversion ratio, percentage points, acceptance rate, or output per hour. A decision regarding improvement should be based on a clearly defined criterion with its numerator and denominator specified.

The first book established the principles of how a photovoltaic device works. This book addresses how to improve a device using that knowledge. Improvement may involve finding a new absorber, reducing contact losses in the existing cell, scaling up a coating to a larger area, or increasing the module’s stability under humidity. These tasks require different equipment, but all require the same research discipline: a measurable target, a reliable starting process, justified intervention, comparable control, and a predefined decision.

This volume is not a catalog of factory recipes. The temperatures, gas flows, ink compositions, or process tolerances that companies do not disclose have not been fabricated. The provided workflows are educational designs derived from published physics and processes; the assumptions used in the numerical examples are stated separately. The complete production recipe, along with the characteristics of the equipment and chemicals used, is verified in the laboratory. The equations in the introductory book are reused here for decision-making.

First, define which product you are developing

In a building with limited roof area, power per square meter becomes crucial. In a roof with low load-bearing capacity, the module mass and mounting method can be decisive. In an indoor sensor, before the efficiency in the standard solar spectrum, the spectrum of the actual illumination, leakage current at low irradiance, and the threshold of the storage circuit become important. The same cell may not be the best choice for all of these applications. The U.S. Department of Energy’s description of the production chain also shows that wafer-based and thin-film production methods consist of different process steps. [D01]

The first page of the development document should answer the following five questions: Where will the product be used? With which existing solution will it be compared? At what scale will it be produced? Under what conditions will it be considered a failure? How will success be verified with an independent measurement? “We will create high-efficiency perovskites” is insufficient as a research objective. “We will develop an interface process that, under the same substrate and measurement conditions, provides a stable increase in maximum power compared to the reference process and is reproducible in independent production batches” is a more functional starting point.

Decision dimension	Target to be recorded.	Incorrect shortcut.
Performance	Area definition, spectrum, temperature, steady-state power, and uncertainty.	Selecting only the best reverse scan
Durability	Stress, electrical operating point, duration, power-retention distribution	Considering shelf life as operational life.
Manufacturability	Area, batch size, acceptance yield, cycle time	Considering a successful pixel as proof of successful mass production.
Resource utilization	Material consumption, energy, process step, waste.	Considering only the absorber raw-material price
Compliance	Module structure, test scope, application condition.	Extending a component certification to the entire product.

Establishing a loss budget

A solar cell’s efficiency is not determined by three independent adjustment parameters; the short-circuit current, open-circuit voltage, and fill factor are all related to the same physical structure. Nevertheless, logarithmic decomposition can help determine research priorities for small variations:

$$\eta = \frac{J_{\mathrm{sc}} V_{\mathrm{oc}} FF}{G}, \qquad \frac{\Delta\eta}{\eta} \approx \frac{\Delta J_{\mathrm{sc}}}{J_{\mathrm{sc}}} + \frac{\Delta V_{\mathrm{oc}}}{V_{\mathrm{oc}}} + \frac{\Delta FF}{FF} - \frac{\Delta G}{G}. \tag{II.1.1}$$

For example, in a cell designed solely for educational purposes, let the current density be 40 mA/cm^2, the voltage be 0.720 V, and the fill factor (FF) be 0.82. At an illumination of 100 mW/cm^2, the efficiency is 23.616%. Increasing the voltage by 10 mV, while keeping the other parameters constant, results in an approximate 1.39% relative power increase. Increasing the FF from 0.82 to 0.83 results in an approximate 1.22% relative increase. These correspond to absolute efficiency gains of approximately 0.33

and 0.29 percentage points. It is necessary to clearly state whether the phrase “one percent increase” refers to a relative percentage or a percentage point.

This calculation does not prove that the interventions are independent. A thicker conductive oxide can reduce the sheet resistance while increasing optical absorption. Stronger doping can reduce the barrier at the contact while increasing Auger recombination. A thinner wafer can reduce material consumption while increasing the fracture rate. The loss budget should not hide these interactions; it should show the expected positive effect and the potential cost of each proposal together.

Why is the reference process the backbone of the research?

The reference process is the initial device that the laboratory can reproduce consistently over a specific time interval. It does not necessarily have to be a record-breaking device. Its critical characteristic is that its normal distribution is known. If the results vary significantly when reference cells are produced on three different days, it becomes difficult to confidently isolate the small effect of the new dopant. In this case, the initial development effort should focus on understanding the variability of the existing process rather than trying out new materials.

The version number of the reference recipe, raw material lot, substrate cleaning history, operator, equipment maintenance status, and measurement files are all maintained in a single record chain. When the reference changes, the old and new versions are compared on the same day or within the same batch using a bridging experiment. This prevents the error of comparing today’s single successful sample with the average from six months ago. As a process evolves, it is natural for the reference to evolve as well; the date and reason for the change should not be lost.

Transforming a hypothesis into a differential experiment

The statement “Our process reduces defects” is strengthened only if defect-free explanations are tested. Voltage increases can result from changes in absorption, contact selectivity, measurement temperature, or pre-conditioning under illumination. A differentiating experiment selects a condition where the hypotheses make different predictions. For example, only the top contact is changed on the same absorber film; while optical absorption remains constant, PL, steady-state power, and contact resistance are monitored together. Complementary measurements are used instead of a single measurement.

To measure the effect of an intervention, control and treatment groups, if possible, are used, separated from the same main batch. Substrates are randomly distributed based on their position; pixels on the same substrate are not counted as independent production repetitions. Obfuscated file names reduce the tendency to carefully select the group that is “expected to perform well” during analysis. Reasons for sample exclusion are defined before the measurement; silently removing short-circuited devices from the table inflates the acceptance rate.

Development gates: another piece of evidence at each stage

The first criterion is the reliability of the measurement. The second criterion is that the effect must exceed the reference scattering. The third criterion is repeatability across independent batches. The fourth criterion is the persistence of the effect when the area increases or the process is transferred to different equipment. The fifth criterion is evaluation in conjunction with durability and production cost. This sequence is not a universal certification standard, but rather the research management framework used in this book.

If one of the approaches fails, it doesn’t necessarily mean the entire study has to turn into a failure story. For example, a passivation process that works in a small area but not in a large area provides valuable negative results regarding homogeneous coating. A film that is stable at low temperatures but degrades under illumination directs the research towards light-induced mechanisms. If the results file includes not only the successful approaches but also the reasons why certain options were eliminated, the same dead ends will not be revisited.

Using this book as a reference

If the measurement setup has not yet been established, the process begins with the second section. The team improving the existing silicon line proceeds to the third and sixth sections. The team working on thin-film or tandem cells reads the seventh through ninth sections, followed by the interface and reliability sections. The design of experiments and scale-up sections are common to all technologies. The company atlas shows which organizations are monitoring the technical processes at the product, pilot, or research level; it is not a purchasing or investment ranking.

Assignment. Write a one-page target card for your project, including: application, reference, primary output, production unit, error margin, two competing explanations, and the next decision point. If any of these fields are unclear, clarify them before producing new samples.

BOOK II · CHAPTER 02 / FOUNDATIONS OF DEVELOPMENT

Development laboratory: first, trust what you can measure

Functions of the components on the measurement bench

To determine the performance of a cell, a light source, a reference for adjusting the light, temperature control, electrical connection, and a recording system are required together. The **solar simulator** provides laboratory light. The **reference cell** correlates the light adjustment with a known response. The **sample holder** not only holds the cell in place but also affects the thermal and contact conditions. The **source-measurement unit** measures the current at the selected voltage or the voltage at the selected current. Each component is an input for the final calculation.

Short circuit is the condition where the terminal voltage is zero; **open circuit** is the condition where the external current is zero. The useful maximum power lies between these two. We use the product of voltage and current, measured simultaneously. Dividing the current by the area gives the **current density**. An incorrect definition of the area can lead to incorrect efficiency values for the same physical power.

How can we verify that we obtain the same result repeatedly?

Repeat measurement refers to measuring the same sample again. **Independent production repeat** involves subjecting a new sample to the same processing steps. The former covers instrument and connection variability, while the latter also includes process variability. Measuring the same cell multiple times does not demonstrate that a new recipe will yield the same result on different days.

Synthetic example: Suppose the same cell is measured three times, giving 20.0%, 20.1%, and 20.0%. These measurements are close to one another. If cells from three separate production days result in 18%, 20%, and 22%, there is much greater variability in the process. If the improvement gain is only 0.2 percentage points, appropriate design and more independent information are needed to distinguish the difference within this variability. Close repeated measurements alone do not eliminate systematic light adjustment errors.

The **measurement record** should include the sample ID, raw curve, masked area, light and temperature, previous dwell time, scan direction, and scan speed. **Preconditioning** refers to subjecting the sample to a specific light, voltage, or temperature history before measurement. This history affects the outcome, especially in devices with slow ionic processes. The report template below converts the screenshot into a re-examinable data package.

Comprehension check: the power changed when the cable was replaced

Since the material has not changed, first check the contact, cable drop, sample temperature, and measurement geometry. A four-wire connection can isolate some conduction losses by sensing voltage separately from the current cable. Understanding the electrical setup is a prerequisite before claiming material improvement.

The value of a research laboratory is not measured by the number of devices it possesses. What determines its worth is its ability to meaningfully compare the same sample on different days, its knowledge of the limitations of a measurement, and its ability to return to the raw data. Before cell production, what needs to be verified is the behavior of the measurement chain itself. The light source, reference cell, temperature, contact geometry, area mask, voltage sweep, and analysis software together constitute a measurement system.

Traceability, starting from the sample identification

Every physical substrate must have a unique identifier. This identifier is maintained throughout the film, device, and module stages. Pixels on the same substrate are assigned separate identifiers. The raw material lot, solution preparation time, storage conditions, and layer sequence are linked to the substrate identifier. This allows us to determine whether the entire group of low-performance devices originated from the same coating day or the same glass box.

The raw measurement files are kept unchanged. The processed results, along with the analysis version and the correction coefficients used, are written to new files. Simply including “best” or “final” in the file name is not sufficient for future traceability. A reliable record includes the sample ID, time, device, measurement type, and the location of the raw data. The efficiency automatically provided by the device software is not accepted as an uncontrolled final value; unit conversion and area calculation are verified independently.

Physical setup for current-voltage measurements

The source-measurement unit applies voltage to the cell and measures the current. In a four-point connection, the current-carrying lines are separated from the voltage-sensing lines, which reduces the influence of cable and contact resistances on the cell voltage. However, a four-point connection does not automatically correct for spreading resistance or poor probe placement on the cell. The probe pressure and whether the contact creates a short circuit at the contact point and a portion of the metal grid should be recorded.

The sign convention for current is explicitly stated. In this book, the current delivered by the illuminated cell to the external circuit is considered positive. The current recorded by the device using the electrical consumer sign convention may be negative. This transformation is verified before the power calculation. Taking the absolute value of all data to correct for reverse connection is an incorrect method, as it can alter the dark or reverse polarization behavior in a way that makes it meaningless.

The scanning range should cover the short-circuit and open-circuit conditions, but unnecessary reverse polarization or high forward current should not be applied to the sample. The voltage step, dwell time, integration time, and compliance limit are recorded. In dynamic devices, a single rapid scan does not represent stable performance. Scanning directions and different speeds are diagnostic measurements used to reveal the effect of the electrical history.

Light, spectrum, and temperature are not interchangeable

A simulator's class is evaluated based on its spectral distribution, the uniformity of irradiance on the measurement plane, and its stability over time. IEC 60904-9:2020 classifies these properties separately; a good class label does not imply that the spectral mismatch of each individual cell is zero. If the spectral response of the new absorber differs from the reference cell, correction is required. [D20]

The temperature sensor should represent the operating temperature of the sample. The substrate temperature may not be the same as the temperature of the cell surface under illumination. Thick glass, poor thermal contact, or a short flash measurement can alter this relationship. The heating effect can be observed by measuring the same reference device after different illumination times. Since the effects of heating and ionic rearrangement in perovskites can also be intertwined, time recording is essential.

The mask's aperture is verified using an optical microscope or appropriate dimensional measurement. The active area, aperture area, and total device area are not the same concept. Reducing the area artificially increases the current density and efficiency. Light scattering at the edge of the mask, charge carrier collection from neighboring unmasked areas, and the reflective substrate effect are evaluated. In a laboratory comparison, masked and unmasked results can be presented together; it must be clear which result belongs to which area definition.

Stable power and EQE cross-check

Maximum power point tracking measures the time-dependent operating power by adjusting the voltage or load around the power peak. It may be beneficial to maintain the MPP voltage obtained from the initial scan as a constant, but this is not the same as true tracking if the device's MPP changes over time. The oscillations of the control algorithm should be separated from the physical fluctuations of the device. The raw voltage, current, and time series are stored; only the smoothed power curve is not presented.

EQE represents the conversion of incident photons into charge collected in the external circuit as a function of wavelength. When the measured EQE is multiplied by the appropriate reference spectrum and integrated, the expected short-circuit current is calculated. Significant discrepancies in the current-voltage measurement are investigated in terms of spectral correction, area, light bias, device non-linearity, or reference calibration. In tandem cells, the individual sub-cells have distinct spectral responses and require appropriate bias light; IEC 60904-1-1 addresses the current-voltage measurement of multijunction devices, highlighting the importance of the required spectral response information. [D19]

$$J_{\mathrm{sc}}^{EQE} = q \int \Phi(\lambda)\, EQE(\lambda)\, d\lambda. \quad \text{(II.2.1)}$$

Here, the photon flux is given per wavelength. If the data is per nanometer, the integration step should also be in nanometers; indiscriminately mixing the wavelength in meters with the spectral density per nanometer leads to a significant unit error. The spectral integral example given in the first book is therefore an example of the daily check performed in the measurement laboratory.

Quantifying uncertainty

For independent, small uncertainties, the relative variances of multiplication and division can be summed. If there is correlation in the actual measurement, covariance terms are also added. The following expression is particularly clear when power and measured area are used directly instead of current density:

$$\eta = \frac{P_{\max}}{GA}, \qquad u_r^2(\eta) \approx u_r^2(P_{\max}) + u_r^2(G) + u_r^2(A). \quad \text{(II.2.2)}$$

In the example, let the standard relative uncertainties be 0.6 percent for power, 1.0 percent for irradiance, and 0.5 percent for area. With the assumption of independence, the combined standard relative uncertainty is approximately 1.27 percent. At 24 percent efficiency, this corresponds to approximately 0.30 percentage points. If an expansion factor of approximately two is used, the range increases further; however, the coverage factor and the interpretation of the coverage must also be specified. In the same setup, common systematic errors in paired comparisons may be partially canceled out; this means that the absolute efficiency uncertainty is not the same as the uncertainty in the difference.

Independent repetition differs from repeated measurement

Reading the same cell ten times provides information about the device's short-term reproducibility. Fabricating ten cells on the same substrate demonstrates the distribution within the substrate. Preparing three separate solutions and performing three separate depositions on different days tests the process reproducibility. Combining these levels and inflating the sample size will make the confidence intervals appear narrower than they actually are. The NIST measurement process framework helps in the separate evaluation of repeatability, reproducibility, and stability over time. [D16]

Control	Application	Problem it can reveal
Daily reference device.	Measurements taken at the beginning and end of the day using the same setup.	Light or device drift.
Repeated contact disconnection and reconnection	Reconnecting the same cell.	Sensitivity to probes and fixtures
Second operator	Measuring several samples while keeping their identities anonymous.	Operator effect
Area verification.	Measure the aperture using an independent dimensional method	Systematic efficiency deviation.
Current calculation using EQE.	Compare the spectral integral with the JV curve.	Spectral or area mismatch
Independent laboratory	Please send the representative and reference samples together.	Laboratory-specific bias.

Minimum measurement report

The report should include the sample structure, area definition, irradiation, spectrum, temperature, scanning direction and speed, pre-conditioning, steady-state power method, reference calibration date, and uncertainty. Failed samples, devices that could not be measured, and reasons for exclusion should also be listed. The median or average of the group, its distribution, and the best device should be shown together. This structure is necessary not to slow down the research, but to be able to distinguish genuine improvements from the outset.

Assignment. Design a small experiment to measure the reference cell in the laboratory over two days, with two operators and three re-connections. Prepare a table in advance that will distinguish between sample changes and measurement changes. The output should be a record showing which variability comes from which process, and not just a single standard deviation.

BOOK II · CHAPTER 03 / MANUFACTURING METHODS

The silicon route: from raw material to clean and textured wafer

What transformations are required to convert sand into a wafer?

In nature, silicon is mostly found in compounds with other elements. **Silicon dioxide**, SiO_2, is a compound of silicon and oxygen; it is not the same material as the crystalline silicon absorber in a solar cell. Producing elemental silicon involves a chemical transformation, and achieving electronic grade silicon is a separate purification challenge. The phrase “very pure in terms of mass” does not fully describe the effects of defects, as even small amounts of certain metals can accelerate the loss of charge carriers.

Polysilicon is a purified silicon raw material containing many crystal grains. The **Czochralski method** involves contacting a seed crystal with molten silicon and controllably pulling it to grow a large crystal. The **ingot** is the resulting large crystal body. A **wafer** is a thin slice cut from this body. During crystal growth, impurity and dopant distribution may not be uniform throughout the ingot; therefore, location and lot information is recorded. [D08]

Cutting, cleaning, and texturing are separate processes

Cutting can leave a damaged layer and mechanical stress on the surface. **Etching** is the controlled removal of material from the surface. **Cleaning** aims to remove dirt or chemical residue that could damage subsequent processing. **Texturing** creates a geometry that reduces light escaping from the surface. Even if these three processes are performed in the same liquid, their objectives are different; their results are measured differently.

Different crystallographic orientations dissolve at different rates under certain etching conditions. This **anisotropy** makes the formation of pyramid-like surfaces possible. Lower reflection can be beneficial; however, the increased surface area can also lead to more defective bonds and more difficult coating. Optical gain should be evaluated in conjunction with the final passivation.

Synthetic mass calculation: Let's consider a 1 cm^2 silicon wafer with a thickness of 150 µm. The thickness is 0.015 cm, and the volume is 0.015 cm^3. If we assume a density of approximately 2.33 g/cm^3, the mass is approximately 0.035 g. Reducing the thickness (20%) also reduces the mass of the material in the ideal geometry (20%).

Without knowing the cutting loss, breakage rate, and acceptance rate, it cannot be said that the material consumption per good cell will decrease proportionally.

Comprehension check: is it sufficient to simply select the surface with the least reflection?

After texturing, evaluate reflection, surface cleanliness, the lifetime after passivation, and the fracture rate together. If the texture is optically good but cannot be coated for the subsequent thin film, the process as a whole does not yield satisfactory results.

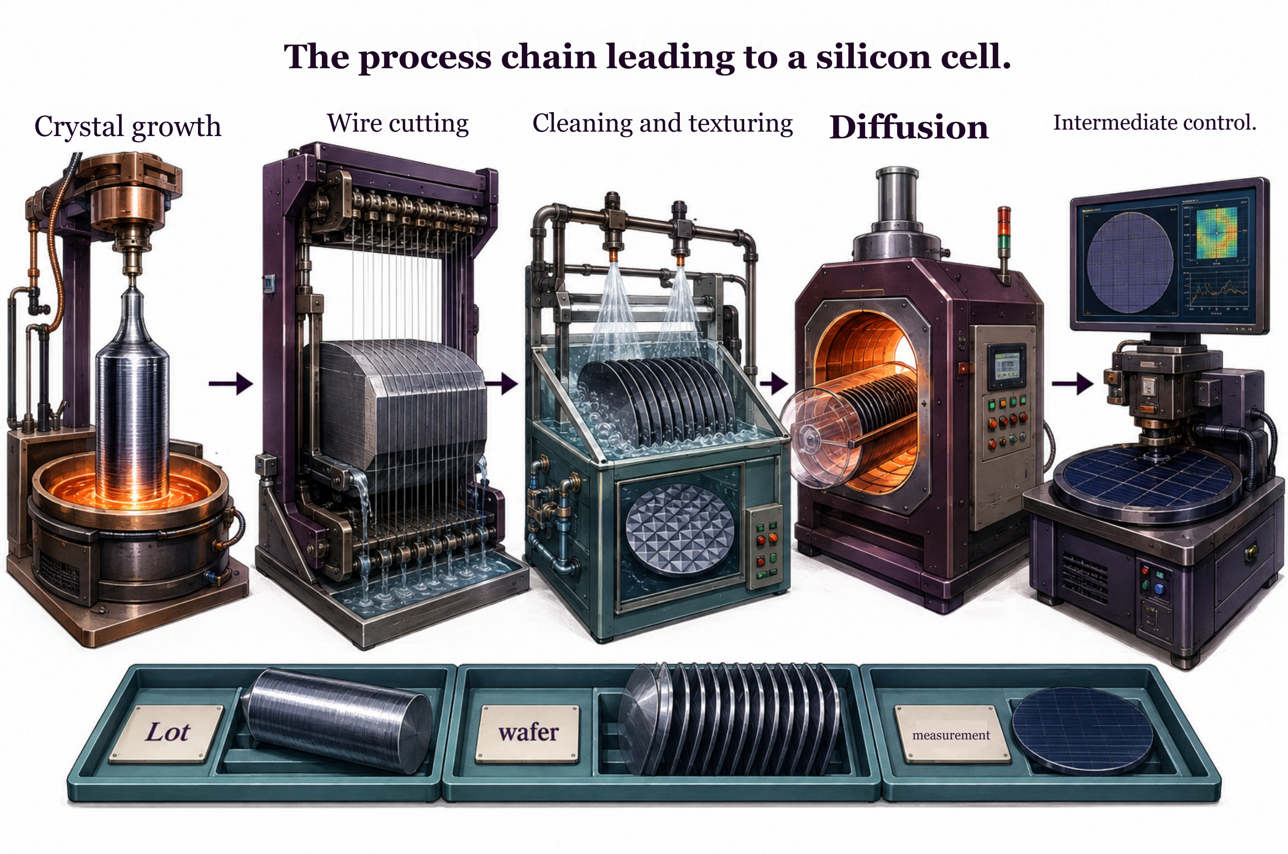


Figure 01. The processing sequence from crystal to cell precursor. Wire sawing, surface preparation, diffusion, and intermediate inspection manage different quality variables; the process flow is not a specific recipe for a particular factory. [D01] [D06] [D07] [D08] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

In silicon cell development, the most noticeable innovation is often the contact architecture; however, the performance that the cell can achieve is also limited by the initial material. Resistivity distribution, lifetime, oxygen and metal contamination, wafer thickness, curvature, and surface damage all interact with subsequent processes. A good coating cannot compensate for all the problems of a poorly chosen initial material. This section addresses the beginning of the production chain, considering the control of variables for subsequent experiments.

Purification and crystal growth are distinct processes

The conversion of metallurgical silicon into high-purity polycrystalline silicon involves chemical purification and deposition steps. Siemens-type rod deposition and fluidized bed approaches operate with different reactor configurations, energy consumptions, and product forms. The subsequent crystal growth stage produces controlled crystals, doping, and geometry from this raw material. Combining the two stages into a single “silicon production” box obscures which impurity or cost source the research question pertains to. [D01]

Setting up an entire purification chain in a university laboratory is not necessary for most cell development questions. When working with purchased wafers, the supplier’s measurement specifications, lot consistency, and acceptance controls are examined. The low metal contamination declared by the company does not, by itself, guarantee that the post-cell lifetime will be the same; the furnace, charge carrier, and wet processes can also add contaminants. Input material and process-related losses should be monitored separately.

Czochralski growth and within-lot variation

In the Czochralski method, a seed crystal is pulled from the molten silicon; the temperature gradient, pulling rate, and rotation conditions affect the growing crystal. Uneven distribution of dopant atoms between the solid and liquid phases can lead to variations in resistivity along the ingot. Interaction with the quartz crucible can affect the oxygen content. Therefore, if wafers taken from the beginning and end of the same ingot are unevenly distributed among the experimental groups, the difference that is assumed to be due to the process may actually originate from the initial material. The UNSW production source explains dopant segregation and the feedback-controlled Cz approach in this context. [D08]

A simple control for this problem is to group the wafers by lot and ingot position. The control group should not be taken from the same box as the test group. If possible, neighboring wafers should be distributed among different test groups. Maps of the initial resistivity, thickness, and lifetime measurements are stored. Even if the group averages are close, single-point measurements are not sufficient because there may be systematic differences in the edge regions.

Thinning, dicing damage, and mechanical acceptance

Thinning the wafer reduces the silicon consumption per unit area. Conversely, fragility becomes a critical factor during handling, printing, furnace loading, and lamination stages. Surface damage from cutting and edge microcracks can remain undetected and persist until the final cell. The success criterion for a thickness reduction project is not solely the cost savings per gram; it is the acceptable material usage per watt and the overall line acceptance rate.

As an educational example, let’s consider two processes where the thickness is reduced by 10 percent. In the first process, if the breakage rate remains unchanged, the material saving directly translates into a benefit. In the second process, if the total yield rate decreases from 98 percent to 87 percent, using less material initially may not provide an advantage per salable product. This example is not sufficient for a complete cost analysis; cutting loss, energy consumption, and reprocessing must also be considered. Nevertheless, it demonstrates why single-parameter optimization can be misleading.

Cleaning: What subsequent process are you preparing the surface for?

Cleaning is not simply about removing visible dirt. Organic residues, metal ions, particles, and surface oxides represent different problems. If the subsequent process involves oxide growth, amorphous silicon coating, or self-assembled monolayers, the target surface condition changes. Instead of using the phrase “cleaner,” it is specified which residue is reduced to what detection limit and what chemical termination the surface achieves.

Chemical cleaning and etching are performed in accordance with the facility’s approved procedures, with adequate ventilation, compatible materials, and waste management. The process description provided here does not replace the training of personnel on device and chemical safety procedures. From a research perspective, a critical point is that the rinsing quality and the time elapsed from cleaning to coating are also part of the recipe. If the surface is left exposed to the air for several hours, it may not remain in the same condition as when it came out of the furnace or bath.

Texture formation and optoelectronic trade-offs

The rate of alkali etching, which depends on the crystal orientation, is used to create a pyramidal surface texture on single-crystal silicon. The inclined surfaces affect the re-encounter of light and its path within the material. However, since the actual surface area increases, the passivation requirement also changes. The UNSW source demonstrates the relationship between the alkali texture, crystal orientation, wetting, and bath conditions. This book suggests that texture optimization should not be limited to reflection at a single wavelength. [D06]

Spectral reflectance should be weighted by the corresponding photon flux. Furthermore, the lifetime should be compared before and after texturing and passivation. A surface with very low reflectance may result in lower overall power due to high surface recombination. In the silicon sub-cell prepared for a tandem structure, higher pyramids may make it difficult to achieve complete coverage of the top film without holes. Thus, the texturing that is good for a single junction needs to be redesigned for tandem integration.

Intervention	Primary observation	Trade-off to monitor alongside it
Etch time or bath condition.	Spectral reflectance, pyramid distribution	Mass loss, surface lifetime.
Thinner wafer.	Thickness and material consumption.	Warpage, handling breakage, rear optical loss
Cleaning sequence.	Surface contamination and wetting	Surface roughness, re-oxidation.
Lot selection	Resistivity and lifetime map.	Cost, supply chain continuity.
Reducing texture size	Top-layer coverage	Light trapping and interface area

The significance of diffusion in process development

In impurity diffusion, the source provision and the impurity's progression into the material can be controlled separately. For the final device, only the total amount of impurity is not important; the depth profile, electrical activation, and the concentration near the surface are also significant. In the simple approach with a constant diffusion coefficient, Fick's equation is as follows:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2}, \qquad D = D_0 \exp\left(-\frac{E_a}{k_B T}\right). \tag{II.3.1}$$

The sign on the right side is positive; the second derivative with a negative sign behaves in the opposite manner to physical diffusion. Deviations from this simple solution are expected when the gas source, boundary condition, and temperature time profile change. It is not assumed that doubling the time doubles the dopant depth; the simple diffusion scale is related to the square root of time. In industrial tube diffusion, the wafer spacing, loading amount, and position relative to the gas flow are also experimental factors. [D07]

The sheet resistance map is a rapid process indicator; different depth profiles can yield the same sheet resistance. Therefore, cross-checking with depth-sensitive measurements such as ECV or SIMS is performed on selected samples. SIMS measures the total elemental concentration, while electrical methods reflect the active charge carrier profile; it is incorrect to directly equate the two.

Example development study: is low reflectance sufficient?

The same wafer lot should be randomly distributed across three texturing conditions. For each condition, the input and output mass, reflection spectrum, and surface image should be recorded. Then, the same passivation process should be applied to all of them, and the lifetime should be measured. If the lifetime of the group with the lowest reflection is significantly lower, the electrical cost of capturing more light becomes apparent. The final decision is made after the same cell flow is completed, based on the current, voltage, fill factor (FF), and acceptance rate.

A strength of this study is its correlation of intermediate measurements with the final power output. A weakness is that the interaction between the coating and the texture remains uncertain if only a single coating batch is used. In the second stage, the process is repeated on a different day, and the texture-passivation interaction is specifically investigated. In this way, the research progresses from assessing the acceptability of a device image to defining a manufacturable process window.

BOOK II · CHAPTER 04 / MANUFACTURING METHODS

TOPCon development: achieving both good passivation and good conductivity

Why is there an oxide in TOPCon?

When a metal makes direct contact with a defective silicon surface, charge carriers can easily be lost at the surface. A good surface passivation layer, however, can make it difficult to extract useful current. **TOPCon** is a passivation contact approach that attempts to resolve this issue by using a very thin oxide layer and a heavily doped silicon layer. The oxide helps to reduce interface defects, and the doped layer on top provides selectivity and electrical connection. It should be specified which surface and which charge carrier it is used for. [D04] [D05]

Tunneling is a quantum transition through a very thin energy barrier. In addition to tunneling at the actual contact, other conduction paths, such as very small local openings, may also play a role. Therefore, the conclusion “oxide is 1.5 nm thick, so the contact is definitely good” cannot be drawn. The **oxide quality** is evaluated together with its thickness distribution, chemical state, and defects. **Selectivity** is the suppression of the loss of the opposite charge carrier while allowing the desired charge carrier to pass through.

What do the abbreviated deposition methods do?

CVD is a family of deposition techniques in which gaseous precursors react chemically on a surface to form a solid film. **LPCVD** is CVD performed at low pressure; **PECVD** is CVD in which the plasma activates the reactions. **Plasma** is an excited gas environment containing electrons and ions. **Annealing** is a heat treatment that modifies the layer's structure and dopant activation. Deposition and the final electronic quality are not the same stage; the film may acquire new properties or be damaged after the process.

Hydrogenation aims to passivate certain active bond defects with hydrogen. However, subsequent temperature and metallization processes can alter this effect.
Metallization is the process of forming the metal contact that collects the electric current. To understand whether the final cell is performing well, we must measure not only the passivation before metallization but also the finished contact resistance and power output.

Synthetic comparison: Let the passivation improvement increase the voltage 1% while reducing the fill factor FF due to transport loss 2%, and let the current remain unchanged. The power ratio becomes $1.01 \times 0.98 = 0.9898$; there is an approximate 1.02% decrease. This does not mean that a good passivation result is worthless; it indicates that transport is not being addressed simultaneously. The sample tree below teaches how to control these two effects separately.

Comprehension check: at which stage should you perform the measurement?

After the oxide and doped layer, measure passivation; after metallization, measure the contact and the total cell power. If gain is observed in the initial stage but disappears later, separately test the subsequent heat treatment, chemical interaction, and metal contact. Measuring only the final cell may conceal the step in which the loss originated.

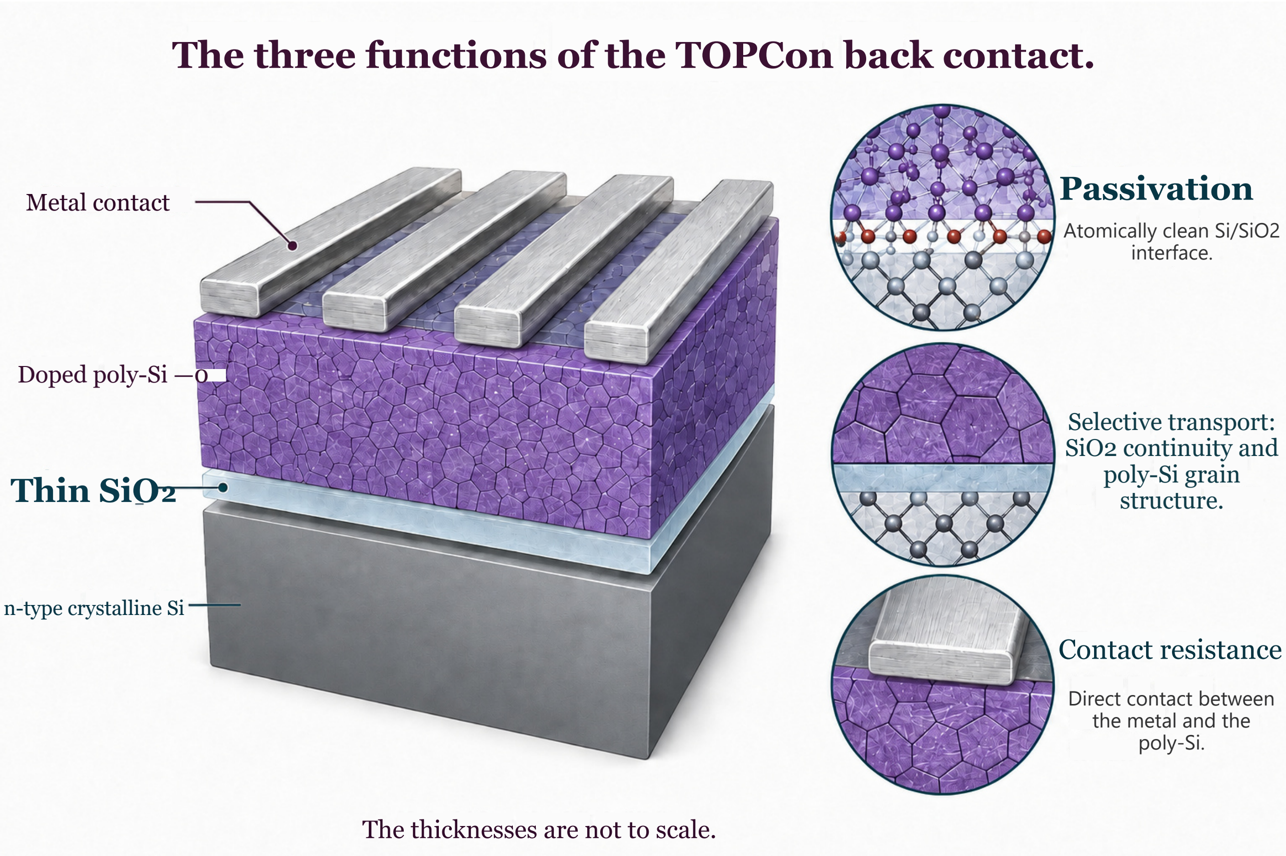


Figure 02. Representative magnified image of the TOPCon back contact. The thin oxide layer on the crystalline Si, the doped poly-Si, and the metal work together; good passivation alone does not guarantee low contact resistance. [D04] [D31] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

The term TOPCon describes a passivated contact approach that combines a silicon layer doped with a very thin layer of silicon oxide. The research question is not simply how thin the oxide layer is. The integrity of the oxide, the doping profile, crystallization, hydrogen, metal contact, and optical absorption are all important together. A good TOPCon contact should suppress minority charge carrier recombination while conducting majority charge carriers with low loss. Achieving both of these goals simultaneously is central to the approach. [D05]

Interpreting the layer sequence as a function map

In a typical n-type cell, the front side features a boron-doped emitter, surface passivation, and an anti-reflection coating, while the back side has an oxide/poly-Si passivated contact. This does not mean that all TOPCon products have the same recipe. The emitter location, doping method, poly-Si coating method, and metallization can vary. When examining a cell cross-section, ask the following questions for each layer: Which charge carrier does it select? Which interface does it passivate? In which direction does the current flow? How much of the light is absorbed in this layer without being utilized?

The Fraunhofer ISE process example, published by Mack and colleagues, utilizes a thermal oxide and in-situ phosphorus-doped LPCVD silicon layer, front-surface passivation, and printed metal contacts. The study involves process comparisons with approximately 80 nm of poly-Si; however, this value is not a universal optimum that can be applied to all manufacturing facilities. The instructive aspect of the study is the evaluation of passivation and the final metal contact on separate samples and in completed cells. [D04]

The oxide thickness alone is not a sufficient descriptor

Thickness measurements provide an average value; electrical behavior can be affected by local fine regions or discontinuities. A highly resistive oxide limits charge carrier transport. An excessively degraded interface, on the other hand, can increase recombination losses in the metal or doped layer. Surface preparation, the oxide formation method, and the subsequent thermal step should be considered together. Observing a good oxide sample in a TEM image does not necessarily prove its charge transport behavior.

In initial experiments, the oxide formation condition and subsequent annealing can be addressed within a factorial design. Symmetric lifetime samples reveal recombination, contact resistance structures indicate transport losses, and completed cells demonstrate the combined effect of both. When plotting the performance curve as a function of oxide thickness, it is verified whether each point has the same doping profile and the same thermal history. Otherwise, although the horizontal axis of the curve appears to represent a single variable, it physically represents a change in multiple variables.

Selection of LPCVD, PECVD, and doping methods

LPCVD refers to low-pressure chemical vapor deposition, while PECVD refers to plasma-enhanced chemical vapor deposition. In in-situ doping, the dopant source is introduced during the deposition process. In ex-situ doping, the silicon layer is first prepared, and then the dopant is introduced and activated. The choice is made considering factors such as deposition rate, single- or double-sided coating, unwanted conformal coating, cleaning requirements, thermal budget, and capacity per tool. The method itself does not guarantee low cost or high efficiency.

Published experimental studies have shown that the final annealing step in a TOPCon structure prepared by PECVD degrades the passivation, and the subsequent hydrogenation process partially recovers it. This observation weakens the assumption that "annealing is complete, and the material is now stable"; the performance of the final product depends on the entire thermal sequence. [D31] Therefore, development records include not only the highest temperature but also the heating and cooling history, dwell time, and time between processes.

Why is metallization considered a separate research area?

The metal paste can penetrate the insulating layer during the firing process, creating electrical contact. If the contact is insufficient, the series resistance remains high. If the contact penetrates too deeply, the underlying layer or the junction may be damaged. Changing the paste also requires re-evaluating the firing profile. It is not assumed that the front and back surfaces will exhibit the same metallization behavior. A high implied voltage before metallization does not guarantee that the same voltage will be achieved after metallization.

$$p_\Omega \approx J_{\mathrm{mpp}}^2 r_s. \tag{II.4.1}$$

For the area-normalized series resistance, this approximate loss density embodies the development priority. In the training example, if the MPP current is 0.038 A/cm^2 and the resistance reduction is 0.10 $\Omega{\cdot}cm^2$, the loss reduction is approximately 0.144 mW/cm^2. Under an input of 100 mW/cm^2, this represents an approximate 0.144 percentage point increase in efficiency. Due to the shift in MPP in the actual device, verification with a full JV solution is required.

Sample set for a TOPCon development experiment

Sample	Modified item	Measurement	Decision question.
Symmetrically passivated wafer	Oxide and poly-Si conditions	Injection-dependent lifetime, PL.	Has recombination actually decreased?

Sample	Modified item	Measurement	Decision question.
Contact test structure	Metallization paste and firing	TLM, line resistance.	Is the current flowing through a sufficiently low resistance?
Cell precursor before metallization	All surface treatments.	Implied voltage.	What voltage can the material and surfaces support?
Complete cell	The same process variant.	JV, Suns-Voc, EQE	Has the gain been transferred to the actual power?
Mini module	Interconnection and encapsulation.	Power, EL, post-stress measurement.	Does the gain persist after encapsulation?

The purpose of this approach is not to perform every analysis on every device. Rapid and inexpensive intermediate tests guide the more expensive, full-device experiments. However, it is also incorrect to declare a condition successful based solely on intermediate tests without observing the final cell. The selected few variants must proceed to full device fabrication and appropriate durability measurements.

Example: the voltage increased, and the fill factor decreased

Suppose a new passivation process increases the implied voltage but decreases the fill factor (FF) in the completed cell. The first explanation is that recombination is reduced, but the contact resistance increases. The second explanation is that the process is beneficial on one surface but detrimental on another. The third explanation is that the sample group differs in metal grid or printing geometry. If the pseudo-FF obtained with Suns-Voc deviates from the actual FF, resistance-related losses are investigated; TLM and line profile measurements complement this.

In the control experiment, passivation is kept constant, and only the metallization is varied. If the fill factor returns and the voltage gain is maintained, it becomes clear that the initial intervention was not entirely detrimental. This result leads to addressing the mismatch between interfaces, rather than prematurely eliminating the variant that “passivation did not work.” What is important in development is not selecting the highest single measurement, but being able to track in which process the loss occurs.

Steps to be followed during the transition to mass production

The wafer's position within the furnace, the number of cycles after equipment cleaning, and the history of the coating carrier can be hidden factors. If a laboratory condition involves working only in a newly cleaned room, the production window is narrow. During process transfer, samples are taken from the beginning, middle, and end of the batch; the optical properties of the back surface, printing morphology, and edge leakage are monitored. The production average, distribution width, and acceptance rate are separate results.

Assignment. Design an experiment with eight conditions to determine which of the following processes - oxidation, hydrogenation, or metallization - is responsible for the observed effect. Instead of comparing the old recipe with a "new recipe" where all factors are changed simultaneously, describe which two intermediate samples will differentiate the two explanations.

BOOK II · CHAPTER 05 / MANUFACTURING METHODS

Heterojunction development: selective contact engineering at low temperatures

In a heterojunction, what does “hetero” refer to?

A **heterojunction** is a junction between different semiconductor structures or materials. In a silicon HJT cell, the crystalline silicon wafer, which absorbs light, is used in conjunction with very thin amorphous or nanocrystalline silicon layers. **Amorphous** indicates the absence of long-range crystalline order, while **nanocrystalline** indicates the presence of very small crystalline regions. These are not merely names referring to the surface appearance, but rather structures that alter the electronic and optical behavior.

In a typical structure, the thin **intrinsic layer** between the crystal surface and the doped selective layer aids in surface passivation. The doped layers preferentially facilitate the transport of electrons or holes. The transparent conductive oxide, abbreviated as **TCO**, on top allows light to pass through while conducting current laterally. The metal grid collects this current for external connection. One layer may be for passivation, another for selectivity, and yet another for lateral conduction; it is not assumed that they all perform the same function.

What does a lower temperature change?

Thin hydrogenated layers and interfaces function well based on a specific processing history. Subsequent high temperatures can disrupt this arrangement. The **thermal budget** is not simply the highest temperature; it refers to which layer is exposed to which temperatures for how long. Therefore, in HJT, the metal paste and interconnection method must also be selected to be compatible with the cell’s layers.

Sputtering is a physical deposition method in which particles are detached from the target material and a film is formed on the surface; it is referred to as sputtering in English. It can be used in the formation of TCO, but the incident particles and plasma conditions can damage the underlying layer. **Contact resistance** is the cost of traversing the interface, while **sheet resistance** is the cost of lateral progression through the thin film. Combining these under a single “conductivity” value makes diagnosis difficult.

Synthetic calculation: As the coating’s transmittance increases from 92% to 94%, let the fill factor (FF) decrease from 0.80 to 0.77 due to electrical transport loss. Under the rough assumption that current is proportional to transmittance and all other effects remain the same, the power ratio becomes (94/92) × (0.77/0.80) ≈ 0.983. The more transparent layer may therefore give approximately 1.7% less power. The definitive decision is determined through full spectral and electrical measurements.

Comprehension check: How would you define a good TCO?

Simply having the lowest sheet resistance or the highest transmittance is not sufficient. The damage it causes in the sublayer, the selectivity of the contact, adhesion, and compatibility with the final metallization also contribute to the cell's performance. A good film is one that performs well in the processing sequence of the target device.

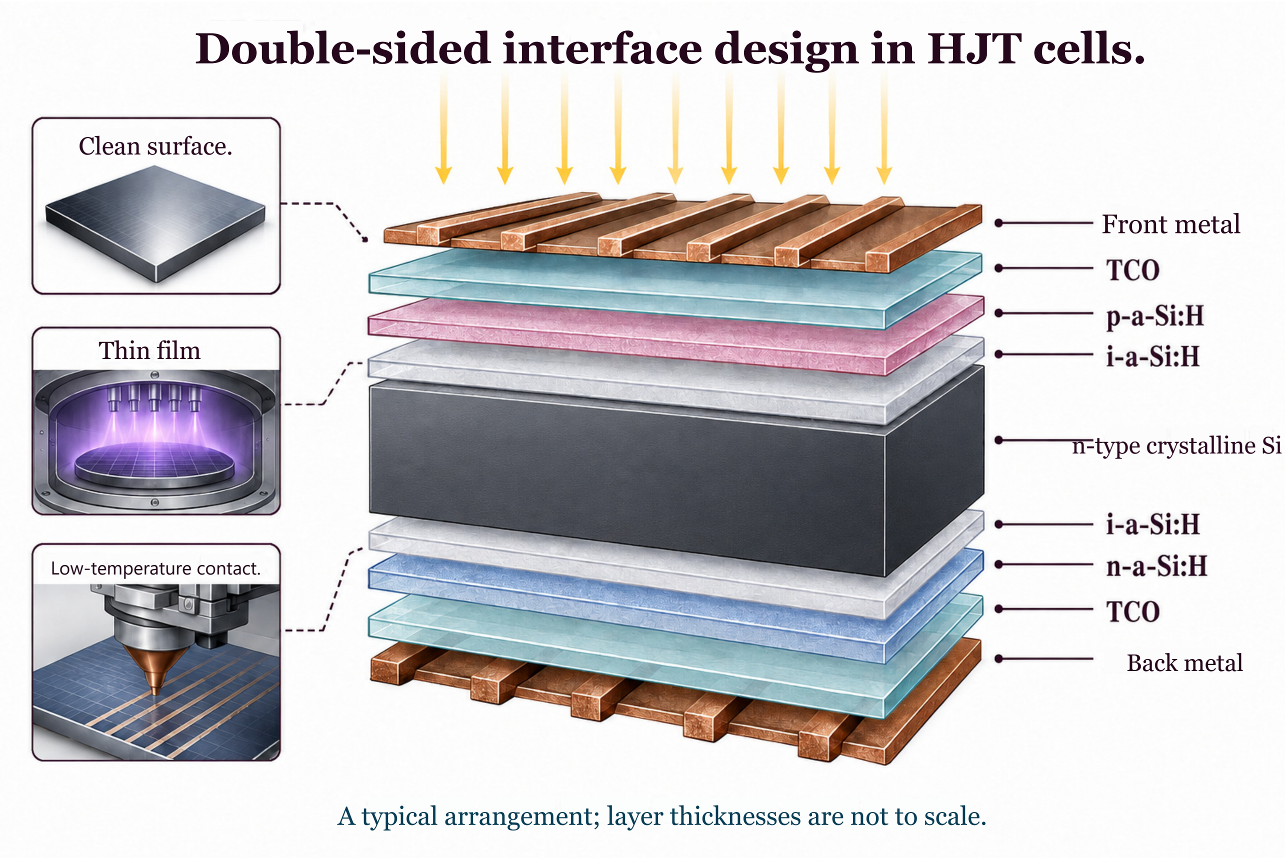


Figure 03. A typical HJT layer sequence using n-type crystalline silicon. The intrinsic films in direct contact with both crystalline surfaces provide passivation; the doped films, TCO, and metal are also optimized. [D09] [D10] [D32] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

The silicon heterojunction cell combines the light absorption capability of crystalline silicon with the surface and contact functions of very thin amorphous or nanocrystalline silicon layers. HJT and SHJ are the names used for this technology family. The developer's task is to protect the surface from defects, select the appropriate charge carrier, avoid light loss, and collect the current with low resistance. These are interconnected targets. It is possible to create a device with good surface passivation but a low fill factor (FF) due to the contact barrier.

Do not mix up the functions of the layers

The thin, undoped, hydrogenated amorphous silicon layer in direct contact with crystalline silicon provides strong surface passivation. Doped layers contribute to charge carrier selectivity. The transparent conductive oxide carries the current laterally and becomes part of the optical stack. The metal grid collects this lateral current and directs it to the external circuit. These functions are not entirely physically separated; for example, the optical absorption of the doped layer or the work function of the conductive oxide also affects other objectives.

Huasun’s published manufacturing process divides cleaning and texturing, bifacial PECVD, conductive oxide deposition, and metallization into four main groups. Each of these groups contains numerous control, transfer, and auxiliary processes; the “four-step” description does not mean that the entire factory consists of only four machine operations. [D09] In the research plan, these main groups should be divided into traceable sub-processes.

Surface cleaning and waiting time

The thin passivation layer is sensitive to the chemistry of the prepared surface. Two wafers subjected to the same cleaning process may not have the same initial interface if they are exposed to air for different durations. Therefore, the time between processing steps is recorded. Particles originating from gloves, charge carriers, cabinets, and transfer boxes are also examined. Failing to control the transfer conditions while only changing the chemical concentration in a cleaning experiment makes it difficult to interpret the results.

The initial test samples can be symmetrical passivation wafers. After the same surface preparation, the same undoped layer is applied to both surfaces, and the injection-dependent lifetime is measured. This sample does not test the selective contact and metal grid behavior; it simply demonstrates the combined effect of surface preparation and initial passivation. In subsequent experiments, as the doped layer and TCO are added, the measurement is repeated. This allows us to see at which stage the loss begins.

PECVD: deposition rate, damage and microstructure

When the plasma power is increased, the deposition rate may change; however, a faster deposition rate does not necessarily mean a better film. Ion bombardment, hydrogen content, nucleation on the surface, and unwanted epitaxial growth are evaluated. Even if the duration is changed to maintain the same film thickness, the plasma condition can produce different microstructures. Therefore, the statement “thickness is the same” in the experimental table should not be interpreted as implying that all other film properties are also the same.

Film thickness can be monitored using ellipsometry, crystallinity using Raman spectroscopy or a suitable structural method, and electrical conductivity using specific test structures. However, the properties of a film prepared on glass may not be exactly the same as those of a few-nanometer-thick layer on textured crystalline silicon. Reference samples are useful; their limitations in representing the growth on the actual device surface should be documented. It should not be assumed that a single characterization method defines the entire interface.

What can nanocrystalline contacts change?

In Lin et al.'s 2023 study, hole contact transport loss was reduced using p-type nanocrystalline silicon and modified TCO. The study reports certified devices, achieving 26.81% on approximately 274 cm^2 of industrial-grade wafers. The highest fill factor (FF) of 86.59% belongs to a different cell; combining these two record values into a single hypothetical cell is misleading. The key takeaway here is not to replicate the record, but rather to separately measure contact conductivity, passivation, and optical loss, and then combine them in the device. [D32]

For a nanocrystal layer experiment, the thickness, gas composition, and plasma conditions are not changed simultaneously without control. First, a feasible coating window is determined; then, the relationship between the selected variables and the contact resistance and optical transmittance is established. If the gain is only observed at high forward bias and not around the MPP, the physical significance of the operating point may have been overlooked. Contact properties should be evaluated within the relevant injection and temperature range.

Optical and electrical calculations of TCO

In a simple, uniform film, the sheet resistance is related to the resistivity divided by the thickness. However, the charge carrier density and mobility can also vary depending on the deposition conditions. A thicker TCO layer can provide lower sheet resistance but may increase parasitic absorption; in particular, free carrier absorption and short-wavelength losses should be examined separately. Simply averaging the visible transmittance is not sufficient. The spectral range used by the cell and optical interference with the underlying layers are important.

$$R_{\square} = \frac{\rho}{t} = \frac{1}{q\,n\,\mu\,t}. \tag{II.5.1}$$

This statement represents a single-carrier, uniform, and homogeneous conduction approach. It is also questioned whether the charge carrier density and mobility obtained from Hall measurements have the same meaning in the multilayer structure of the device. In the research, the transmittance, reflectance, sheet resistance, and contact resistance of a TCO variant are reported together. If the energy alignment of a "more conductive" TCO with the selective layer is degraded, the overall power may decrease.

Low-temperature metallization and the copper option

The thermal budget of a heterojunction stack differs from that of conventional high-temperature contact annealing. Therefore, suitable low-temperature pastes, multi-wire bonding, or coating-based metallization become important. Metallization research addresses conductivity, adhesion, line width, surface damage, and contact stability after aging. Reducing silver consumption alone is not the ultimate goal; a low acceptance rate or difficult recycling can lead to other costs.

In the copper plating process, in addition to electrical contact, diffusion barriers, selective deposition, masking, corrosion, and connection compatibility are evaluated. The term "silver-free" does not necessarily prove that the entire supply chain has a low environmental impact. Process chemicals, waste treatment, equipment maintenance, and thickness control are included in the cost calculation. This section does not describe the proprietary plating recipe of a specific company; it defines which functions will be verified during the research.

Problem-solving matrix

Observation	Possible explanation.	Discriminating measurement
The lifetime after coating is low.	Surface contamination or plasma damage.	Cleaning control; lifetime measured after each stage
Good implied voltage, low FF	Selective contact or TCO resistance.	Suns-Voc, TLM, temperature-dependent JV
Low current, voltage maintained.	Parasitic absorption or reflection.	EQE, spectral reflectance/transmittance, optical model
Initial power is good, followed by a decrease after connection.	Mechanical or thermal processing damage.	EL and JV measurements before/after interconnection.
Performance changes at the end of the batch	Coating buildup in the chamber; source drift	Cycle order, witness-sample map

Research example: Why didn't the film with the lowest resistance win?

Let's consider three TCO variants. The first provides the lowest sheet resistance, the second provides the highest light transmittance, and the third provides the best overall cell performance. The third option may balance optical and electrical losses. To demonstrate this, each variant should be compared using the same metal grid geometry, and the finger spacing should be optimized separately. The best TCO selection is not independent of the grid design.

In the next step, the two best TCOs are tested with two different grid spacings. This allows us to determine whether the material that performed poorly in the initial selection performs better under a different geometry. This experimental approach transforms the development of HJT from a process of "optimizing a single layer" into a process of designing the multi-layer device as a whole.

BOOK II · CHAPTER 06 / MANUFACTURING METHODS

Back-contact cells: patterning, insulation, and carrier transport length

What problem does moving the contacts to the back solve?

The metal on the front surface blocks some of the light. The **rear contact** approach can reduce this shading by moving the electron and hole connections to the rear surface. The two charge carriers must still go to separate selective contacts. Therefore, the rear surface is arranged in interdigitated but electrically isolated regions. **Patterning** is the process of creating the location and dimensions of these regions.

The contact area and the contact material represent different design axes. The rear contact configuration can be combined with various passivation and heterojunction approaches. Companies' commercial abbreviations may refer to specific combinations of these options; however, seeing the abbreviation does not necessarily reveal the exact layer composition.

Distance, insulation, and alignment change simultaneously

Line spacing is the distance between adjacent pattern elements. If the spacing increases, some charge carriers travel a longer lateral distance. If the spacing decreases, the patterning and insulation can require greater precision. A **shunt** is an unwanted electrical leakage between regions that should be separated. **Alignment tolerance** defines how much a process pattern can deviate from the previous pattern.

Synthetic geometry: Let the designed insulation gap between the two metal regions be 40 µm. If an uncontrolled overflow or positional change of 10 µm per edge occurs, the usable gap significantly decreases. This simple number alone does not represent the process tolerance calculation; the line width, the correlation between the two edges, and the measurement definition are also required. Ensuring that the gap, which looks good in the design, is reliably maintained during production is a separate problem.

Laser processing can locally remove or modify layers using energy deposition. **Masking** ensures that only the selected area is exposed to the process. **Etching** removes the target layer. All of these methods can create geometries; however, the damage and residue they leave on the underlying layer are not the same. Seeing a smooth line under a microscope does not guarantee electrical insulation.

The rear surface can also reflect light or accept light in a bifacial design. Therefore, changing the position of the contacts is not only an electrical modification but also an optical design change. The following development experiments will correlate pattern quality, carrier transport distance, and passivation with separately observable parameters.

Comprehension check: the line is good, the cell has a low fill factor

The image confirms a portion of the geometry. Additionally, measure the insulation leakage, contact resistance, and process damage for FF loss. If the carrier transport distance changes simultaneously when the line width is changed, you cannot speak of a single effect; the control design must account for this difference.

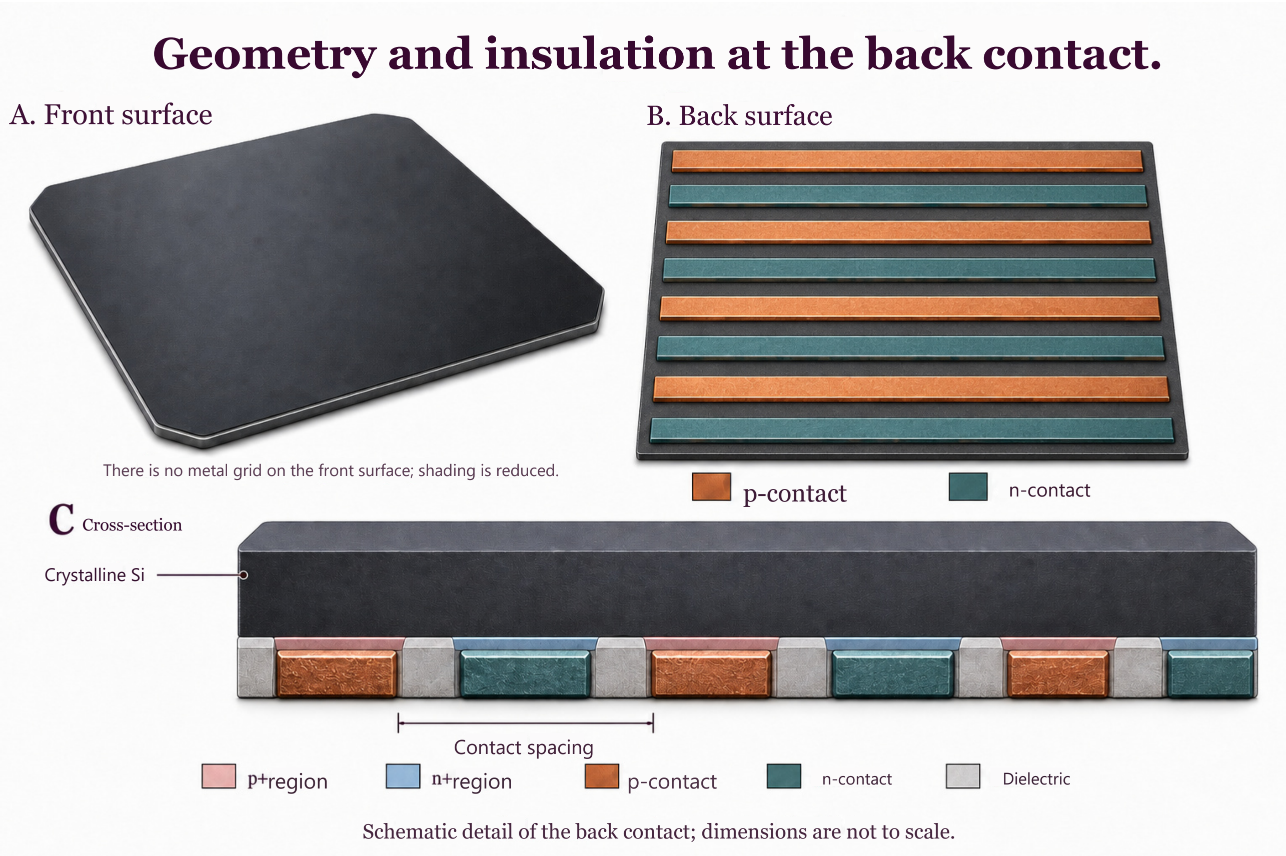


Figure 04. In the design of the back contact, the front surface optics and the back surface pattern have different functions. The two contact grids must remain isolated; alignment, spacing, and transport distance should be considered together. The contact physics depend on the chosen architecture. [C01] [C02] [D10] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

In the rear contact architecture, the electron and hole collection regions are moved to the rear side of the cell. Reducing the metal grid shading on the front surface provides an optical advantage; in return, the two polarities must be isolated from each other on the rear side, charge carriers must reach the correct contact region, and the metal contacts must be patterned reliably. BC is a layout family. Whether passivation is performed in a TOPCon-like manner, based on a heterojunction, or with other selective contacts is a separate choice.

BC, TOPCon, and HJT do not belong to the same classification category

A three-layer classification is used to translate a product name into its physical architecture. The first layer is the absorber: crystalline silicon, perovskite, or another material. The second layer is the contact physics: diffused junction, oxide/poly-Si passivated contact, amorphous silicon heterojunction, etc. The third layer is the contact layout: front-back, all-back, bifacial, or another arrangement. If this distinction is not made, the question "BC or HJT?" can be incorrectly framed as if there were only two mutually exclusive options.

The 2017 study by Yoshikawa and colleagues presents a large-area silicon cell as an example, combining a heterojunction with an interdigitated back contact configuration. The published approach relies on simultaneously improving lifetime, optical properties, and series resistance losses. This historical demonstration reveals that BC is not simply about eliminating the front grid. [D10] Current company brands do not necessarily mean that they directly use the same process as in this article.

Carrier collection geometry

On the rear side, there are two intermeshing contact grids. These grids must be electrically isolated from each other and positioned at intervals that allow charge carriers to reach them without recombination. As the contact spacing increases, the patterning may become easier, but the lateral transport distance increases. As the spacing decreases, the conduction path can be shortened; however, the alignment tolerance, insulation gap, and process complexity become more stringent. The actual optimum depends on the wafer lifetime and surface passivation.

$$L = \sqrt{D\tau}. \quad \text{(II.6.1)}$$

The diffusion length here serves as an initial screening parameter. There is no sharp threshold, such as "if the contact spacing is less than L, everything will be collected." The generation depth, junction shape, electric field, injection, surface losses, and three-dimensional current paths all influence the outcome. Therefore, the geometric design should be tested with the optical generation profile and electrical model, and subsequently verified with local measurements.

Patterning methods and common problems

Masking, photolithography, laser processing, or selective chemical etching offer different patterning methods. Common questions arise for each method: How repeatable is the edge positioning? Does damage remain beneath the removed layer? Is there any conductive residue between the two poles? Does wafer warpage affect alignment? When the processing area increases, is pattern accuracy maintained? These questions define the tolerances required by the geometry before device fabrication.

If a laser is used, only the average power is not recorded. The pulse energy, repetition rate, focus condition, scanning speed, pulse overlap, and thermal history of the substrate are significant. The same energy density can cause different damage at different pulse durations. A line that appears clean may not necessarily be electrically isolated. Optical microscopy, profile measurement, and local electrical tests are used together.

Establishing an alignment budget

The layout budget collectively addresses the permissible positional errors of overlapping processes. The designed isolation gap must be able to withstand variations in printing width, laser line position, wafer dimensional changes, and machine alignment errors. Summing all tolerances in the worst-case scenario is overly conservative; combining them with the sum of squares without measuring their independence may be overly optimistic. In the initial stage, the distributions are measured, and critical overflow scenarios are identified.

In the training example, let the nominal hole size be 100 µm. If the metal edge expands by 20 µm on each side, and the alignment error also affects the same direction by 30 µm, the remaining safety margin becomes very small. These numbers are not specific to the design of a particular BC product; they are a geometric example demonstrating why tolerances can determine the short-circuit acceptance rate before power-conversion efficiency. It is risky to move to a narrower line width before the dimensional budget is completed.

Rear-side optics and bifaciality

The absence of a grid on the front surface does not mean that all optical losses are eliminated. Front passivation and reflection, the reflectivity of the rear metal, parasitic absorption of the passivated contacts, and module encapsulation still remain important. If light is to be collected from the rear side, there is an additional trade-off between the metal fill factor and electrical resistance. It is not assumed that the BC must be single-sided, or that all BC cells exhibit high bifaciality.

Therefore, during product comparisons, the initial efficiency, bifaciality factor, and actual on-site rear irradiance are provided separately. A cell with high rear response may not provide the same gain on a dark, low-reflectivity roof. The conversion of cell architecture to field values is calculated together with the mounting height, row spacing, and surface reflectivity. The annual energy difference provided in the company brochure is interpreted only within the defined scenario.

Transforming the company name into a technical question

LONGi's HPBC 2.0/Hi-MO X10 descriptions outline a product roadmap centered around hybrid passivation, back contact, and interconnection design. AIKO's ABC descriptions all emphasize the back contact layout and silver-free metallization approach. [C01] [C02] These are the companies' own statements; it cannot be said that all products using the same letter group are equivalent in process or performance. A detailed and dated company comparison is in the sixteenth chapter.

Based on these explanations, the researcher should formulate a research question: To what extent has contact shadowing been reduced? How much of the gain comes from area utilization or cell arrangement? How was the effect of the metallization change on contact resistance and durability measured? Are the area definitions for the cells and modules used consistent? These questions are more instructive than simply repeating a large percentage from the brochure.

Example experiment: is it the line quality or the material quality?

In the two rear pattern variants, use the same initial wafer and passivation. In one, the fill factor (FF) should be low, and in the other, the voltage should be low. In the first group, consider discontinuous metal lines or long current paths; in the second group, consider laser damage or inter-electrode leakage. EL images are compared at the same current, and dark JV and local resistance measurements are added. It should be noted that if the image brightness is normalized using an automatic color scale, the actual difference may be hidden.

Indication	First check	Next intervention.
Dark stripes at regular intervals.	Contact continuity and lateral transport	Finger spacing or metal thickness.
Leakage at the pattern boundary.	Residual film, damage, alignment	Removal and insulation conditions
Low voltage across the entire cell.	Lifetime and surface passivation.	Thermal/cleaning history

Indication	First check	Next intervention.
Low acceptance rate at the edges.	Edge isolation, pattern overflow.	Edge geometry and fixture
Power loss after module fabrication	Interconnection and mechanical stress.	Cell interconnection design.

Success criterion

Success in BC development is not limited to the aesthetic appearance of the front surface or the efficiency of the best cell. The production of the same pattern over a large area and in multiple batches, the control of short-circuit and breakage rates, module transfer loss, and reliability are all considered together. As much as the number of process steps, the window width of each step is important. Small variations in a few critical alignment steps can determine the overall cell acceptance rate.

Assignment. Describe the cross-section and top view pattern of the rear-contact cell you designed as separate drawings. Specify the charge carrier selection in each layer, the electrical connection in each line, and the purpose of insulation in each gap. Then, list three possible short-circuit paths and the measurements that would detect them.

BOOK II · CHAPTER 07 / MANUFACTURING METHODS

Perovskite development: from composition to ink, from ink to homogeneous film

Ink is more than just a formula

In perovskite film production, the **ink** is a processing mixture consisting of precursors, solvents, and any additives that provide the target composition. **Concentration** refers to the amount of substance present per unit volume or mass. A **mole** is a unit of quantity representing approximately 6.022 × 10^{23} entities of a substance. **Stoichiometry** refers to the numerical ratios in a reaction or target composition. The same stoichiometry may not yield the same coating behavior with different solvents and aging histories.

Viscosity refers to the resistance to flow; **surface tension** describes the tendency of a liquid surface to minimize its area. **Wetting** is the manner in which a liquid spreads on a solid surface. A **meniscus** is the curved liquid surface formed at the edge of a coating. These properties help to understand why a film, even with the correct chemical composition, may exhibit striping, pinholes, or thickness variations.

The pathway from the wet film to the crystal

During coating, the liquid is distributed across the surface. As the solvent evaporates, the concentration increases, leading to **nucleation**, which is the initiation of crystal formation, and the growth of these nuclei. **Drying** refers to the evaporation of the solvent, while **crystallization** is the process of atoms and ions forming an ordered structure. The two processes influence each other but are not the same. Even when the surface appears dry, unwanted intermediate phases or solvent residues may be present.

Spin coating distributes the liquid on a rotating surface. **Blade coating** creates a wet film using a moving edge. A **slot die** is a coating head that feeds a controlled flow rate onto a surface with a specific width. **Flow rate** is the volume passing per unit of time. In an ideal continuous coating, the wet thickness is related to the flow rate divided by the coating width and speed. **Synthetic example:** assuming all other conditions remain the same, if the speed is doubled and the flow rate remains constant, the wet thickness is halved. In reality, a stable meniscus and drying conditions must also be maintained.

Vacuum deposition builds up layers using vapor or particle fluxes instead of solvent-based inks. **Co-evaporation** is the simultaneous flow of multiple components; **sequential deposition** involves the delivery of components in different steps. The method name alone does not guarantee the homogeneity of the composition and thickness. Below, we will compare the methods based on the physical control they provide and the new errors they may introduce.

Comprehension check: Why did the same recipe yield different films?

Compare the solvent ratio, ink dwell time, surface cleaning, ambient humidity, speed, flow rate, and drying history. The single chemical formula in the recipe does not define the entire process condition. In the sample record, keep the ink preparation separate from the coating and annealing steps.

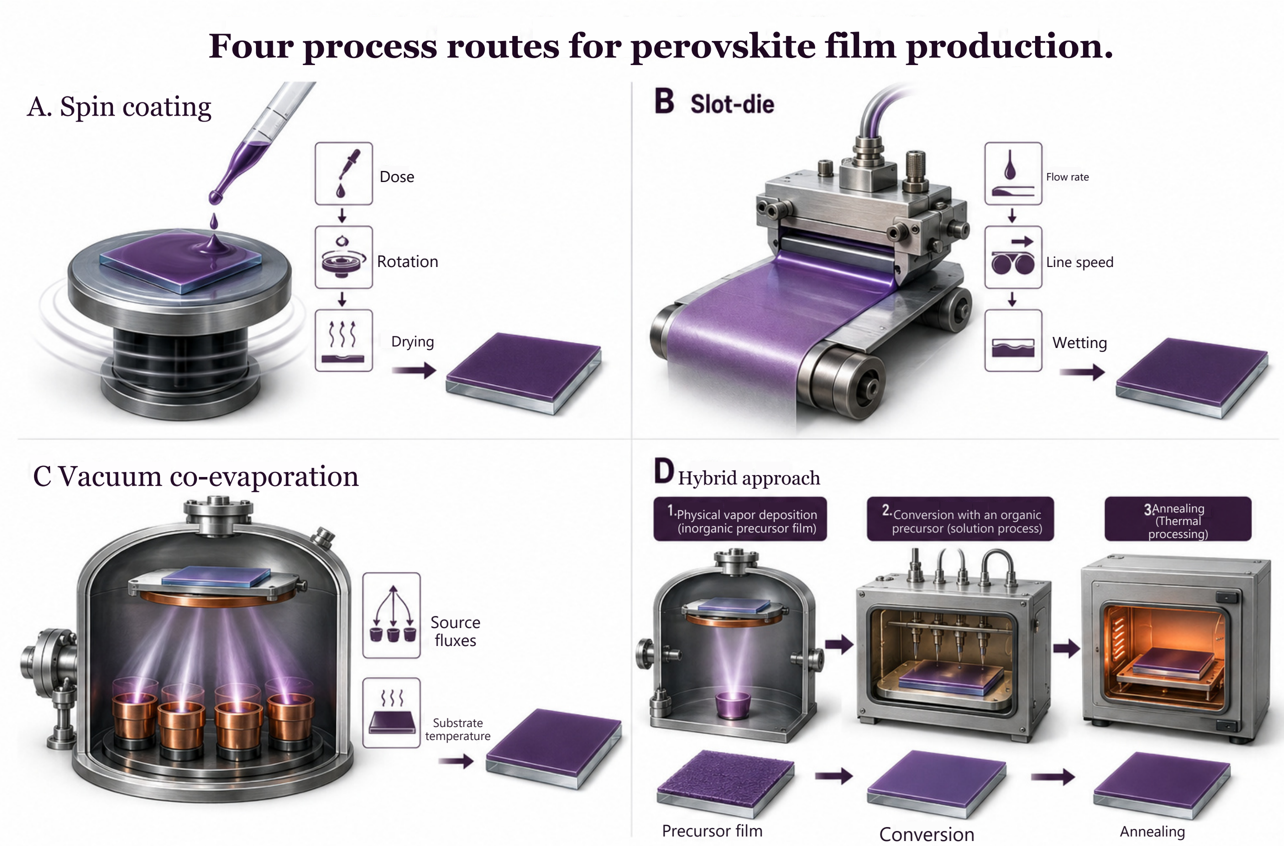


Figure 05. Four representative perovskite coating methods. In liquid methods, flow and drying are emphasized; in vacuum and hybrid methods, source flux, surface reaction, and conversion are emphasized. A method name alone does not determine film quality. [D12] [D13] [D33] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

Developing a perovskite solar cell is more than just coating a salt mixture and measuring its efficiency. The absorber composition, solvent coordination, intermediate phases, nucleation, drying, grain boundaries, and the two interfaces together constitute the device. This is why a successful spin-coating recipe for a small area cannot be directly transferred to a slot-die line. The development question is not just “which chemical?”, but rather “which chemical, under which flow and drying history, on which surface?”.

First, define the device architecture

The n-i-p and p-i-n sequences refer to the arrangement of charge carrier selective layers from the side where the light impinges. Changing the electron and hole transport layers also alters the wetting of the bottom surface, film nucleation, and the tolerance of the top contact process. Therefore, if the charge carrier layers are also changed in an experiment that claims to only compare perovskite compositions, the results cannot be interpreted as being solely due to the effect of a single composition.

The initial reference device should be fabricated with as few variables as possible. The substrate/TCO, bottom selective layer, absorber, top selective layer, and metal electrode versions are determined. The fact that one surface of the coating wets better does not, in itself, indicate that it provides better electrical contact. It is necessary to verify that good wetting is accompanied by low interface recombination. For each new molecule, the complete device, the thin film, and the appropriate half-stack control answer different questions.

Four distinct axes of compositional design

The halogen composition of compounds with A and B cations affects the band gap, phase stability, defect chemistry, and crystallization. Reducing each of these to a single geometric tolerance factor is insufficient. When modifying the halogen composition for a wide band gap, compositional decomposition or stress loss under illumination is investigated. For narrow band gaps, when transitioning to tin-containing systems, oxidation and doping control become important. A high initial efficiency does not prove that the composition remains unchanged during operation.

It is stated that the ratios used in compositional scanning represent mole fractions, precursor ratios, or elemental ratios measured in the final film. The ratio added to the solution may not be equal to the ratio in the final film due to the loss of volatile components or incomplete conversion. XRF, XPS, and ICP-type methods require different sampling depths and preparation procedures. The surface ratio obtained from one method should not be presented as if it represents the volume composition of the entire film.

Defining ink as a material

Ink tracking includes the precursor identity and purity, lot number, solvent types, total concentration, mixing and waiting time, filtration, storage conditions, and shelf life. Viscosity, surface tension, and volatility determine the coating behavior. Two inks with the same concentration may not exhibit the same nucleation rate due to different solvent coordination. Changing the solvent volume sometimes alters not only the thickness but also the formation of the intermediate phase.

Ink aging can be systematically tested. Samples from the same preparation batch are separated and coated after different waiting periods; a freshly prepared control is added to each coating day. Otherwise, the ink age will be confused with the day-to-day variations in the laboratory. For inter-batch repetition, a new weighing and a new solvent are used; sub-samples taken from a single bottle do not count as independent chemical preparation repetitions.

What does spin coating do well, and what does it not represent?

Spin coating is useful for film deposition on small substrates and for chemical comparison. The rotation speed, acceleration, dispensing time, environment, and anti-solvent application affect film formation. A significant portion of the material can be discarded outside the substrate. The flow geometry and drying history differ from a coating that moves along a continuous line. Therefore, it is not assumed that the best additive for spin coating will also be the best for slot-die coating.

A scale-up study involves two stages. First, the same ink is tested using different methods to assess the impact of the method. Then, separately optimized inks for each method are compared. The first comparison addresses the transferability of the process, while the second addresses the practical performance achievable by each method. Combining these two questions into a single table can unfairly portray a method as being either weak or strong.

Blade coating: moving meniscus and drying

In blade coating, the liquid forms a film over a meniscus created by the moving blade or substrate. The blade gap, speed, substrate temperature, surface energy, and gas flow are critical variables. The wet film thickness is not equal to the blade gap in every regime. As the flow, capillary forces, and the relative importance of evaporation change, the speed-thickness relationship can also change. The experimental range should not be excessively extended using a single linear model.

The 2018 study by Deng et al. provides a historical example demonstrating that very small surface-active additives can alter the drying flow and wetting behavior. In the same study, results for small cells and modules with larger aperture areas are reported separately. This distinction shows that, in scale-up, film homogeneity and contact losses are as important as the cell chemistry. [D13] Therefore, it cannot be concluded that “the same additive should be added to every ink.”

Slot-die coating: an initial flow-rate and speed calculation

In a slot-die coating head, the ink is dispensed through a slit with a controlled flow rate. In a simple, stable, and lossless wet coating process, the conservation of volume yields the following initial estimate:

$$h_{\mathrm{wet}} \approx \frac{Q}{w\,v}. \quad \text{(II.7.1)}$$

Here, Q represents the volumetric flow rate, w the coating width, and v the substrate speed. If Q = 0.10 mL/min, w = 5 cm, and v = 100 cm/min are selected in the example, the wet thickness will be approximately 2 µm. If the solid volume fraction is assumed to be 20 percent, the dry thickness will be approximately 0.4 µm using a simple shrinkage approach. In the actual film, solvent loss, reaction, density difference, edge flow, and crystallization can alter this estimate. The calculation is not a device recipe but rather a unit and flow rate control.

Increasing the thickness by increasing the wetting angle can disrupt the meniscus stability. The header-substrate gap, wetting limit, striping, and edge buildup are monitored. The coating map is not only taken from the center; the beginning, stable region, end, and both edges are evaluated separately. In continuous production, the age and temperature of the ink tank can also change over time. Therefore, a single good sample does not represent the homogeneity of a long roll.

Drying and crystallization are separate control points

The solvent loss from a wet film and its transformation into the desired crystalline phase are not the same event. Gas drying, vacuum assistance, heated substrates, or anti-solvents create different nucleation histories. Very rapid nucleation can lead to a dense nucleus distribution; however, coverage and defect formation may be affected differently. Very slow drying, on the other hand, can lead to dewetting, compositional decomposition, or large but irregular grains. The generalization that “large grains are always good” is therefore weak.

Time-resolved optical imaging, in situ diffraction, or appropriate spectroscopy can reveal at which point in the film formation process the difference begins. Observing the final XRD pattern alone does not explain the evolution of transient intermediate phases. Films that reach the same final crystalline phase with two different drying histories may exhibit different residual stresses or interface qualities. Process development should record this history.

Vacuum deposition and hybrid methods

The 2013 study by Liu, Johnston, and Snaith is among the early examples demonstrating that vapor-deposited planar perovskite devices can exhibit high performance. [D12] In simultaneous deposition from multiple sources, the source fluxes and stoichiometry are important; in sequential deposition, the conversion depth and reaction integrity of the layers are important. The rate read by the quartz crystal monitor may not directly reflect the retention rate of all chemical species on the actual substrate.

Hybrid methods, which combine vacuum and solution processes, have been used in the coating of textured substrates. An advantage of such a method is the ability to prepare different layers using different techniques; however, the drawbacks include increased transfer steps, interface limitations, and process complexity. Simple comparisons such as “vacuum is expensive, solution is cheap” do not take into account the material utilization rate, acceptance rate, maintenance, and encapsulation costs.

To examine the interface process causally

In the 2023 study by Park and colleagues, the coverage and interface loss of a self-assembled molecular layer on textured substrates are addressed. The approach of reducing molecular clustering through the use of a co-adsorbent establishes a mechanistic link between surface chemistry and electrical loss. [D11] A methodological lesson for researchers is that the interface process should be examined not only in terms of the final efficiency but also through surface distribution and independent optoelectronic measurements.

For a new passivation molecule, at least four comparisons are considered: an untreated control, a solvent-only control, the target molecule, and, if possible, a similar molecule from the same chemical family that does not exhibit the expected function. If absorption, film thickness, and morphology change, it becomes difficult to attribute the PL increase solely to defect reduction. The absolute PL quantum yield is interpreted in conjunction with the stable power of the completed device, under the same excitation and optical collection conditions.

Making all layers scalable

Simply coating the absorber over a large area is not sufficient. The bottom selective layer, top transport layer, electrode, and interconnect must also be prepared with appropriate speed and area. The 2024 study by Weerasinghe et al. is an example of research that makes the entire process chain compatible with roll-to-roll production; the reported module efficiency with an approximate active area of 50 cm^2 reaches 11 percent. This value does not fall into the same category as small-cell records. [D33]

Assignment. For a device that will be transferred from spin coating to slot-die coating, divide the variables into three groups: chemical composition, flow/drying, and interface. For each group, list the variables that will be kept constant, the intermediate outputs to be measured, and the reasons for rejecting failed films. The initial target is to achieve a homogeneous and reproducible film window, rather than maximizing the performance of a single cell.

How do we connect deposition flux in a vacuum with an optical map?

In vacuum deposition, the **flux** is the amount of material arriving per unit area per unit time. Not every particle reaching the surface will permanently become part of the film: adhesion, re-evaporation, and surface reactions are also important. Since the substrate temperature can alter these processes, simply matching the nominal deposition rates of the sources does not guarantee the same composition. As the material and method change, the appropriate monitoring changes as well; there is no single universal temperature recipe.

An **optical map** shows the spatial distribution by measuring, for example, the absorption or luminescence signal at different locations on the film. The fact that the map appears uniform does not necessarily mean that electrical power or durability is being measured. Under the same optical conditions, homogeneity control, stable power measurement of the finished device, and its change over time are used together. This allows researchers to investigate at which stage losses occur between the ink, the film, and the functioning cell.

BOOK II · CHAPTER 08 / MANUFACTURING METHODS

Tandem development: converting two good cells into a single, high-performance product

Tandem development does not simply involve combining two complete cells

The two-absorber tandem cell shares light: the top cell utilizes a portion of the high-energy photons, and the bottom cell utilizes the transmitted light. **2T** is a series-connected configuration with two external terminals; **4T** is a configuration where the terminals of each sub-cell are used separately. In 2T, the same current flows through both cells, and the voltages are summed at that current. In 4T, the power can be tracked at separate operating points. In both cases, the light incident on the bottom cell has been modified by the top stack.

The **filtered spectrum** is the wavelength distribution remaining after passing through the upper layers. Directly measuring the power of the bottom cell in sunlight and adding it to the power of the top cell does not provide an accurate assessment. **Current matching** involves aligning the usable currents of series-connected subcells; it depends not only on the band gap but also on thickness, reflection, and parasitic absorption.

Integration budgets

The **thermal budget** refers to the temperature-time profile to which the underlying layers may be exposed during subsequent processing steps. **Chemical compatibility** indicates whether the solvent or reagent degrades the previous layer. **Topographical compatibility** refers to the ability of the top film to cover the textured surface without pinholes and with adequate thickness. If these budgets are exceeded, a successful top-cell recipe alone may fail on a tandem structure.

Synthetic comparison: Let the reference value for the bottom cell before the top process be 100 units, 98 units when only the solvent is applied, and 90 units after the complete thermal history. Before directly attributing the loss in the final tandem to the composition of the top absorber, the possibility of thermal damage becomes apparent. This experiment does not calculate the actual tandem power; it demonstrates which effect of the process steps is being isolated. In a real-world study, the control samples should share the same time and environmental history.

Light biasing refers to adjusting the state of a sub-cell in a multijunction measurement using selected light. **Voltage biasing** is an externally applied voltage condition. These may be necessary to differentiate the spectral response of the sub-cells. A light adjustment that is sufficient for a single junction may not bring both sub-cells of a tandem structure to the correct condition simultaneously. Therefore, in tandem development, the measurement setup is designed as an integral part of the architecture.

Comprehension check: low current in the bottom cell

First, calculate how much current the device should produce under the expected filtered illumination. Then, separately assess the material damage resulting from the previous process. Remaining without photons and collecting fewer charges from the same photons are different problems and require different repair procedures.

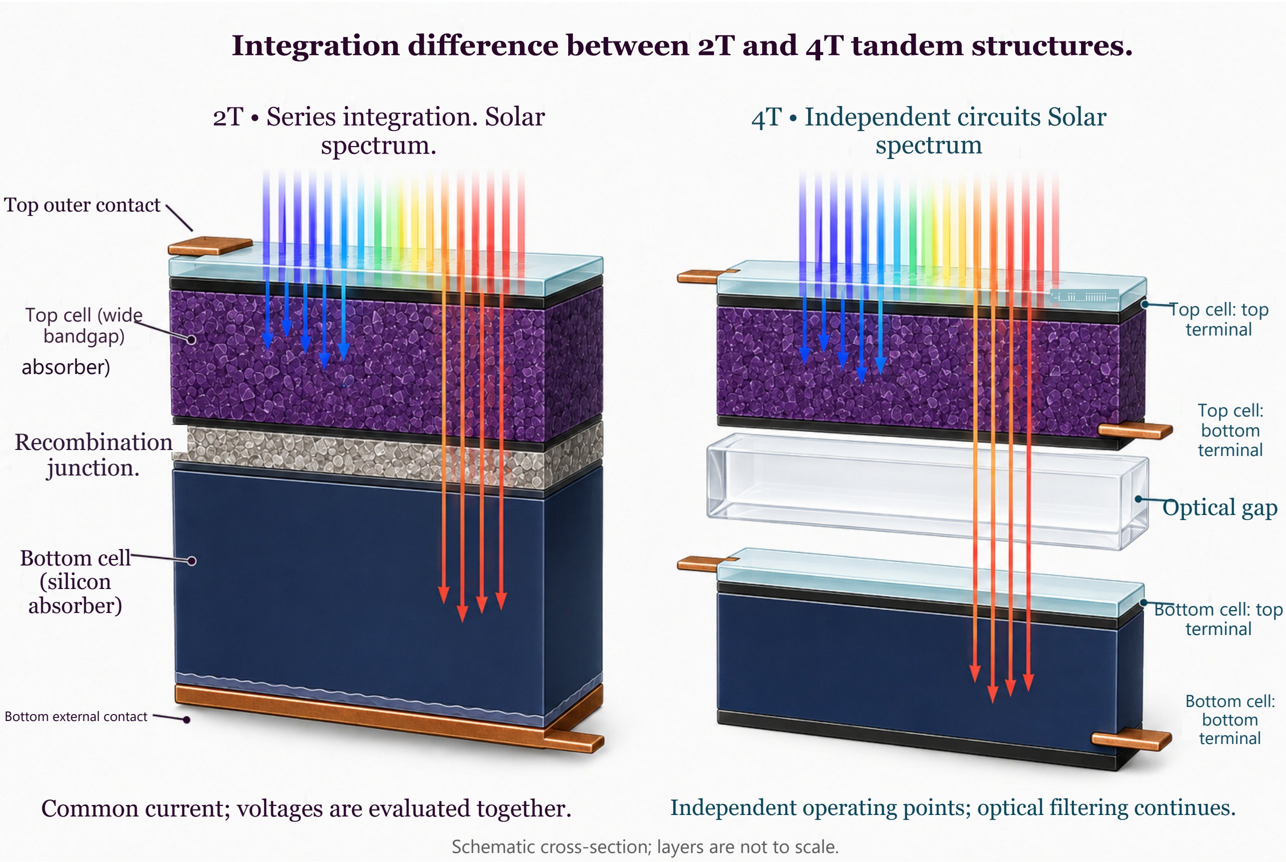


Figure 06. In the 2T structure, the sub-cells operate electrically in series; in the 4T structure, there are two independent operating points. In both architectures, the optical filtering of the top cell affects the bottom cell. The diagram illustrates the connection logic. [D34] [D19] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

A tandem does not automatically sum the efficiencies of two independent cells. The top cell modifies the spectrum seen by the bottom cell. The common interconnection must provide not only optical transmission but also electrical recombination. The deposition, annealing, and electrode processes of the top cell can affect the surface of the bottom cell. The result is a device that differs from the sum of two separate laboratory records. The development effort lies in managing these dependencies.

Connecting the selection of 2T and 4T to the application

In a two-terminal monolithic structure, the sub-cells operate electrically in series. In a four-terminal optical stack, the two sub-cells can be operated in separate circuits at their maximum power points. The 2T configuration may offer fewer independent electrical outputs and fewer intermediate optical layers in a suitable design; however, it requires current matching and direct process integration. The 4T configuration provides flexibility in independent electrical operation; additional transparent electrodes, interconnections, area utilization, and power electronics must be considered.

$$P_{2T} = \max_I I\,[V_{\mathrm{top}}(I) + V_{\mathrm{bottom}}(I)], \qquad P_{4T} = P_{\mathrm{top,mpp}} + P_{\mathrm{bottom,mpp}}. \tag{II.8.1}$$

When comparing devices with the same optical conditions and the same sub-cell curves, the sum of the individual maximums cannot be less than the power obtained when operating at the same current. However, real 2T and 4T devices do not have the same optical stack or the same losses. It is also incorrect to interpret this mathematical inequality as an automatic 4T superiority among real products, or to infer a universal 2T superiority from a single record table. Architectural comparisons are made with matched assumptions.

Evaluating the bottom cell under the correct spectrum

The current measured from the silicon sub-cell under standard full-spectrum illumination is not the current of the tandem cell. The photons passing through the top cell and intermediate layers determine the generation in the sub-cell. Therefore, the EQE of the sub-cell accounts for the transmittance of the top stack and parasitic absorption. In the optical model, it should be determined in which layer the absorption occurs; even though the total light absorption of the stack is high, a portion of this light may be wasted in the conductive oxide or transport layer.

During thickness sweeps, the current of the top cell may increase while the current of the bottom cell decreases. For 2T, the target is not simply to perfectly equalize the currents under standard spectrum conditions. If temperature and variations in the spectrum throughout the year are considered, a slightly different design may yield higher annual energy output. This result depends on the site and climate assumptions. The simulation output should specify which meteorological data, which spectral model, and which module temperature were used for the calculations.

Coating on textured silicon

The textured surface aids in light management; it also creates height variations and corner geometries for the top film. If the film thins at the peaks or accumulates in the valleys, local leakage and carrier transport variations can occur. When a cross-sectional image is taken from only one location, it does not represent the entire wafer coverage. Sampling is performed between the peaks, valleys, center, and edges; electrical maps are evaluated in conjunction with the morphology.

Sahli and colleagues' 2018 study is an early demonstration of a hybrid fabrication route for monolithic perovskite/silicon tandems on fully textured silicon. [D34] This seminal work is significant because it shows that efficient light trapping can be achieved without the need for planarization. It does not imply that a specific hybrid recipe can be directly transferred to every texture and composition. Modern process selection is re-validated in its own wafer and top-cell architecture.

The interconnect is not a cable

In a monolithic tandem cell, the interconnect should combine the electrons of one sub-cell with the holes of the other with minimal loss. Optical transparency, electrical contact, surface passivation, and chemical compatibility are all desired simultaneously. An additional absorbing or barrier interlayer can turn a good upper and lower cell into a tandem cell with a low fill factor (FF). It is beneficial to sketch the interface band; it should be remembered that the actual work functions, interface dipoles, and defect states cannot be determined solely from the bare surface values in the literature.

In the development of interconnects, simple test stacks are used. Questions are asked such as: Is the current-voltage relationship linear? Is there a temperature-sensitive barrier? Do subsequent processes alter the resistance? However, the two-terminal resistance of the test stack is not equivalent to all the charge transport and recombination processes in a real tandem device. The final decision is supported by the stable power, spectral response, and temperature behavior of the complete device.

Thermal and chemical budget

After the fabrication of a sub-cell is complete, it is subjected to additional thermal, solvent, plasma, and mechanical treatments. The loads applied to the sub-cell for each subsequent layer process are listed. A single maximum temperature threshold does not fully describe the compatibility; duration, atmosphere, and sequence are important. Even a low-temperature plasma can cause damage with energetic particles. A solvent that appears chemically mild can dissolve or rearrange the underlying molecular layer.

The simplest integration control is to put the bottom cell through the full processing history of the top cell while omitting the active top absorber, and measure the bottom cell before and after this sequence. This “blank process” control separates optical filtering losses from processing damage. Apply the same idea to the top cell: compare bare stacks before and after the final transparent-electrode deposition. If a protective buffer layer is added, also measure its optical and resistive penalties.

Voltage issues with the wide bandgap top cell

Increasing the band gap enhances the theoretical voltage potential of the top cell; however, the actual open-circuit voltage may not increase at the same rate. Interface recombination, compositional degradation, and charge carrier accumulation are investigated. The shift in the PL peak under illumination alone does not prove that the entire device has transitioned to the same band gap; the spatial and temporal sensitivity of the measurement is evaluated. Reversible changes induced by short-term illumination are distinguished from permanent degradation.

In the development experiment, the single-junction reference for the top cell is maintained. If the same top structure yields a lower voltage when combined with the bottom cell, the interconnect or process integration is investigated. If the single-junction reference also exhibits low voltage, the top cell chemistry and interfaces are first examined. In this way, each loss within the tandem structure is not simply estimated based on the total voltage of the entire device.

Independent spectral control in tandem measurements

The fact that a simulator is suitable for a single-junction silicon cell does not necessarily mean that it can accurately simulate the two sub-cells of a tandem cell. EQE measurements with the spectral responses and light bias of the sub-cells are required. IEC 60904-1-1 directly addresses this multijunction measurement issue. [D19] In the research report, the sub-cell currents, spectral tuning, area, and steady-state power method should be clearly stated.

During the sweep, if ionic processes are active, the change in the common current point over time is also evaluated. The light and voltage history prior to the measurement is recorded. Achieving a high fill factor (FF) in a single sweep does not guarantee the same power output during continuous maximum power point (MPP) operation. If the results change when the order of measurements on the same device is altered, the measurement protocol and dynamic behavior should first be understood.

Cell-to-module transition

Tandem cell cutting can create new edge surfaces. The interconnection temperature, encapsulant chemistry, and lamination stress can affect the top cell. Therefore, the mini-module is not just a demonstration tool but also an integration experiment. The power of the same cell group is compared before interconnection, after interconnection, and after lamination. Optical gains and electrical losses within the module are kept separate.

Development step.	Reference	Critical difference to be measured.
Apply the top-cell process history to the bottom cell	Untreated subcell	Voltage, lifetime, and surface loss.
Transferring the top cell to a textured surface.	Top cell on a planar substrate	Coverage, leakage, spatial distribution
Change of interconnection layer	Fixed top/bottom cell stack.	Fill factor and temperature-dependent transport.
Transparent electrode coating	Half-stack before coating.	Plasma damage and parasitic absorption.
Mini-module lamination	Initial summed power of the same cells	Power transfer and damage map.

Reading the levels of evidence together

Oxford PV's announcement of its first commercial shipment in 2024, Qcells' announcement of stress testing for its 2025 pilot line modules, and GCL's announcement of its 2025 production base are all different types of evidence. [C10] [C11] [C12] One reports on shipments, another on a specific testing scope, and the third on a facility stage. None of them, on their own, demonstrate that all tandem technologies have achieved the same cost and field lifetime. The company atlas specifically preserves these distinctions.

Assignment. Prepare three separate error budgets for a 2T tandem cell: optical, electrical, and process-related. For each budget, include a quick test, a full device verification, and a potential misinterpretation. Explain in which two ways an intervention that increases the current of the top cell can reduce the overall power.

BOOK II · CHAPTER 09 / MANUFACTURING METHODS

Other avenues for development: CdTe, CIGS, III-V, and solution-based technologies

Comparing alternative methods based on their common functions

CdTe, CIGS, III-V, organic, dye-sensitized, and quantum dot cells are not simply different names for the same manufacturing technique. In all of them, light absorption, charge separation, transport, and external collection are required; however, the material in which these processes occur differs. When learning a method, it is helpful to first diagram the function of the layers, which prevents confusion between chemical and device names.

CdTe is cadmium telluride. **CdSeTe** refers to a family of alloys in which selenium is also incorporated into the composition. Post-growth processing can alter the grain and defect structure. **CIGS** is the $Cu(In,Ga)Se_2$ family; the indium and gallium ratio can be varied along the depth of the layer. This **composition gradient** may not be apparent from a simple average chemical analysis. Depth information is important due to its effect on the electric field and band edge profile.

In **III-V** cells, **epitaxy** refers to the process where the new crystalline layer follows the crystal structure of the underlying layer. **MOCVD** is a chemical vapor deposition method that uses metal-organic precursors, while **MBE** is a molecular beam epitaxy method. Both methods aim for controlled growth, but the equipment, growth rate, and material flow control differ. Lattice matching, defect formation, and the cost of the substrate play a role in the selection process.

Distance to the interface in solution-processable systems

In an organic cell, light primarily generates bound electron-hole pairs, i.e., an **exciton**. The donor-acceptor interface helps to separate these, after which the separated charges must find continuous transport pathways. In a dye-sensitized cell, the dye absorbs light, the electron is transferred to another semiconductor, and the charge state of the dye is replenished. In a quantum dot film, the surface molecules of the small semiconductor particles, i.e., the **ligands**, affect both the mixture stability and the electrical connection.

Synthetic process comparison: Route A yields high power but results in 50 accepted samples out of 100, while route B yields slightly lower power but results in 90 accepted samples. It is not yet known which route is more cost-effective; energy, material, processing time, and equipment costs must also be considered. The same logic applies to all technology families. We will evaluate the following methods not only based on their record percentages but also based on the controlled variables and the cost per good product.

Comprehension check: what can be transferred from one material family to another?

The measurement methodology and loss budget can often be transferred to other families. However, the same solvent, the same annealing process, or the same interpretation of defects cannot be automatically transferred. It is necessary to re-evaluate which charge carrier state, which interface, and which chemical equilibrium are critical in the new family.

A manufacturing method is not selected solely based on the highest cell efficiency. The substrate to be used, area, weight, lighting conditions, temperature budget, material availability, and product lifetime all influence the selection. This section translates the material physics from the first book into process decisions. For each technology, a working reference flow should first be established, and then changes to the absorber, interface, and packaging should be analyzed. The presence of record percentages from different technologies in the same table does not necessarily mean that they satisfy the same product requirements.

CdTe and CdSeTe: post-growth chemistry

In a typical glass-substrate thin-film process, a transparent conductive front electrode, a suitable window or buffer layer, an absorber, and a back contact are present. The layer sequence and composition vary depending on the manufacturer. The absorber, which is grown by close-spaced sublimation, vapor transport, or other deposition methods, cannot be considered independently of subsequent activation and doping processes. Simply increasing the film thickness does not necessarily lead to better collection; the charge carrier lifetime, electric field, grain boundary chemistry, and back contact collectively determine the overall result.

Four distinct questions are addressed in the development of CdTe. The first question concerns the continuity and structure of the growing film. The second question is how defects and grain boundaries change after activation. The third question is what doping and thermal history are required to achieve the desired charge carrier concentration. The fourth question is whether the back contact efficiently collects charge carriers with low loss and remains stable during aging. Condensing these questions into a single efficiency value makes process diagnostics difficult.

The 2025 study by Kuciauskas et al. on CdSeTe is a good example of a mechanism: phosphorus doping, under the specific conditions of the study, was associated with disorder caused by anion vacancies; the device efficiency increased from 19.3% to 20.2%. The 25% level discussed in the article is a model potential and should not be confused with the measured 20.2%. This result does not imply that phosphorus will provide the same gain in every CdTe line. [D36]

Suggested experiment. Cross activation and doping conditions on samples split from the same growth batch. Verify thickness and composition; produce optical and electrical characterization specimens as well as complete cells. A voltage increase with unchanged long-wavelength EQE points to a different explanation than increases in both voltage and collection. Test a rear-contact change in a separate branch. If lifetime decreases as carrier density rises, maximizing density alone is not the right target.

Closed-loop material management in cadmium-containing processes, proper industrial hygiene, and waste recovery are part of the process design. The method described here does not replace the facility's chemical operating instructions. Monitor material usage not only by mass per cell but also by target utilization efficiency and recovered flow.

CIGS: from average composition to a depth profile

For CIGS, co-evaporation and the conversion of metal precursors through selenization or sulfurization represent different process families. Even if the average Cu, In, and Ga ratio is the same, the film's profile across its thickness, surface composition, grain structure, and alkali distribution can vary. Therefore, a single surface measurement cannot be considered representative of the entire absorber. Total composition measurements, such as XRF, are complemented by appropriate depth analysis and cross-sectional examination.

In the 2024 study by Keller et al., the certified 23.64% result relies on co-designed interventions such as silver alloying, a strong Ga increase near the back contact, and a post-RbF process. The researchers aimed to reduce band gap fluctuations in the lateral and depth directions. This single example does not prove that the same profile is optimal for all CIGS devices; however, it demonstrates that the phrase "adjusting the composition" refers to a spatial profile design. [D37]

In a development workflow, keep the absorber composition constant while changing the buffer layer; then, keep the buffer layer constant and change the absorber profile. Performing both changes simultaneously obscures the source of the voltage gain. If the light soaking and the previous voltage condition have an effect, standardize the pre-measurement conditioning. Store the initial and post-conditioning measurements together. Also, compare EQE with transmittance measurements to separate the optical loss of the front electrode and the buffer layer from the carrier collection loss.

III-V: epitaxy, lattice matching, and product category

III-V cell development involves the selection of a suitable substrate, control of the epitaxial layer composition and doping, and the coordinated management of inter-junction connections and optical design. In the MOVPE/MOCVD approach, gas-phase precursors react on a heated surface, causing crystal layers to grow. Temperature, flow rates, pressure, and reactor history can affect not only the thickness but also the composition and defect formation. Lattice-matched design and metamorphic design that manages strain relaxation do not have the same acceptance criteria.

AZUR SPACE states in its production description that multilayer III-V structures are produced on germanium substrates using MOVPE. Space cell products represent a separate application family. In the AM0 spectrum, a given product result for specific radiation conditions cannot be directly compared with the terrestrial AM1.5G module efficiency. [D38]

Use a witness sample in the epitaxy development process. Measure the layer thickness, composition, and crystal quality; then, verify the sub-junction currents in the completed device under appropriate bias conditions. If current mismatch is observed, first evaluate the spectral generation, and then the collection losses. It is necessary to examine not only the dark characteristics of the tunnel junction but also its behavior at the target current density. In concentrated applications, contact resistance and thermal management gain different importance.

The suggestion of reusing the substrate or epitaxially lifting it is not automatically included as a cost saving in the cost calculation. The delamination yield, surface renewal, quality of subsequent growth, number of available reuses, and the risk of breakage must be measured. If the substrate is made cheaper but the cell efficiency or production acceptance rate decreases, there may be no net cost saving.

Organic PV: Developing chemistry and morphology in tandem

In organic devices, both the energy levels of the donor and acceptor, as well as the morphology of the mixture, are important. The choice of solvent, dopant, drying rate, annealing, and coating method alter the phase separation and charge transport pathways. A good small-area spin-coating recipe is not expected to work directly on a slot-die or printing line. During film drying, the solvent concentration and temperature history differ.

Zhang and colleagues' study, published in 2024, demonstrates that to achieve high performance in different solvents, the molecular structure and in-solution interactions should be considered in conjunction with the morphology. The key takeaway from this is that, instead of searching for a single "good solvent," solvent sensitivity should also be incorporated as a design variable. [D39]

In the proposed control sequence, the ink age, solids content, and film thickness are kept constant; only the drying or annealing process is varied. Absorption and scattering, morphology-sensitive measurements, transport measurements, and total cell power are used together. If the fill factor (FF) decreases in the thick film, the transport and series resistance contributions are first separated. In an indoor application, the lux value alone is not the input power; the spectrum of the light source and the radiometric power density are reported. Outdoor efficiency and low-light efficiency are not placed in the same category.

Heliatek's manufacturing approach exemplifies the deposition of small-molecule organic layers onto a continuous flexible substrate in a vacuum. This demonstrates that the notion of all organic PVs being solution-processed is incorrect. The company's product and manufacturing statements are dated in the company's profile. [C14]

Dye-sensitized solar cells: component matching

In DSSC development, the porous semiconductor electrode, dye attached to the surface, charge regeneration medium, and counter electrode work together. Simply increasing the surface area to bind more dye is not sufficient if electron transport or electrolyte access is compromised. The photocurrent depends on dye absorption as well as injection, dye regeneration, and competing recombination. The fundamental mechanism described in the first book translates here into decisions regarding electrode preparation and cell encapsulation.

In the experiment, first fix the electrode thickness and pore structure, and then vary the dye adsorption time separately. When comparing the new dye, report the amount loaded and the spectral range. If the open-circuit voltage increases when the electrolyte is changed, do not solely attribute this to the energy level of the dye; the interface potential and recombination may also have changed. Sealing, solvent loss, and light-induced chemical conversion are tested under application conditions.

Quantum dots: the cost of ligand exchange

Colloidal quantum dots can be stabilized in solution with long ligands; however, the same organic environment can hinder charge transport in the solid film. Ligand exchange affects both interparticle coupling and surface traps. Short ligands are not necessarily better in all cases: while transport may improve, surface passivation can be compromised. Film cracking, deposition, and redissolution of the previous layer should also be monitored.

Yang and colleagues' 2017 study presents a historical example of combining n-type and p-type components from quantum dots that have been functionalized in different ways. Subsequent orthogonal ink studies address the issue of not dissolving the underlying layer while printing the top layer. These should be viewed as examples of methods for surface chemistry and multilayer coating design, rather than as a current record list. [D40] [D41]

Comparison task. Compare organic, DSSC, and quantum dot approaches for a flexible and lightweight sensor power source. First, specify the light source, power requirements, and packaging constraints. Then, for each technology, define three experiments, two significant failure mechanisms, and one stopping criterion. Do not base your product selection solely on the band gap.

BOOK II · CHAPTER 10 / MANUFACTURING METHODS

Simultaneous optimization of optical properties, passivation, and contacts

Achieving three functions within the same sample

Optical design regulates the arrival of useful light at the absorber and its utilization there. **Passivation** is the reduction of active defects or the arrival of unwanted charge carriers at the defective region. **Contact engineering** involves transporting the correct charge to the external circuit with minimal loss. A coating can affect these three functions in different ways. Therefore, the modification is tested not only on its own, but also on the finished cell.

Dielectric refers to a material that is electrically insulating and capable of polarization in this context. **TCO** stands for transparent conductive oxide. **Metal** generally conducts electricity very well but blocks light. The refractive index, absorption, thickness, and contact properties of these layers are different. A single adjective, such as "transparent," "insulating," or "conductive," does not provide a complete material definition for design purposes.

Selecting the deposition method based on its operational principle

ALD is atomic layer deposition. A thin film is grown on the surface through sequential reaction steps that are self-limiting. **Conformal coating** is a coating that follows the contours and features of a surface with similar thickness. ALD can be useful for this; however, the initial surface and process conditions must be appropriate. **Evaporation** converts the material into a vapor and condenses it on the surface. **Sputtering** removes particles from the target solid. **PECVD** is plasma-enhanced chemical vapor deposition. The methods differ in terms of speed, damage, surface coverage, and material options.

Distinguishing between two types of resistance

Sheet resistance summarizes the lateral conductivity of a thin film along with its thickness; it is expressed in ohms/square. Here, "square" is not a unit of physical area but a geometric ratio. In a homogeneous film, the rectangular resistance measured between two edges is the product of the sheet resistance and the length/width ratio. **Specific contact resistivity** describes the transition across the interface of two different materials and is normalized by area.

Synthetic example: In a film with a sheet resistance of 50 ohms/square, if the current path length is twice the width, the simple geometric resistance is 100 ohms. This calculation does not include the contact resistance at the metal-film interface. The lateral resistance can be reduced by increasing the film thickness; however, parasitic absorption may increase. The following experiments will evaluate the optical cost of conductivity gain in the same device.

Comprehension check: Does the name of the method guarantee the result?

Saying that something was “made using ALD” does not necessarily mean that the film is flawless on every surface or that every device is performing well. We must evaluate the thickness, coating uniformity, interface chemistry, electrical leakage, and the functionality of the finished cell in terms of its power output. The method is just a tool; measurement determines whether the target has been achieved.

The function of a layer cannot be explained solely by its name. A “transparent electrode” must transmit light, conduct current laterally, establish appropriate contact with the adjacent layer, and remain undamaged during subsequent processing steps. A “passivation layer” may excessively hinder charge carrier transport while reducing surface defects. The goal of development is to ensure that these functions work together within the same device. The flow in this section connects the optical and selective contact physics from the first book to measurable design variables.

Defining optical gain correctly

A reduction in reflection does not always mean an increase in absorption. Light can also be absorbed by a TCO, metal, transport layer, or encapsulant. In a simple energy balance, incident light is distributed among reflection, transmission, and total absorption. The total absorption is then shared between the useful part in the absorber and the parasitic layers. In a layered system, due to interface interference, the optical field of each layer depends on its neighbors.

$$R(\lambda) + T(\lambda) + \sum_j A_j(\lambda) = 1. \qquad \text{(II.10.1)}$$

This equation applies to normalized energy fluxes with the same optical geometry. In a measurement where scattered light is excluded from the detector, it would be incorrect to directly equate the missing signal with absorption. In rough or textured samples, total and specular reflection are separated; an integrating sphere is used if necessary. Whether the optical constants extracted from thin films using ellipsometry are unique is also investigated through model sensitivity analysis.

The development target could be “spectrally weighted collection gain” instead of “minimum average reflectance.” An antireflection coating might perform very well at short wavelengths but poorly at long wavelengths, where the cell is less efficient. Compare the change in EQE with the change in reflectance on the same wavelength axis. If the reflectance decreases but the EQE does not change, the light may be absorbed in a different layer, or the newly generated charge carriers may not be collected.

An example of layer thickness

Under the assumption of a single wavelength and lossless single-layer, the quarter-wave optical thickness is useful for the initial design:

$$n_f d = \frac{\lambda_0}{4}. \tag{II.10.2}$$

For example, for a center wavelength of 600 nm and a refractive index of 2.0, the geometric thickness is 75 nm. This calculation is not automatically optimal for a product with a broad solar spectrum, angular distribution, and actual absorption. In the next step, a sensitivity analysis is performed with thickness and optical constant uncertainty. If there is a texture or a multilayer stack, the appropriate optical model is selected; the transfer matrix for a flat film does not inherently account for arbitrarily large textures.

Using conditions such as 65, 75, and 85 nm in a process scan is merely an illustrative design example. The actual range is selected from the feasible window of the current process. Do not label the recipe duration as “thickness” without measuring the thickness of every sample; the deposition rate may vary depending on the equipment history.

Selecting the coating method based on its function

Method family	The function in which it excels.	A critical question in development.
ALD	Thin and conformal layers through surface reactions.	Are surface saturation, initial growth and cycle time suitable?
PVD / sputtering	Physical deposition of TCO and metal.	Do plasma and energetic species degrade the underlying layer?
PECVD	Silicon and dielectric thin films.	Are hydrogen, plasma chemistry, and surface passivation controlled together?
Solution coating	Large-area film at low temperature.	Is the wetting, drying, and chemical resistance of the underlying layer adequate?
Metallization by printing and plating	Local conductive paths	How are contact, adhesion, barrier, and long-term corrosion verified?

This table does not represent a ranking of purchasing decisions. The processing window varies depending on the equipment used, even with the same method. The success of conformal coating in a laboratory device does not necessarily indicate that the line speed is sufficient. Similarly, a high coating speed does not guarantee the desired interface quality. HJT and TOPCon samples exemplify these dependencies. [D04] [D09] [D32]

Distinguishing between sheet resistance and contact resistance

Sheet resistance describes lateral conduction within a film, while specific contact resistance defines the current transfer between two materials. A poor contact can exist beneath a good conductor. Four-point probe measurements help determine sheet resistance by minimizing contact parasitics; the TLM structure, under appropriate geometry and modeling, isolates the contact contribution. In TLM analysis, current spreading, contact length, and the adequacy of the measured interval are important.

In the simple linear TLM approach, the total resistance between two contacts of the same width changes linearly with the contact spacing:

$$R_{\text{tot}}(d) = 2R_c + \frac{R_{\text{sheet}}}{W}d. \tag{II.10.3}$$

Here, the intercept represents the sum of the two contact resistances. If the line does not fit well, do not rely solely on the apparent high value from the linear fit; check different spacings, leakage paths, film homogeneity, and the probe contact. For thin or short contacts, a transfer length correction is required. The parameter obtained from TLM does not account for the total series loss in the entire cell; metal finger, busbar, and connection losses are present separately.

Optimize the metal pattern together

Increasing the finger density can shorten the lateral transport path; however, it may also increase shading and metal usage. Narrowing the fingers can reduce shading but may affect the printing continuity, height, and resistance. Therefore, finger width, height, spacing, material resistivity, and contact resistance are considered together. Although the microscopic image of a fine line may appear aesthetically pleasing, discontinuous regions or poor adhesion can compromise product reliability.

In an illustrative loss analysis, if optical adjustment increases the current by 0.8% while decreasing the fill factor (FF) by a relative 0.5%, and the voltage remains constant, the net power factor becomes 1.008 × 0.995 = 1.00296, representing an approximate 0.30% gain. This small difference should be compared with measurement uncertainty and batch variation. If the same intervention reduces the production acceptance rate, the cost per watt may worsen further. This example does not represent data from an actual company.

How do we diagnose interface changes?

First, design test samples that can be measured before and after the complete cell fabrication process. Lifetime or PL measurements provide information about the passivation before contact; however, selectivity and resistance also come into play when contact is established. It is not surprising that a surface that improves before contact does not yield the same gain in the complete cell. The implied voltage, actual open-circuit voltage, and FF are read together. Depending on the source of the difference, experiments are conducted to analyze metallization, selective layer, or process damage.

The proposed experimental design consists of three arms: a sample with a varying interface treatment, a control sample subjected to the same chemical or thermal process but without active material deposition, and a reference sample with no treatment. The thickness and optical properties of all three arms are measured after coating. This allows us to test whether the gain, which is assumed to be due to “chemical passivation,” is actually due to optical changes or a cleaning effect.

Chapter exercise. Reducing the TCO thickness increases the short-circuit current, decreases the fill factor, and leaves the open-circuit voltage unchanged. Generate at least three explanations. Which of the sheet resistance, contact resistance, and EQE measurements would differentiate between these explanations? Design the next experiment to be more informative than simply reverting one layer’s thickness.

BOOK II · CHAPTER 11 / FROM EXPERIMENT TO PRODUCT

Experimental design: from a good sample to a reliable process window

Why is a systematic combination required in process development?

When modifying a process, we call the condition that affects the outcome a **factor**, the tested value a **level**, and the measured result a **response**. For example, annealing time and dopant concentration are two factors; short-long and low-high are their levels. A **full factorial design** tests all combinations of these levels. Two factors, each with two levels, yield four combinations. The goal is not only to have more samples but also to see whether the effects are interdependent.

Let's construct a synthetic table using words: Let 18% represent the efficiency for the undoped-short process, 20% for the doped-short process, 21% for the undoped-long process, and 20% for the doped-long process. The effect of doping is +2 percentage points for the short process and -1 percentage point for the long process. This difference is the **interaction**. The general statement "Doping increases efficiency" does not accurately summarize these four results. The process time must be specified.

The optimal point differs from the process window

The **optimum** is the point where the chosen criterion is best. A **robust process** stays within acceptance limits despite small setting deviations. A route giving 25% at a very narrow peak is not always superior in production to a route giving 24% over a broad range. Measurement uncertainty and the equipment's actual setting variability can make the peak difficult to reproduce.

A **block** is an experimental group that shares a common effect, such as the same day or lot. If each block contains both control and new treatments, the confounding of the day effect with the treatment effect is reduced. **Randomization** reduces the accumulation of device drift or time effects in a single group. An **independent replicate** is a re-manufacture of the sample; measuring multiple points on the same cell does not achieve this.

Measurement system analysis attempts to separate the variability of the device, operator, and repeated measurements. **Gauge R&R** is a family of methods that examines the repeatability and reproducibility components. If the measurement noise is greater than the targeted gain, simply scanning more recipes may be ineffective. First, the precision of the measurement or experimental setup is improved. The final confirmation experiment is conducted with samples separate from the data on which the selection was made; restating the best-looking point on the same data is not validation.

Comprehension check: why should a control be included every day?

On Monday, only control measurements are taken; on Tuesday, if a new process is produced, the difference between the days cannot be separated from the process difference. Producing both measurements in the appropriate order each day reinforces this distinction. Before reading the data, it is necessary to understand how the groups were formed, regardless of the number of cells.

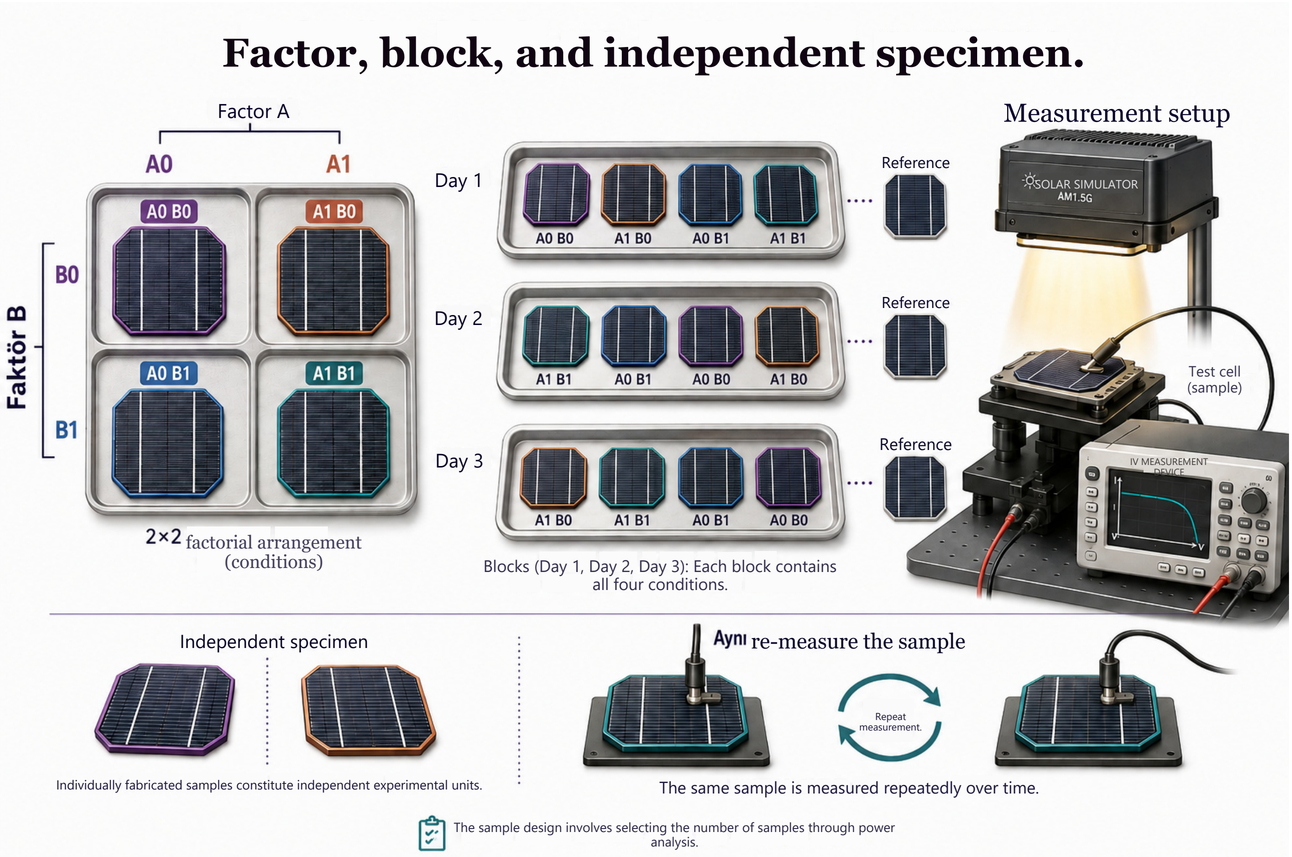


Figure 07. An example layout distributing factorial conditions within day blocks. Each day includes all conditions; independent wafer replicates and repeated readings of the same sample probe different uncertainties. The sample size here is not a recommendation derived from a power analysis. [D14] [D16] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

Often, a researcher needs a better experimental design before conducting more experiments. Comparing each new recipe with the reference from the previous week can confound the effects of day, ink age, oven condition, and operator with the recipe effect. A good design determines which question will be answered by which comparison before the experiment begins. NIST's design of experiments framework is a useful reference for establishing the relationship between the objective, factors, model, and experimental design. [D14]

Define the response and experimental unit

The primary response should not solely be the highest efficiency. Depending on the research mechanism, stable power, voltage loss, contact resistance, power after a specific aging period, or acceptance rate can be selected. Secondary responses help explain the mechanism. If the primary response is changed to the most appealing measurement after the experiment, selection bias occurs. If a change is necessary, it is clearly recorded as a new analysis.

The experimental unit is the smallest unit to which the intervention is applied independently. Ten cells produced on a single coating do not represent ten independent coating repetitions. Measuring the same cell five times is a measurement repetition; it does not represent a production repetition. When investigating the effect of an additive on film formation, independent ink preparation and coating batches are important. The cells demonstrate the distribution within a batch; they do not, on their own, provide information about the distribution between batches.

This distinction should be reflected in the report's data structure. Within the sample ID, experiment, batch, substrate, and cell information are stored in separate fields. It is specified at which level the average and error bar were calculated. If a hierarchical structure exists, a model including the batch effect or an appropriate aggregation method is used. Avoid creating artificial independence by increasing the number of cells.

A full-factorial example

Let's consider two factors: A, low and high annealing conditions; B, two interface processes. The following numbers are entirely synthetic and represent mean stabilized efficiencies. It is assumed that each condition has independent production repetitions on different days. This is not a suggestion for a real recipe.

A level	B level	Average efficiency (%)
Low	Low	20,0
High	Low	20,6
Low	High	20,4
High	High	21,6

The effect of A at low B is 0.6 percentage points, and at high B, it is 1.2 percentage points. Therefore, the effect of A depends on B. The effect of B at low A is 0.4, and at high A, it is 1.0 percentage points. The average main effects are 0.9 for A and 0.7 for B. The difference of the differences is 0.6 percentage points; in the factorial effect definition used, the interaction effect is half of this.

If coded factors of -1 and +1 are used, the model that describes the four means is as follows:

$$y = 20.65 + 0.45x_A + 0.35x_B + 0.15x_Ax_B. \qquad \text{(II.11.1)}$$

This model fully explains the four points; however, this success does not necessarily mean that the model is validated. If there is no repetition, experimental error cannot be predicted. If there is no intermediate level, curvature cannot be observed. Witness measurements are required to draw conclusions about the inter-factor mechanism. For example, the hypothesis that high temperature activates the effective interface material should be tested with appropriate chemical or passivation measurements.

When is it insufficient to change only one factor at a time?

Scanning A at a low B value first, and then scanning B at a selected A value, can mask the interaction. However, a large full factorial design is not mandatory at the beginning of every study. A small preliminary scan is beneficial if there are unknown applicability limits, equipment safety concerns, or areas where film does not form. The purpose of the preliminary scan differs from that of the confirmatory experiment. The preliminary scan selects a candidate range; the confirmatory experiment tests whether the selection actually works.

As the number of factors increases, fractional designs can reduce costs; however, some effects become aliased. Which effects are aliased is documented in the experimental design. The assumption of “no interaction” is not simply made invisible to justify performing fewer experiments. If the sum of the mixture ratios is constant, an independent factors approach may not be appropriate; a mixture design is required. The way in which one ratio is increased while others are decreased has chemical significance.

Randomization and blocking

Randomization reduces the likelihood of a time-varying factor consistently coinciding with the same condition. Blocking makes known day or lot effects apparent in the design. If only one recipe is produced each day, there is no separation between recipe and day. A better approach is to produce reference and variant samples together each day, as much as possible. If the furnace position is important, the positions of the samples are also balanced.

Since some factors are difficult to modify, complete randomization is not possible. While the furnace temperature cannot be changed for each cell, the contact pattern can be. In this case, a split-plot-like design and appropriate error levels are required. Analyzing a factor that is difficult to modify as if it were independently applied to each cell unnecessarily narrows the confidence interval.

Measurement system capability

Increasing the number of trials is not the only solution if the difference between processes is smaller than the measurement noise. The operator, day, and device components are analyzed separately. Repeated measurements of the same samples test the measurement system; they do not measure production variability. If the samples age during the measurement process, the order of the repetitions is also important. The Gauge R&R concept raises the question of how much of the total variability comes from the measurement process. [D16]

Use pre-defined acceptance criteria. For example, if the control measurement of the reference cell falls outside the specified range, the results for that day can be flagged for review. This range should not be changed to filter out poor results after the experiment. Data excluded due to device failure is not deleted; instead, the reason, date, and the specific evidence indicating the failure are recorded.

The optimum condition differs from the process window

A single peak can exist on a surface; in manufacturing, the behavior around this peak is important. A narrow optimum may be unusable if it yields a large loss with a small change in temperature or flow rate. The goal is sometimes to select a broad region that remains above the acceptance threshold, rather than the highest average. This also includes noise factors such as the raw material lot and the equipment maintenance status.

If the process is stable and the assumption of a normal distribution is met, capability indices can be used. In the approach defined by NIST, the tolerance interval is compared with the process spread. [D15]

$$C_p = \frac{USL - LSL}{6\sigma}, \qquad C_{\text{pk}} = \min\left(\frac{USL - \mu}{3\sigma}, \frac{\mu - LSL}{3\sigma}\right). \tag{II.11.2}$$

These indicators do not correct a process that is out of control. Reporting a high Cpk using a single sigma can be misleading for data that drift over time or follow a mixture distribution. If the product requirement is one-sided, do not apply the two-sided formula without considering this distinction. Measurement error also broadens the distribution; separate the error sources first.

Final validation experiment

The best batch used in the optimization is not selected and reported. Instead, the selected conditions are repeated according to a predefined plan with new material, a new day, and, if possible, a different operator. The reference is located in the same batch. Not only the average gain is evaluated, but also the tail behavior, acceptance rate, and any new failure mechanisms. If the expected gain is not reproduced, this result is retained as a failed experiment and may become one of the most valuable constraints for the subsequent model.

Assignment. The high-high condition was selected in the synthetic table. The result for the new batch was 20.3. Write a validation plan that differentiates between the explanations that the optimization is incorrect, the measurement has drifted, or there is a hidden factor. Specify which samples need to be produced on the same day and which data needs to be frozen beforehand.

BOOK II · CHAPTER 12 / FROM EXPERIMENT TO PRODUCT

Improving durability and identifying failure mechanisms

Distinguishing between the symptom, the mechanism, and the root cause

When a module's power decreases, the **symptom** is power loss. The **mechanism** is the physical or chemical process that causes this loss: such as contact corrosion, interface delamination, or changes in ion distribution. The **root cause** is why the mechanism became active in that particular product: it could be inadequate edge sealing or improper curing history. The statement "moisture ingress occurred" is not a complete diagnosis unless it specifies which material, path, and electrical consequence are involved.

Stress is the demanding condition applied to a device. Temperature, humidity, light, and electrical voltage are different types of stress. A **control sample** enables comparison when one of these is changed. Increasing all stresses simultaneously can create rapid degradation, but it makes it difficult to determine which one is responsible. In this respect, a development test and a simple qualification test may have different objectives.

Threshold and timescale

T80 is the time it takes for the defined initial power to decrease to 80%. If the initial power is 10 W, the threshold is 8 W; for an initial power of 12 W, the threshold is 9.6 W. If we exclude the initial short-term variation, we must explain which time and justification we are using. If the test ends before the threshold is reached, the time is **censored**; the full lifetime has not been determined.

Synthetic diagnosis: After the same stress test, the current changes slightly, the voltage remains stable, and the fill factor decreases. The possibility of contact or electrical transport loss becomes significant, but it is not the sole definitive cause. The electrical curve, resistance diagnosis, and the location of the damage are analyzed together. Immediately cutting and opening the sample can irreversibly alter the previous measurement conditions; the order of inspection should be planned.

The **acceleration factor** is a model output that correlates the rates of a mechanism under test and usage conditions. It is not a universal constant. If a different failure mode initiates at a high temperature, the field life cannot be calculated using that factor. **Recovery** refers to the partial restoration of performance after a period of rest or under different conditions; it is reported separately from permanent loss. The stress matrix below establishes the comparisons that will differentiate the mechanisms and allows for the retesting of the repaired product.

Comprehension check: a repair, or merely shifting the failure elsewhere?

New encapsulation methods may reduce moisture ingress while increasing thermal stress. Success in a single, conventional failure test is not sufficient; appropriate controls are needed to address the new mechanical, optical, and electrical risks affected by the change. The improvement should maintain the acceptance of the entire product under defined operating conditions.

A device may have a high initial power; the value of the product depends on how this power changes under operating conditions. A durability study is not simply subjecting a sample to harsh conditions and measuring the final power. It should be explained which mechanism is being accelerated, how closely the laboratory stress resembles field conditions, and how the measurement addresses reversible changes. The reliability concepts from the first book are translated here into an experimental design and diagnostic sequence.

Symptom, mechanism, and root cause

Power loss is a symptom. Corrosion, cracking, ion migration, or interface reaction can be a mechanism. Insufficient edge sealing, a dirty surface, or an inappropriate process window can be a manufacturing cause that triggers the mechanism. When these levels are not separated, explanations such as “moisture damage” are insufficient to improve the process. The questions that need to be asked are: how did the moisture enter, with which material did it interact, and what electrical loss did it cause?

The first step is to check the measurement itself. Are the reference, contact, mask, and temperature consistent? Is the power loss observed under stable operating conditions or during a rapid scan? Does the sample recover when left in the dark? Recovery does not necessarily mean that there is no permanent damage; reversible and permanent components can coexist. Aging curves should not be compared without recording the rest period before the measurement.

Observed symptom	Possible explanations.	Discriminating examination
The current decreases, and there is a spectral shift.	Optical yellowing, delamination, collection loss	Transmittance/reflectance, EQE, cross-section.
The fill factor decreases, and the voltage changes only slightly.	Contact or interconnection resistance, local leakage	Dark J-V curve, EL, thermography, contact test

Observed symptom	Possible explanations.	Discriminating examination
The voltage is decreasing.	Recombination, shunt, interface modification.	PL/EL, dark J-V curve, irradiance dependence
Localized darkening or a hot spot	Crack, disconnection, mismatch.	EL and current distribution, controlled thermography
Change dependent on the measurement history.	Metastability, ionic or capacitive process.	Fixed protocol, time-resolved monitoring

The table does not provide a diagnosis; it suggests the next measurement to be taken. Avoid determining the entire mechanism from a single image. For example, an EL dark area can be caused by both an electrical connection issue and an optical obstruction. The before-and-after images must be taken at the same current and temperature.

Constructing the stress matrix

Heat, humidity, light, electrical voltage, and mechanical loads can create interactions as well as individual effects. A dark, humid heat test does not fully represent a cell operating under illumination. First, a mechanism hypothesis is established; then, a stress is selected to differentiate it. Packaged and unpackaged samples answer different questions. An unpackaged film exhibits chemical sensitivity, while a packaged device also includes barrier and edge design.

In perovskite research, the ISOS agreement is an important framework that aims to ensure comparability of test conditions and reporting. The initial definition should clearly state the environment, electrical operating conditions, and the measurement method used over time. Implementing an ISOS condition does not imply commercial module certification. [D17]

The IEC 61215 family concerns design qualification and type approval; the IEC 61730 family concerns module safety. The catalog entry indicates the scope of the standard; it does not replace the entire detailed procedure. This book explicitly states when catalog access is used in place of reading the full standard. Passing a test sequence does not guarantee a definitive thirty-year lifetime in a specific field. The need for retesting when the design or material changes is evaluated separately; IEC 62915 is one of the reference frameworks for this. [D21] [D22] [D23]

T80 definition and censoring

T80 is the time it takes to reach 80%, which represents the selected reference power. The reference initial measurement can be the power or another definition after the initial stabilization; whichever it is, it is clearly stated. Reporting a longer lifetime by ignoring the initial rapid decrease is misleading. If a series normalized with both the initial power and the stabilized power is required, it is provided together.

When the test is finished, if the sample is still on 80%, T80 has not been measured. It is known to be longer than the last observation period; this is right-censored data. If two out of five samples fail and three continue to operate, it would be incorrect to provide the average of only the two failed samples as the "lifetime." If the time resolution is low, the threshold crossing may occur between two measurements; this interval also contains uncertainty.

Synthetic example. In four samples, the 80% threshold is exceeded at 820, 1060, and 1390 hours; the fourth remains at the 87% power level after 1500 hours. The T80 of the fourth sample is not 1500. The result is stored as "three threshold exceedances, one right-censored observation." To compare the opposing recipes, the number of samples, stress condition, and initial definition are matched. Four samples may not be sufficient to definitively determine the wide production distribution.

Conditions for Arrhenius acceleration

Assuming a single, thermally activated rate-determining mechanism, the rate can vary with temperature in an Arrhenius fashion. The acceleration factor for test and operating temperatures is expressed by the following model:

$$AF = \exp\left[\frac{E_a}{k_B}\left(\frac{1}{T_{\text{use}}} - \frac{1}{T_{\text{test}}}\right)\right]. \tag{II.12.1}$$

Here, the temperature should be in Kelvin, and the activation energy and Boltzmann constant should be in consistent units. This equation is not merely a curve-fitting tool; the same mechanism must remain valid. If a phase change, package softening, or a different reaction begins at high temperatures, the direct outward transport is disrupted. The effects of humidity and light cannot be hidden within a temperature factor.

In the illustrative calculation, if the activation energy is taken as 0.5 eV, the operating temperature as 25 °C, and the test temperature as 85 °C, the multiplier is approximately 26. This number is not the lifetime multiplier of a real PV module; it is the result of the chosen model. If the activation energy is unknown, do not select an arbitrary literature value to derive a warranty duration in years. Mechanism and rate data at different temperatures are required; a field comparison is performed separately.

Preserving the sample for diagnosis

In failure analysis, the most valuable sample should not be consumed during the initial processing step. First, photographic imaging, electrical measurements, and non-destructive inspections are performed. Then, a plan is developed for cross-sectional or chemical analysis. Contamination and handling conditions are recorded. The signal obtained from the damaged area is compared with the signal from the undamaged area of the same sample and an unprocessed reference sample.

The IEA PVPS's failure assessments regarding new cell and module technologies emphasize that failure modes should be re-evaluated as the technology changes. A successful encapsulation or test procedure for a previous technology should not be directly transferred to the new layer structure. [D18]

Acceptance of the improvement

The new barrier, while providing longer durability, can create optical losses. The new passivation, while increasing the initial power, may degrade faster under illumination. Therefore, the initial power distribution, the remaining power after stress, the failure mode, and manufacturability are all included in the same decision file. Evaluate the gain not only based on the best sample but also based on a pre-defined sample group.

Assignment. A perovskite cell is stable in dark storage but degrades rapidly under illumination; it partially recovers in the dark. Design a matrix that separates the effects of light, temperature, electrical operating point, and packaging. Describe which measurements will test for reversible changes and which will test for permanent damage. Do not add a field lifetime to the report when it has not been established.

BOOK II · CHAPTER 13 / FROM EXPERIMENT TO PRODUCT

From cell to module: interconnection, encapsulation and pilot production

In the module, the current path and the protection path are established together

Cells are connected using **ribbons**, **wires**, or other conductive interconnections. In a series connection, since the same current flows, the performance distribution and matching of the cells are important. Cutting a cell in half can change the current and the conduction geometry, and it can also create new edge and processing damage. The **cell-to-module power ratio**, or CTM, compares the module power to the total power of the cells used. Optical gain and electrical loss can occur within the same ratio.

Lamination is the process of combining the cells and protective layers under defined temperature, pressure, and duration. The **encapsulant** is the protective and bonding material between the layers. **Curing** is the process of chemical cross-linking and the development of final properties in certain polymers. **Delamination** is the separation of the layers. The presence of air gaps within a module can affect its optical, mechanical, and electrical reliability.

Why are P1, P2, and P3 three separate scribes in a thin-film module?

Instead of using a continuous thin film on a glass substrate as a single large cell, it can be divided into strip cells. In a typical sequential manufacturing process, **P1** forms the line that isolates the first conductive layer, **P2** forms the opening for establishing electrical connection to the adjacent cell, and **P3** forms the insulating line that separates the subsequent layers. The precise removal of layers and the sequence depend on the architecture. These three steps are not simply three parallel lines; they are distinct functions of the series connection.

Synthetic area calculation: Assume that the width of each repetition is 10 mm, and the total width of the connections and insulation, which do not effectively utilize the light, is 0.5 mm. In a simple strip geometry, the usable width ratio is 95%. Narrowing the inactive connection and insulation line can increase the usable area; however, it can also reduce the insulation tolerance and increase the risk of leakage. A good module design considers both of these effects together.

The **pilot line** is a production environment where the process is tested on a larger scale, and its control is learned. The **control plan** specifies which parameter will be measured, how, and how often at each step. The pilot output is not only good samples but also transfer knowledge that can be applied to other equipment and devices. The following section connects these records from cell measurement to line acceptance.

Comprehension check: why is P2 not merely an isolation step?

The function of P2 is to reach the appropriate layer and establish a connection between adjacent cells. Designing it as simply “another scratch” can lead to an open circuit or high contact resistance. In a cross-section, illustrate which layer each line removes and which it protects.

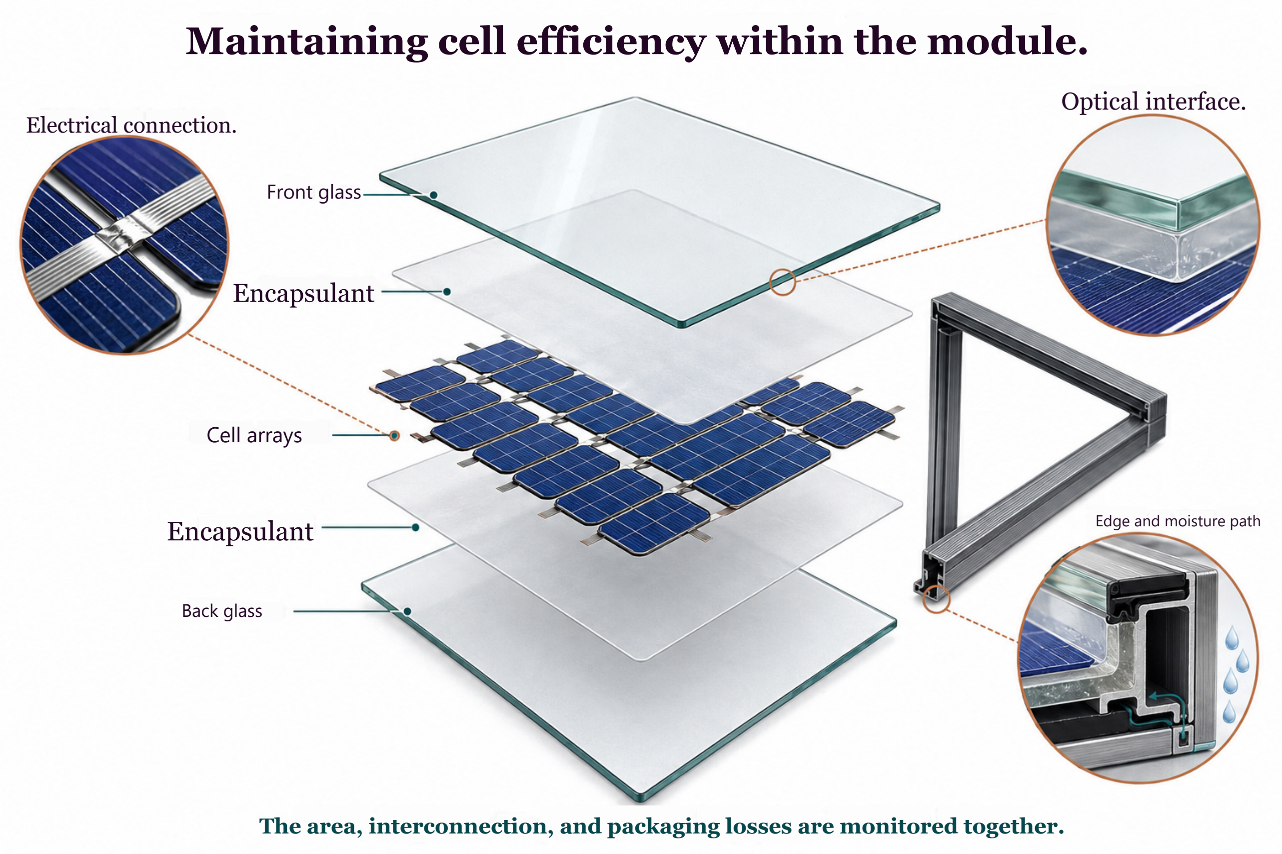


Figure 08. Representative layers and critical interfaces of a glass-glass module using crystalline silicon. Electrical connection, optical transmission, and edge protection collectively affect the power generated and the durability of the cell. [D01] [D18] [D22] Conceptual illustration prepared with an image-generation tool; it is not a measurement image.

The cell measured in the laboratory is only one component of the module. Cutting, connecting, and packaging the cells, as well as determining the product area, creates new losses. Optical matching can also provide gains under certain conditions. Therefore, simply multiplying the cell efficiency by the module area is not sufficient. The development process should track which cell characteristic contributes to which module loss.

Establishing the CTM balance

The cell-to-module ratio is defined as the ratio of the module power to the sum of the individual powers of the cells used, under specified conditions. The spectral, temperature, and area definitions for cell and module measurements must be consistent. Since the optical environment changes, some contributions may be positive, while others, such as resistance and mismatch, may be negative. It is incorrect to assume that the CTM is simply a loss percentage.

$$CTM = \frac{P_{\text{module}}}{\sum_i P_{\text{cell,i}}}. \tag{II.13.1}$$

Synthetic example. Let the sum of individually measured cell powers be 600 W. Within the package, let the optical matching result in a gain of 1.5%; the connection result in a loss of 2%, and the mismatch result in a loss of 1%. In the multiplicative simple model, the module power becomes 600 × 1.015 × 0.98 × 0.99 = 590.85 W. The CTM is approximately 98.48%. The loss terms may not actually be completely independent of each other; this calculation is for teaching purposes. Additionally, the aperture or total product area is specified for the module efficiency.

Cell cutting and matching

Dividing the cell into smaller pieces can alter the current and connection losses, and it also creates new edges. The cutting method, edge damage, micro-cracks, and subsequent passivation are important. Compare the total power before and after cutting under the same conditions. Measuring only the better of the two pieces will mask the cutting loss. EL imaging, electrical data, and mechanical strength are evaluated together.

In a series string, all cells carry the same current; discrepancies cannot be explained solely by differences in short-circuit current. The shape of the curves and the reverse voltage behavior under temperature and shading are also important. The cell matching algorithm can be validated with real curves. A bypass diode does not eliminate internal cell defects; it provides a current path under specific string conditions. Layout, enclosure temperature, and reliability are separate design considerations.

Connection options

The ribbon, multi-wire, shingling, or other interconnection approach alters shading, metal length, mechanical stress, and processing temperature. A low-resistance interconnection is insufficient for the product if it exhibits poor adhesion. The stress between different materials with varying thermal expansion during temperature cycling must be monitored. Tensile or peel tests, along with electrical continuity and power measurements after aging, are performed to compare different interconnection versions.

In the new interconnect material, the first test can be for electrical contact, the second for mechanical strength, and the third for aging within the package. These three results cannot be used interchangeably. Selecting only the highest instantaneous adhesion force in the interconnect press, soldering, or adhesive setting, without considering whether it damages the cell, would be incorrect optimization.

In a thin-film module, P1, P2, and P3

A monolithic thin-film module can interconnect sub-cell strips on a glass or film substrate. P1 typically defines the initial electrode segments; P2 opens the area for connection to the electrode of the subsequent cell; P3 separates the final conductive stack, preventing unwanted short circuits between adjacent strips. The layer from which each pattern is etched should be indicated along with the actual stack and the etching sequence. Do not assume that the P1-P2-P3 nomenclature refers to the same layer list in all architectures.

Yang and his colleagues' study on perovskite module interconnection serves as an example demonstrating that the interconnection region is not merely a geometric void; the local material and contact behavior also influence the module's performance. Separately providing the active area efficiency and the open-circuit area efficiency makes the area loss apparent. [D35]

In laser development, wavelength, pulse duration, energy density, repetition rate, focus, scanning speed, and pulse overlap are considered together. A visually appealing scratch may have damaged the underlying electrode or left conductive residue on the sidewall. In addition to optical imaging, insulation and contact resistance are measured along the scratch. While reducing the scratch width, the risk of short circuits due to residual material and misalignment is evaluated.

$$GFF = \frac{A_{\text{active}}}{A_{\text{aperture}}}. \tag{II.13.2}$$

GFF is the geometric fill factor; it is not the same as the electrical J-V fill factor. In a **synthetic calculation**, if the active area efficiency is 22% and the GFF is 95%, then, assuming no other losses, the aperture efficiency is 20.9%. In a real module, connection and lateral transport losses are added to this simple area factor. When comparing a large area to a small cell, report which area is in the denominator.

Packaging layers constitute a system

The glass or front sheet performs optical, mechanical, and environmental functions. The encapsulant provides optical coupling and mechanical support; it may also involve chemical interaction. The back sheet or second glass, together with the edge sealant and cable outlets, forms the barrier system. It is not assumed that if a single material has low water vapor permeability, the entire module will exhibit the same barrier performance.

In lamination, the temperature-time-pressure profile is related to the material's flow and curing. Excessive flow can alter the cell position or connection; insufficient flow can leave voids. New absorber or contact chemistry may not be compatible with the encapsulant. Therefore, empty packages, witness films, small modules, and target area modules are used in different stages. After packaging, not only the power output but also the optical appearance, adhesion, and electrical safety are checked.

Control plan for the pilot line

The pilot line is not a miniature factory; it is a tool for understanding process variation. It must be possible to trace which version of the sample passed through which station. Intermediate checks should identify errors before proceeding to the next step. Placing all measurements at each station may be costly; however, only detecting critical defects in the final test is also expensive. Control points are selected based on where the defect occurs and the cost of missing it.

Stage	Example check	Information to be linked upon registration.
Cell input.	Power distribution, EL, dimensions.	Lot, grade, cutting history
Connection	Resistance, alignment, mechanical sample.	Equipment and material versions
Arrangement	Spacing, arrangement, connectivity integrity.	Product diagram and tolerances.
Lamination	Profile, voids, adhesion witness sample	Encapsulant lot and cycle record

Stage	Example check	Information to be linked upon registration.
Final test.	Power, EL (Electroluminescence), insulation, and visual inspection.	Calibration, acceptance decision.

Initially, the limits are derived from product and test requirements. Do not subsequently widen the control limits merely to make all products pass. Suspect products are segregated; if reprocessing is applied, the history is preserved. The impact of a material change on existing qualification tests is reviewed. [D21] [D22] [D23]

Transfer packet

The delivery of a module development is not just a good example; it should include the cell layout, bill of materials, connection diagram, process windows, measurement protocols, failure examples, and change log, all delivered together. Which part of the recipe has been validated, and which part has been assumed? At what equipment scale has it been tested? Which acceptance criterion has not yet been tested? If these questions remain unanswered, the next team will rediscover the same problem.

Exercise. A change that provides a relative gain at the cell level, 1%, is lost in the module. Set up a staged production experiment to separate the explanations for cell trimming, interconnection, optical encapsulation, and lamination damage. At each stage, select a suitable reference sample for measuring the power and for assessing the unmeasurable effects.

BOOK II · CHAPTER 14 / FROM EXPERIMENT TO PRODUCT

Scale-up: capacity, saleable watts and process economics

Nameplate capacity is not actual output

Nominal capacity refers to the potential production under specific speed and operating time assumptions. **Actual output** is the amount produced during a specific period. **Accepted output** is the portion that meets the specifications. **Capacity utilization rate** indicates how much of the defined capacity is being used. If the same GW/year figure is used for any of these different concepts, a direct comparison cannot be made.

Availability refers to the portion of the planned time during which the line is operational. **Throughput performance** indicates how close the actual operating speed is to the nominal speed. The **quality ratio** represents the percentage of accepted products. By multiplying these three factors, we can establish a rough initial assessment of losses; a more detailed model may be required to account for bottlenecks, rework, and product variations in a real production line.

Synthetic example: A nominal 1000 cells/hour line, using 80% availability, 90% speed, and 95% acceptance rate, yields 1000 × 0.80 × 0.90 × 0.95 = 684 accepted cells/hour. If each accepted cell is 5 W, the output is a production capacity of 3420 W/hour. This means that the factory produces products with a rated power of 3420 W in one hour, rather than generating electricity. It is necessary to distinguish between power and production rate units.

An increasing area alters the probability of defect formation

The absence of a defect in a small sample does not indicate the absence of defects in a larger area. **Defect density** is the ratio of the defined number of defects to the area or volume. In simple models where defects are assumed to be independent and homogeneously distributed, the probability of encountering at least one defect increases as the area increases. In actual production, clustering and accumulation in specific regions may occur; these assumptions need to be verified through measurements.

Cost per accepted watt is the ratio of the total cost to the accepted rated power. **Fixed costs** are those that do not change proportionally with the production volume in the short term; **variable costs** are inputs consumed depending on production. A **bottleneck** is a step that limits the flow of the line. If another device is accelerated by a factor of two, but the bottleneck remains the same, the total output will not be doubled.

Scaling up involves not only a larger coating area but also maintaining the flow and acceptance rate over time.

Comprehension check: the chemical price has halved

Will the total cost per good watt also be halved? No. The proportion of that chemical in the total cost, the consumption rate, the acceptance rate, and other expenses must be determined. Furthermore, if the new purity level lowers the acceptance rate, a cheaper input may result in a more expensive good product.

The economic value of a research idea does not solely stem from using a cheaper material. Coating speed, line downtime, target utilization efficiency, quality distribution, maintenance, and product power can all have an impact. All the numerical examples in this section are synthetic and should not be interpreted as current factory costs or company margins. The goal is to teach the calculation structure that links laboratory changes to the decision of scaling up.

Different meanings of capacity

The installed nameplate capacity represents the annual potential of a production line based on specific assumptions. Actual production, accepted product, shipped, and sold wattages are all different quantities. A factory opening or capacity announcement does not confirm all of these. When the power per unit changes, the same production rate yields a different wattage capacity. The figures in the company's datasheet should be interpreted with this distinction in mind.

The line capacity depends on the flow between stations. In a serial flow, the slowest process can be the bottleneck; parallel equipment, intermediate storage, batch furnaces, and maintenance schedules change the simple minimum calculation. A coating tool with a high nominal speed will not deliver the expected output if frequent cleaning is required. Accelerating a station may not increase the total output if the bottleneck is located elsewhere.

Availability, speed, and quality

The OEE approach helps to separate the availability, performance, and quality components. For this to be useful, the denominators must be consistent. If quality loss is counted in both the speed component and the acceptance rate, double counting will occur. It is also specified on which time basis the planned downtime is based. The following example in this book is a simple model with clear definitions:

$$N_{\mathrm{good}} = r_{\mathrm{ideal}}\, t_{\mathrm{scheduled}}\, A\, P\, Y. \qquad \text{(II.14.1)}$$

Let the ideal rate be 1000 units per hour, the planned duration be 8000 hours, the availability be 0.85, the rate ratio be 0.90, and the first-pass yield be 0.95. The good output will be 5,814,000 units. If each accepted product is 10 W, then the total power is 58.14 MW. This result should not be confused with a claim of producing 8 million units simultaneously with 95% quality. If there are reworked products, the additional time, cost, and acceptance rate are calculated separately.

Cost per saleable watt

In the simplified annual calculation, fixed and variable costs are divided by the total accepted electrical power. If the product classes are different, the power and economic value of each class can be considered separately. The recoverable material within the scrap is also included in the calculation with a clear assumption. The energy price, utilization rate, and financing assumptions of a one-year model are time-dependent.

$$c_W = \frac{C_{\text{fixed}} + C_{\text{material}} + C_{\text{energy}} + C_{\text{labor}} + C_{\text{maintenance}} + C_{\text{quality}}}{W_{\text{good}}}. \qquad \text{(II.14.2)}$$

If a material change reduces the cost per unit 2% and also reduces the product power 1%, and lowers the acceptance rate 3%, the overall economics may worsen. With simple multipliers, the new cost/good watt ratio becomes approximately 0.98/(0.99 × 0.97) = 1.0205: an approximate 2.05% increase. Even the assumption that other costs remain constant does not fully explain a real production line; for example, it shows that the savings in a single input are not sufficient.

As the area increases, the probability of defects increases

The absence of rare defects in a small cell does not prove the absence of defects in a large area. In the ideal model where independent, equally probable lethal defects are distributed according to a Poisson process, the probability of a defect-free area is as follows:

$$Y_0(A) = \exp(-DA). \qquad \text{(II.14.3)}$$

Let D be the density of lethal defects per unit area. Synthetically, for 0.01 defects/cm^2, the defect-free area of 1 cm^2 is approximately 99.0%; for an area of 100 cm^2, it is 36.8%. In real films, defects can cluster, some may not be lethal, and strip design or repair may be effective. Therefore, this model is not a realistic estimate of the actual acceptance rate; it demonstrates why increasing the area requires new information.

Do not reduce a defect map to its average density. Clustering at the edge, a streak along the coating direction, a recurring roller mark, or a defect linked to the carrier position indicate different causes. Record the production direction and sample orientation in the data file. A good spatial map can be more informative than a random search for new recipes.

Quantities to be preserved when scaling up the laboratory recipe

Increasing the coating volume at the same rate as the area is not always sufficient. The flow regime, surface tension, evaporation, and heat and mass transfer change with scale. For slot-die coating, the flow rate, line speed, and coating width are determined together; however, meniscus stability and drying history are verified separately. In vacuum, the source geometry and substrate movement affect the uniformity of the film. In an oven, the fill level and gas flow can alter the actual conditions experienced by the sample.

Therefore, the phrase “same temperature” alone is not sufficient for transfer. Where is the sensor located, at what rate does the sample heat up, and how much do the surface and bulk temperatures differ? Similarly, “same pressure” does not fully define the local flux, and “same plasma power” does not fully define the particle energy arriving at the surface. Recipe transfer between equipment is first calibrated with equivalent output criteria.

Supply, maintenance, and design modification

If a dopant has only one supplier, the product implementation plan should include purity requirements, alternative source verification, and lot acceptance testing. When a new lot arrives, the process should not be considered equivalent simply because the chemical name is the same. Impurities, water content, particles, and storage history may be significant. Similarly, changes to the target, electrode, pump, or chamber wall can affect coating quality.

The maintenance plan is not just about downtime costs. If there is a quality difference between the first production run after cleaning and the last production run of the cycle, a window is defined. When the equipment parts that come into contact with the product are changed, a new qualification is performed using the reference sample. Changes in the measurement device software or analysis version can also affect the results; the change log is not limited to the physical recipe.

Energy, material, and environmental balance

When calculating production energy, a distinction is made between the in-plant processing limit and the life cycle limit, which includes raw material production. Indicators such as energy per unit area, energy per unit watt, and lifetime energy address different questions. High efficiency can reduce the area required; however, additional processing or a low manufacturing yield can offset this gain. The environmental impact of using thin materials is assessed in conjunction with toxicity, recyclability, and lifetime.

Use the same electricity mix, product lifetime, and system boundary in the comparison. Do not claim an advantage for a new technology whose service life is still unknown by assuming the warranty period of a mature technology. Present the scenarios separately; use sensitivity analysis to identify which unknown changes the decision most.

Assignment. The new coating method is twice as fast, but the cleaning frequency doubles, and the acceptance rate decreases. First, list which time intervals need to be measured. Then, design a table to calculate the good watt-hour cost for the optimistic, baseline, and pessimistic scenarios. Finally, select which single experiment will most effectively reduce economic uncertainty.

BOOK II · CHAPTER 15 / FROM EXPERIMENT TO PRODUCT

Computational development: from candidate material to a testable device

The links of a calculation chain

DFT is a method that approximately determines the energy and electronic properties of a crystal using quantum calculations based on electron density. The **optical model** calculates how much light is absorbed in each layer. The **device model** determines the current-voltage behavior by analyzing the movement, loss, and contacts of the generated charges. The **manufacturing model** correlates process speed, acceptance, and consumption. A good result in one step does not necessarily mean that the entire chain has been validated.

Input uncertainty refers to the incomplete knowledge of the properties used. **Model error** arises when the approximation does not fully represent the real physical system. **Numerical error** results from solving the chosen model with finite detail on a computer. These three must be distinguished. A finer computational mesh can reduce numerical error; it does not automatically add missing chemical reactions to the model.

Why are stability and band gap separate screening gates?

A crystal can absorb light at a suitable energy, but it may tend to decompose into other compounds with lower energy. A **phase** is a state with a specific structural and compositional order. The **competing phase space** represents the options that can form the same total elements into different compound mixtures. The calculation of the **convex hull** establishes their energy boundary. **Metastable** refers to a state that, although not at the absolute lowest energy, can persist due to barriers to transformation. How long this will last cannot be determined solely from the energy difference.

Synthetic example: Suppose a device model gives 28% efficiency for a lifetime of 1 ms and 14% for a lifetime of 1 µs. Selecting the 1 ms assumption for an uncharacterized material and presenting 28% as the “predicted actual efficiency” is misleading. The result shows that lifetime is a determining factor, and this property needs to be measured. Instead of using an optimistic point to select the candidate, it is necessary to examine under what conditions it wins or loses.

Screening involves eliminating a large number of candidates using low-cost rules; **validation** involves testing the critical assumptions of the remaining candidates using more robust methods or experiments. **Identifiability** refers to the ability to uniquely determine different model parameters from the measured data. **Active learning** selects the next calculation based on its potential for information gain or contribution to the target. These methods can accelerate the thought process, but they do not automatically make unknown interfaces and synthesis behavior known.

Comprehension check: what single quantity should the laboratory measure?

Identify the parameter that most significantly affects the model's outcome and has the greatest uncertainty within its current range. If it can be measured appropriately, it is a strong candidate for the initial experiment. However, simply selecting the most expensive or newest measurement method may not provide the information that will most significantly influence the decision.

The calculation helps determine which experiment in the research is worth conducting. Conversely, a band gap or theoretical efficiency cannot replace a synthesized and measured cell. In the development chain, the output of each model is the input for the next stage; model error is also propagated. This section transforms the DFT, transport, and machine learning sections of the first book into a program with decision gates.

First, transform the product question into a calculation question

"Find a new PV material" is a very broad task. More useful questions are: Is there a wide bandgap absorber that can be grown within a specific temperature budget? Is there an interface that improves the band alignment of the existing contact? Is there a chemical condition that reduces the formation of a defect? As the question becomes more specific, the required accuracy and the most cost-effective characterization method are also determined.

The candidate list is not solely ranked based on high theoretical efficiency. Element availability, possible phases, chemical stability, optical absorption, transport, defects, and process compatibility are all considered together. If information is missing in some areas, do not fill the empty table cell with an optimistic assumption. The unknown is recorded as a topic for further investigation. If competing phases are present but not investigated due to resource limitations, specify the scope of the scanned pool instead of "overall stability."

Calculation setup and convergence

The crystal structure source, atom types, magnetic state, functional form, pseudopotential, cutoff energy, k-point grid, and relaxation tolerances are saved. The total energy convergence must be more accurate than the targeted energy difference. Convergence in a single structure may not be sufficient; the compared phases must be calculated with consistent settings. If the unit cell changes, the sampling density in reciprocal space is considered instead of the number of k-points.

An energy difference of 5 meV/atom does not provide strong ordering if the numerical uncertainty is 20 meV/atom. Before switching to a more expensive method, convergence is checked using the same method. In the low-cost screening, candidate structures are selected; the higher-accuracy stage is applied only to the selected candidates. Negative results, failed relaxations, and different initial states are saved; only the best final structures are archived.

Thermodynamic stability and synthesizability

A formation energy indicates the stability of a compound relative to its constituent elements. To assess decomposition into competing compounds, the convex hull in phase space is required. The Materials Project documentation explains how the energy above the convex hull is defined with respect to stable phase combinations. This assessment depends on the chosen energy model and phase set. [D24]

Zero energy above the hull does not automatically guarantee synthesis. Entropy at finite temperature, chemical potentials, surfaces and interfaces, kinetic barriers and the growth route change the outcome. A phase above the hull can also exist metastably under suitable kinetic conditions. However, “it may be metastable” cannot serve as a justification for every high-energy candidate. The relevant growth and degradation mechanisms must be investigated separately.

Synthetic example. Let’s assume that in a limited phase space, the envelope of a candidate has an energy of 15 meV/atom. If a newly discovered competing phase envelope pulls the candidate down by 20 meV/atom, the candidate’s difference will be 35 meV/atom. Although the candidate’s own energy does not change, the interpretation of stability changes. Therefore, the result package should include not only the candidate structure but also the list of competing phases and their energy levels.

Band gap and optical performance

The electronic band gap and the onset of optical absorption are not the same under all conditions. Direct or indirect transitions, the exciton effect, allowed transitions, and temperature are all important. Adding a constant correction to a low-level DFT band gap does not yield the same accuracy for all materials. If hybrid functionals or more advanced methods are to be used, the convergence and comparison scope should be specified.

An estimate of optical efficiency involves assumptions about the absorber thickness, absorption, and recombination. In an ideal radiative model, a high result does not eliminate real contact and defect losses. The phrase “potential with the following assumptions in the model” and “measured cell efficiency” should be on separate lines. In the initial experiment, the goal is not to achieve the total ideal efficiency, but to demonstrate that the basic absorption and collection mechanism is functioning.

Defect calculation: capture is as important as density

The defect formation energy depends on atom exchange, charge state, Fermi level, and finite-size cell corrections. Chemical potentials must be selected within the physical phase boundaries. For charged defects, the cell size and electrostatic corrections are controlled. The transition level indicates at which Fermi level a defect changes its charge state; it does not provide the charge carrier capture rate on its own.

The effect of a defect on a solar cell is a combination of its formation probability, electronic level, and capture dynamics. A rare, strong trap can be significant; a common, shallow defect may behave differently. When evaluating a negative outcome, the question is whether the defect never forms, is electronically benign, or whether the capture process is not included in the model being examined. This distinction is necessary for deciding whether to modify the synthesis conditions.

Device model and parameter identifiability

Tools like SCAPS can be used to investigate transport, defect, and interface effects in layered devices. The program's official website provides links to the basic model and algorithm sources. The fact that a software produces results does not necessarily indicate that the input material parameters are correct. [D25]

A single J-V curve can be explained by a combination of several parameters. Mobility, lifetime, dopant concentration, contact barrier, and resistance can partially mimic each other's effects. Therefore, the model is not fitted to a single curve alone. It is tested with different illumination and temperatures, dark curves, EQE, and independent thickness/optical measurements. Measured parameters are fixed as much as possible; the reliable ranges of the remaining parameters are reported.

If the result changes when the mesh is refined, the numerical error is resolved before the physical interpretation. The accuracy of the boundary conditions and signs is verified using a simple, well-known example. If the cell under investigation exhibits ionic transitions, it should not be expected that only a static electronic model can explain the scanning hysteresis. Hiding the mechanism that the model does not include in the fitting parameter does not provide a valid explanation.

Selecting experiments using machine learning

If variants of the same sample in the dataset are distributed across the training and testing sets, data leakage can occur. Similar compositions or samples from the same laboratory batch will exhibit overly optimistic performance in a random row split. The split should be appropriate for the research question: generalization on new chemistry, new batches, or new equipment are separate tasks. The test set is protected from model and hyperparameter selection.

In active learning, the next experiment does not necessarily have to select the highest predicted value. An experiment that reduces uncertainty can also be valuable. However, if the model uncertainty is not well-calibrated, a high uncertainty score may select physically meaningless regions. First, the feasibility limits, then the information value, and finally the expected performance are evaluated together. Unsuccessful syntheses should not be removed from the database; they teach the limits of the feasible region.

Transition to the experiment

For a given candidate, the transfer package should answer the following questions: which property was calculated using which method; which convergence test was performed; which competing explanations were eliminated; which result is still a hypothesis; and which falsifiable prediction will the initial experiment test? The initial experiment should be inexpensive and decisive. For example, if no phase formation is observed, it may be premature to proceed to advanced cell optimization. If film formation occurs, the initial optical and electrical verification is performed, followed by contact and packaging.

Assignment. The model predicts high efficiency, but the first cell produces only a weak photocurrent. List model error, phase impurities, poor contacts, and short lifetime as possible explanations. State which explanations you could distinguish with the two least expensive measurements. Do not classify the candidate as a “discovery” or a “successful cell” without a new experiment.

BOOK II · CHAPTER 16 / COMPANIES AND RESEARCH PROGRAMME

Company atlas: which company is developing which technology, and at what stage of maturity?

Differentiating a company profile from product advertising

In this section, companies are evaluated not by a “who is better?” ranking, but by which technical approach they employ and with what evidence. A **cell manufacturer** produces the efficient electrical converter. A **module manufacturer** can connect and package the cells; they are not necessarily required to manufacture the cells themselves. A **wafer manufacturer** converts the crystal into thin slices. An **equipment supplier** provides the devices that perform these operations. **Vertical integration** refers to having several steps in the value chain within the same company. A company “manufacturing solar panels” does not necessarily mean that it performs all of these steps.

Commercial product is a defined product offered to the customer. **Pilot production** is the stage for transferring and scaling up the manufacturing process. **Laboratory record** refers to the result obtained for a specific sample under specific conditions. **Capacity target** is a plan for the future; **installed capacity** is the defined production capability of the facility; **shipment** is the quantity of products that have been shipped. Because the GW figure appears in the same sentence, these terms cannot be used interchangeably.

Converting commercial names into physical questions

TOPCon refers to the passivated contact approach using a thin oxide and doped silicon; **HJT** refers to the heterojunction between the crystalline silicon and different silicon layers; **BC** refers to the contacts being located on the back surface. Company names such as HPBC, ABC, TNC, or similar may be commercial names for specific product and process families. No undisclosed layer thickness or confidential manufacturing recipe can be derived from these. The publicly available information is limited to the details provided.

Synthetic news reading: Let’s say the statement is, “A 1 GW production line was opened, and the cell showed 30%.” This does not prove that 1 GW of 30% efficient modules were sold annually. The production line capacity, the efficiency measurement category (cell/module and area), independent verification, actual output, and shipment are all checked separately. This distinction is particularly important for emerging tandem technologies.

The company descriptions in this atlas are based on records compiled on **September 8, 2026**. They should not be interpreted as a continuously updated list of the current or future commercial status. The objective of this section is to teach how to translate the publicly available claims of companies into technical mechanisms and levels of maturity. When making a purchase or collaboration decision, the current datasheet and evidence for the relevant product should also be checked.

Comprehension check: Write five lines for a company

The role in the value chain, the technology used, the scale of the product offered, the type of evidence, and the date of the description. Without filling in these five lines, selecting a method based solely on the brand or the number of records is insufficient. “Unspecified” can also be recorded as a result; do not fill in the undisclosed process with assumptions.

This atlas is based on selected primary sources accessed on September 8, 2026. Companies cannot be reduced to a single technology; the following cards identify the product or development line that was examined. The list is not an inventory of all global manufacturers, nor does it provide an investment or purchasing ranking. The goal is to understand technical approaches through real-world company examples and to transform company descriptions into research questions.

In each card, the information verified at the source is separate from the research interpretation in this book. The company’s own statement is indicated as a company declaration. If an independent certificate is mentioned, its complete measurement scope is also important. A commercial cell, a pilot module, a certified research cell, the declared capacity, and the annual shipment do not represent the same level of maturity. The source’s date should not be confused with the access date.

In silicon, there are three distinct axes

TOPCon and HJT describe charge carrier selective contact and passivation approaches. The rear contact represents an architectural aspect related to the arrangement of contacts. A company’s “BC” product does not fully define its entire layer chemistry. Wafer size, cutting, metallization, bifaciality, and module interconnection can vary within these families. Comparing companies’ commercial names without translating them into fundamental physical terms leads to inaccurate comparisons.

Company or group	The investigated path.	Method for reading the evidence.
LONGi; AIKO	Rear contact product families	Separate the layout from the contact physics.
JinkoSolar; Trina; JA Solar; Tongwei	TOPCon development and products	Differentiate recipe innovation from production distribution.
REC; Huasun	HJT cell/module approach	Let's examine the layer, TCO, and interconnection together.
First Solar	CdTe thin film	Distinguish the commercial line from transition to a new process
Oxford PV; Qcells; GCL; Swift Solar	Tandem/perovskite approaches.	Differentiate between shipment, pilot production, capacity, and plan.
Heliatek	Organic thin film	Examine the application-specific product requirements.
Kalyon PV; Smart Solar; CW Energy	Production and integration in Turkey.	Differentiate between the cell, module, and plant stages.

LONGi: HPBC and back contact integration

As stated by the source. LONGi's 2024 HPBC 2.0 and Hi-MO X10 launch associates the rear contact approach with its cell and module product family. This is a company product announcement; it is not assumed to disclose all the details of the commercial name's formulation. [C01]

Research interpretation. When examining this approach, consider the front-side shading gain in conjunction with the transport and alignment costs associated with the back pattern. A "cleaner front side" may offer a physical advantage; however, the overall product gain depends on back-side illumination, temperature, cutting, and module interconnection. A comparative experiment should separate optical gain from electrical loss under the same wafer and measurement conditions. The desired data should include not only the best efficiency but also batch distribution, back-pattern tolerance, and post-module power.

AIKO: Translating the ABC product language into the language of physics

As stated by the source: AIKO's official technology page presents the ABC back contact product line and technology development. The records and product statements on the page should be interpreted within their respective date and measurement categories. [C02]

Research interpretation. Do not try to infer a complete cell recipe from the ABC label. Important questions for the research include how the selective regions are separated, how the contacts and passivation are protected, and what losses are caused by patterning errors. When the cell size changes within the same architecture, the transport distance and mechanical tolerance also change. Therefore, an area scaling experiment is necessary when transitioning from a small prototype to a large cell.

JinkoSolar: TOPCon version upgrade and capacity target

According to the source. JinkoSolar's second-quarter results announcement for 2026 includes the transition towards TOPCon 3.0 and a target of exceeding 40 GW of capacity by the end of the year. As of this date, it cannot be stated that the year-end target has been achieved in terms of production. [C03]

Research interpretation. The value of a technology iteration is determined by which physical loss is reduced. If new passivation, edge treatment, or metallization is implemented, their contributions should be measured separately. An increase in capacity alone does not indicate the cell quality distribution. To evaluate product performance, request cell/module results with the same dimensions, area definition, and test conditions, preferably including the production median and the lower tail.

Trina Solar: From TOPCon cells to module products

According to the source. Trina's announcement of TOPCon Ultra links its technology advancement with global product delivery. The company's product names and performance claims are within the scope of the relevant product version. [C04]

Research interpretation. The performance of a cell can vary depending on the module cutting, interconnection, and encapsulation processes. A technical review should correlate the power distribution from cell production with the module CTM (Current-Voltage-Temperature) characteristics. If a new edge or contact process is claimed, a pre- and post-cutting comparison can be a more informative initial experiment than a full module test. If system energy data is available, also request information on location, backlighting, and temperature conditions.

JA Solar: Bycium+ and DeepBlue product lines

According to the source. JA Solar's 2024 annual report includes information on the Bycium+ n-type cell approach and the DeepBlue product developments expected in early 2025. The report period and the publication date are kept separate. [C05]

Research interpretation. It is necessary to track the relationship between the cell brand and the module family; the same commercial family may include different power classes and components over time. The practical datasheet to be examined should bring together the cell architecture, wafer/area, interconnection, encapsulant, and measurement version in the same table. Otherwise, the cell record of one year may be incorrectly combined with the product datasheet of another year.

Tongwei: TNC and in-process interventions

According to the source. Tongwei's TNC 3.0 announcement dated June 5, 2026, highlights process components such as edge passivation, patterned polysilicon, and printing. These are the company's technology statements. [C08]

Research interpretation. When evaluating such a multi-component package, each innovation requires separate validation. For edge passivation, a comparison should be made between patterned and unpatterned samples; for polysilicon patterning, optical loss and contact measurements should be performed; and for printing, line morphology and resistance should be compared. Observing high performance in the packaged device does not necessarily indicate that each step provides an independent benefit to every cell design.

REC: HJT-based Alpha Pure-RX

As stated by the source. REC's Alpha Pure-RX product page describes the HJT cell module family, interconnection scheme, and product specifications. The technical datasheet available on the access date pertains to a specific product version. [C06]

Research interpretation. Differentiate the contribution of HJT's cell physics from the module interconnection. The fact that a product is resistant to a specific degradation mechanism does not mean that all power losses are eliminated. The comparative analysis should include initial power, temperature behavior, interconnection loss, and appropriate aging results. The warranty conditions for a product should not be used in place of a physical lifetime model.

Huasun: HJT process integration

According to the source. Huasun describes HJT cell/module production and the wafer cleaning-texturing, thin film, TCO, and metallization processes on its official product and process pages. The four main groups mentioned in the marketing materials do not necessarily mean that there are only four processes involved. [C07] [D09]

Research interpretation. In the development of HJT cells, the history of the surface transfer from one station to another can be critical. Therefore, intermediate waiting times, ambient conditions, and plasma damage should be considered as separate experimental parameters. Instead of selecting the TCO solely based on high transmittance, evaluate it in conjunction with resistance, selectivity, and metal contact. Low-temperature processing can be an advantage; appropriate contact and packaging material verification is still required.

First Solar: Commercial CdTe and new process transition

According to the source. First Solar's 2025 annual report describes its CdTe-based Series 6/7 products and the CuRe process transition, which is planned to begin in 2026. The forward-looking transition timeline in the report does not present the transition as being completed in all factories. Perovskite research activities are also not in the same category as CdTe commercial production. [C09]

Research interpretation. This example demonstrates that new PV development does not necessarily require replacing the entire absorber. Modifications within an existing product, such as changes to the dopant, interface, or contact, can represent a significant avenue for improvement. The researcher's question is how the new process generates voltage and durability gains, which existing equipment it is compatible with, and how the acceptance rate changes during the transition.

Oxford PV: from tandem to the first commercial shipment

According to the source. Oxford PV announced the first commercial shipment of perovskite-silicon tandem modules on September 5, 2024. The reported initial shipment is a company statement indicating the technology's transition to the product stage; it does not, in itself, define the level of high-volume annual production. [C10]

Research interpretation. When analyzing this path, the cell record, module area, stable power, production distribution, and conditions of the delivered product are considered separately. If the tandem gain is to be converted into annual energy, spectral distribution and temperature are important. The optical stack of the research prototype should not be assumed to be equivalent to the package structure of the shipped product.

Qcells: pilot module and stability evidence

According to the source. Qcells' announcement in May 2025 describes a milestone in the stability testing of M10-sized tandem pilot modules, as outlined in IEC/UL 61215-2. The stated test success does not necessarily imply an automatic thirty-year field lifetime or full-scale mass production. [C11]

Research interpretation. The pilot module provides more information about area and packaging compared to the small cell. However, the number of samples, the test sequence, pre-conditioning, and post-test stable power results are required. Applying multiple stresses sequentially to the same sample produces different evidence compared to applying a single stress to separate samples.

GCL: distinguishing a perovskite production base from actual output

According to the source. GCL's announcement on June 24, 2025, states that the perovskite production facility has been put into operation and is approaching a GW-scale capacity. The capacity indicated on the nameplate does not necessarily prove that the same amount of high-quality product is produced and sold in a year. [C12]

Research interpretation. In scale-up assessments, large-area homogeneity, laser interconnection losses, packaging, acceptance rate, and downtime should be considered together. The most useful data to examine is often not the highest module efficiency, but rather the first-pass acceptance rate and defect map over time. If this data is not publicly available, the limitation is clearly stated.

Swift Solar: HJT foundation and tandem plan

According to the source. In a statement on March 12, 2026, Swift Solar described Meyer Burger's acquisition of specific HJT production assets and intellectual property, as well as its plans for silicon production and subsequent tandem technology development in the United States. The asset acquisition is a completed transaction; the future factory and tandem technology timeline are separate plans. [C13]

Research interpretation. This strategy demonstrates the importance of connecting a new top cell to a mature bottom cell platform. However, it does not conclude that HJT is a mandatory or universally optimal choice for every tandem cell. The selection of the bottom cell is evaluated based on optical losses, thermal budget, surface texture, contact compatibility, and the existing production infrastructure.

Heliatek: flexible organic PV and application focus

According to the source. Heliatek's production page describes the continuous deposition of organic layers on a web in a vacuum. This method demonstrates that organic PV is not limited to solution processing. The stated capacity is kept separate from the actual output. [C14]

Research interpretation. For lightweight and flexible products, not only the percentage efficiency but also surface applicability, weight, adhesion, barrier properties, and lifetime energy are important. A roof's load-bearing limit or the requirement for a curved surface can influence the technology selection. Research should be conducted using samples that mimic the light and mechanical conditions of the target application.

Turkey: Kalyon PV

According to the source. Kalyon's announcement on May 7, 2026, published on KAP, states that the G12R TOPCONPlus cell line has been commissioned and production has begun; the company indicates that the cell capacity has increased from 1 GW/year to 2.1 GW/year. This represents a stage beyond the previously stated investment target; it is not the realized annual output figure. [C15]

Research interpretation. Questions should be asked regarding which research samples the new cell line can accept in a local development collaboration, how recipe changes are differentiated, and how the pilot trial is linked to the production quality system. Integrated production can facilitate the tracking of raw materials and intermediate products; however, it should not be assumed that a specific research service is available.

Turkey: Smart Güneş Teknolojileri

What the source says. Smart's announcement of 10 March 2026 on the Public Disclosure Platform (KAP) reports the implementation of domestic cell production and the use, at the Niğde Bor power plant, of panels manufactured with these cells at the integrated facility in Aliağa. This document has a different scope from an older report that only stated that the module line was TOPCon-compatible. [C16]

Research interpretation. Cell production and module production have separate capacity and quality criteria. It cannot be inferred from the term "domestic product" that the absorber, wafer, or the entire machine park originates from the same source. For the purpose of the research, the technical sample flow, measurement capability, and change control must be clearly defined before the supply chain origin.

Turkey: CW Enerji

According to the source. CW Energy's announcement on August 12, 2026, published on the KAP (Public Disclosure Platform), states that the first phase of the 1.2 GW cell plant will be commissioned in June 2025, and the decision to increase capacity to 2.5 GW will be implemented in April 2026. This decision does not necessarily mean that the entire expansion has been completed. Attributing this announcement to a different Turkish manufacturer would be an incorrect company association. [C17]

Research interpretation. When examining vertical integration, the crystal growth process is separated from the slicing of the purchased ingot. Local production of cells, modules, frames, and other materials represents distinct technical work packages. Creating separate rows in the company comparison table for each step prevents misinterpreting the scope of the term “integrated.”

From the company’s statement to the research file

When starting to work on a company, the product data sheet, dated technical announcement, activity report, and any available independent test records are collected together. The product version and area definition are matched within the documents. A record-breaking cell does not imply a commercial module guarantee, and completed production is not deducted from purchased equipment. Non-public process recipes are not written as if they were factual, even as estimates.

Assignment. Select a module from two different companies with the same power rating. Compile the cell technology, module area, temperature coefficient, interconnection method, bifaciality, and test conditions into a single table. Leave any missing information blank. Then, write down which three independent data points would be needed to test a company’s claim of improvement. The goal is not to declare a winner, but to establish under what conditions the comparison is meaningful.

BOOK II · CHAPTER 17 / COMPANIES AND RESEARCH PROGRAMME

Research infrastructure, equipment, and collaboration models

What exactly does a research service deliver?

The presence of XRD or a coating system in an institution's equipment list does not necessarily mean that the required method for your sample is available. **Competence** encompasses the equipment, appropriate process, trained personnel, calibration, and data interpretation. What is the **service output**: just a graph, raw data, an uncertainty report, or a reproducible recipe? Clearly defining the expected deliverables from the outset clarifies the technical scope of the collaboration.

A **specification** is a document that outlines the desired functionality and acceptance criteria. An **acceptance test** verifies whether the delivered equipment or service meets these criteria. **FAT** stands for Factory Acceptance Test, and **SAT** stands for Site Acceptance Test. The fact that a device operates at the manufacturer's facility does not, by itself, guarantee that it will produce the same results under the gas, electrical, environmental, and integration conditions at your facility. Tests must be linked to the actual usage requirements.

Specifying an instrument by its output criteria rather than its name

Instead of using the term "good coating device," one can define the film area, material family, thickness range, homogeneity measurement, processing speed, and substrate conditions. **Homogeneity** refers to how much a particular property varies across the surface. Having the average thickness at the target value can mask significant deviations at the edges. The specification should clearly state which points are measured and which formula is used to report the deviation.

Synthetic example: The target is a 100 nm film, and measurements are taken at five points, resulting in values of 90, 95, 100, 105, and 110 nm. The average is exactly 100 nm, and the range is 20 nm. The statement "The thickness matches the target" is only true based on the average. If the product requires 98-102 nm at each point, this film would not be accepted. The same numbers will yield different decisions with different acceptance criteria.

The **sample package** encompasses the measurement question along with information on identity, structure, size, expected signal, storage, and processing history. Unknown content or inadequate preparation will affect both device conformity and the outcome.

The **scope of collaboration** defines which party will provide which task and which data. Contractual details, such as confidentiality and intellectual property rights, are project-specific; here, we address how the technical work package should be defined.

Comprehension check: Did you purchase the measurement, and did you receive the explanation?

The raw signal, processed result, used model, and uncertainty can be provided separately. Before collaboration, specify which of these you require. If a mechanism is claimed, also indicate whether a single measurement is sufficient to distinguish it; do not use the device name as a guarantee of the result.

A PV program does not necessarily need to encompass all tools within its own infrastructure. The correct infrastructure is one that can test the research question in a timely and reliable manner. An expensive characterization device will not answer the question if the sample is improperly prepared. Conversely, a well-chosen external measurement can prevent months of incorrect optimization. This section teaches readers to view institutions not just as lists of names, but as entities with functions within the development chain.

Instead of asking about the institution's name, inquire about its capabilities

A laboratory's publication of high-efficiency cells does not necessarily mean that it provides the same service to every external sample. Research partnerships, paid measurements, technology licensing, and equipment access are separate models. Before starting a project, the type of sample to be measured, the area, the expected accuracy, the raw data to be delivered, and the scope of the report should be documented. A publicly available promotional page is an indication of capability; the current acceptance conditions for a specific service are verified separately.

Fraunhofer ISE's PV-TEC infrastructure serves to bridge the gap between laboratory findings and production; the CalLab and TestLab families assume distinct roles in measurement and testing activities. It is important not to reduce these roles to a single "certification laboratory" heading. [D42] The perovskite tandem group at HZB, along with PVcomB activities, represents research examples that link material and device development to scale-up and characterization issues. [D43]

CSEM's solar research is related to the challenges of transitioning from device concepts to industrial applications; the historical tandem studies conducted in collaboration with EPFL are examples of this connection. [D44] The thin-film research conducted within the Imec/EnergyVille and Solliance ecosystems is relevant to coating and module integration. It should not be assumed that the future date on an old roadmap is being realized today. [D45]

The National Laboratory of the Rockies, previously known as NREL in earlier publications, conducts PV material and device research, addressing performance and reliability together. In the bibliography, the institution name of the older article is preserved in its historical form. [D46] Empa's thin-film and photovoltaic laboratory explores different absorber and flexible substrate approaches. [D47] UNSW's PV Manufacturing educational resources are useful for learning about silicon production processes; however, a single educational page is not a current and complete copy of the commercial recipe. [D06] [D08]

Describing the equipment based on the process output

The purchase order or service specification should not begin with the device's marketing name. The target output should be specified: which substrate, which area, which layer, which homogeneity, which process temperature, which repeatability? Then, it should be asked under what conditions the equipment produces this output. The best specifications obtained in a vacuum chamber may differ from the behavior of a real sample and under a full production load.

Equipment family	Example supplier and source	Focus of the acceptance test
PVD and vacuum coating.	VON ARDENNE [D49]	Optical/electrical quality and homogeneity on the actual substrate.
Diffusion, PECVD, thermal processing.	centrotherm [D50]	Process distribution and subsequent cell outcome at full load.
Wet chemical surface treatment.	RENA [D51]	Texture, cleanliness, chemical consumption and lot stability
Laser micromachining.	InnoLas Solutions [D52]	Target layer selectivity, damage, and electrical isolation.

These examples do not represent a ranking of supplier recommendations. VON ARDENNE's PV coating solutions, centrotherm's thermal and coating equipment, RENA's wet surface treatment systems, and InnoLas's laser solutions serve different functions. A provider's general technology datasheet does not indicate that a specific recipe will be provided with a license or that a target performance will be guaranteed.

Factory acceptance and on-site acceptance

During equipment acceptance, simply observing mechanical movement or nominal speed is not sufficient. Representative samples should be coated or processed, and pre-defined criteria should be verified through independent measurements. Acceptance at the equipment manufacturer's facility differs from acceptance at the user's facility, as it is conducted under different conditions. Factors such as gas, water, electricity, exhaust, vibration, and environmental differences can have an impact.

Acceptance samples are not selected solely from the ideal region of the equipment. The beginning, middle, and end of the charge carrier, different locations, and multiple cycles are measured. The initial condition after maintenance or cleaning is separated from the stable production condition. Even if the thickness homogeneity is good, the cell power distribution may be poor; verification extending to the electrical output is required. It must be clearly stated which criterion is the responsibility of the device, which is the responsibility of the recipe, and which is the responsibility of the user sample.

Sample package for measurement services

The technical documentation to be sent to the external laboratory includes the sample ID, architecture, measurable area, contact arrangement, expected current/voltage, specific environmental conditions, and desired measurement. The surface of the sample that needs protection and the transportation conditions are specified. The duration a perovskite cell is kept in the dark or the bias under which a tandem cell is measured can affect the results. This information is not left to the general term "standard solar cell."

The required deliverables must also be specific: raw J-V file, stable power series, temperature and irradiance log, area definition, calibration chain, uncertainty, and pre-measurement conditioning. The final efficiency percentage alone is insufficient for research diagnostics. Measuring the same sample before and after it is sent to the laboratory helps to assess the impact of transportation or time.

Information and scope of the collaboration

A measurement service differs from a new process development service. In a collaborative research project, the objectives, work packages, samples to be used, and deliverables are specified. Existing knowledge is separated from new knowledge generated during the study. Confidentiality and intellectual property agreements are prepared based on the specific contributions of the parties; this book is not a legal contract template.

The technical scope should not be written as a guarantee of success. “Producing a specific number of controlled samples and delivering the following measurements” is a verifiable work package. “Developing a world-record cell” alone is not a work plan. It is also required to report negative results, failed samples, and conditions that deviate from the process. This ensures that the research service does not simply become the delivery of only positive results.

Prioritization when establishing infrastructure

Initially, sample traceability, reliable electrical measurements, and simple optical inspections are of high importance. Subsequently, depending on the dominant uncertainty of the research, lifetime, surface analysis, microscopy, or advanced spectroscopy are added. For each device, the expected frequency of use, operator proficiency, calibration, maintenance, and the need for sample preparation are considered. For low usage, outsourcing may be more efficient; daily measurements requiring rapid feedback can be performed in-house.

Assignment. You have only a solar simulator and an optical microscope available for an HJT contact project. Which measurements would you perform in-house, and which would you outsource to an external laboratory? Justify your answer based on the hypotheses you will test and the expected turnaround time, not on the reputation of the equipment. Write a one-page sample and delivery description for the first outsourced measurement.

BOOK II · CHAPTER 18 / COMPANIES AND RESEARCH PROGRAMME

Research program: three cases, decision gates and worksheets

The outcome of a research program should be a decision

This final section applies the previous methods to three case studies. A **case study** is an example of a study built around a specific initial dataset and problem. A **decision gate** specifies the evidence required to proceed to the next step. If the **continue**, **modify**, and **stop** options are defined from the beginning, it becomes more difficult to change the criteria after the results are observed. The goal is not to achieve positive results in every experiment, but to learn which approach works and why.

First, a **baseline** is established: what distribution did the current process yield across multiple independent production runs? Then, the **intervention**, i.e., the process to be changed, is determined. Next, a **discriminating measurement** is selected to observe how competing factors will behave differently. Finally, the **acceptance criterion** is evaluated, taking into account the uncertainty of the gain and the production cost. This sequence transforms the pursuit of only the best cell into a comprehensive process development.

Which thinking habit do the three cases exercise?

In the TOPCon case, while the voltage increases, the power may not; we differentiate between contact and transport losses. In the large-area perovskite case, the success of small cells may not be transferable to large areas; we investigate homogeneity, line defects, and connectivity. In the newly calculated absorber case, a candidate with good electronic properties may fail the phase-stability or defect-validation criteria; we differentiate between the calculated result and the experimental device. All three investigate the same evidence discipline, but not necessarily the same physical problem.

Synthetic decision example: Suppose the new method increases the average power by 1%, but decreases the acceptance rate from 95% to 85%. The method can be rejected based on the target value per product, or it can be investigated only for a specific sub-application. The loss in acceptance is not concealed by stating, “There is a positive efficiency result.” If the control and the new method were produced on different days, it is first reassessed whether this comparison is sufficient.

Pre-experiment record: This involves writing down the hypothesis and analysis before the data is observed. **Process card:** This tracks the steps the sample undergoes. **Result card:** This distinguishes between the observed data and the inferences and limitations derived from it. **Transfer card:** This indicates which conditions of the method taken from the literature have been transferred to your system. The forms below should be used as a record of the thought process for the case, not as blank documents.

Comprehension check: How do you know when the program has finished?

“There are no more experiments to be done” is often not a realistic criterion. Sufficient evidence that answers the initial question, independent verification that the target has been achieved, or a definitive negative result that eliminates a path can serve as a completion criterion. In the final report, list the answered question separately from the remaining unanswered question; carry only the latter forward to the next stage.

This final section connects the methods to a practical research framework. The following case studies are illustrative and synthetic; they are not based on experiments that have been conducted or verified new products. The goal is to understand which observation necessitates which subsequent step. Durations depend on equipment, sample availability, and laboratory capabilities; decision points precede the timeline.

Gate 0: Are we working on the right question?

The program begins with a product and a physical bottleneck. An example target could be to increase the full module power of an existing silicon cell by an amount greater than the measurement uncertainty. The statement “increase efficiency” alone is not sufficient. The initial recipe is written, including the area, test condition, acceptance distribution, and expected magnitude of the effect. It is determined which resources can be used and which processes will be outsourced.

The output of this stage is a brief target card. Known parameters, assumptions, and missing measurements are listed separately. If the reliability of the initial data is lacking, the process does not proceed directly to the synthesis of new material; instead, a reference and measurement infrastructure is established first. The success of the initial step is not high efficiency, but rather the measurability of the problem and the initial state.

Gate 1: Can the reference be reproduced?

The reference is applied to at least one or more independent production batches. Multiple cells on the same substrate demonstrate intra-batch variation; this does not substitute for independent production repetitions. A device control sample is included on each measurement day. Raw data, out-of-specification samples, and reasons for exclusion are recorded. It is difficult to interpret small gains without knowing the mean and distribution of the reference.

If measurement repeatability is sufficient but the production spread is large, the process sources are investigated. If production is good but the device-to-device variation is large, calibration and area definition are checked. These two issues require different solutions. Once the reference is stabilized, the variation experiment is performed; if the reference changes later, a new version is initiated.

Case A: In TOPCon cells, the voltage increases, but the power does not

Synthetic start. In the reference cell, let the short-circuit current be 40.0 mA/cm^2, the open-circuit voltage be 0.720 V, and the fill factor be 0.820. The new passivation condition increases the voltage to 0.730 V, reduces the fill factor to 0.805; the current remains unchanged. At an input of 100 mW/cm^2, the efficiencies are 23.616% and 23.506%, respectively. The higher voltage alone did not result in higher power.

The first explanation is that passivation improves, but contact resistance increases. The second explanation is that the pre-contact gain is lost during metallization, or a new leakage current is created. The third explanation is that the observed voltage difference remains within the production distribution. All of these explanations do not require the same additional data.

Discrimination experiment. The reference and new interface are manufactured in the same batch and cross-compared using two metallization conditions. Contact-before lifetime or implied voltage, TLM, dark J-V, and steady-state power are measured. If the contact-before gain of the new interface is repeatable and a more suitable metallization restores the fill factor (FF), the process mismatch hypothesis is strengthened. If the gain is absent in an independent batch, repeatability is addressed first.

Decision gate. The new condition must demonstrate a net power gain, not only in the good cells but also in the pre-selected sample group; contact and aging results must remain within acceptable limits. Threshold values are selected based on the product requirements prior to the experiment. A universal mV or percentage threshold is not defined for this case.

Case B: Small perovskite cells perform well, but large-area cells perform poorly

Synthetic beginning. 0.1 cm^2 cells exhibit a high and narrow power distribution; 25 cm^2 mini-modules exhibit a lower and wider distribution. It is premature to attribute the entire decline to “perovskite instability.” Coating homogeneity, critical defects, the P1-P2-P3 area, lateral resistance, and package damage are separate candidate causes.

Initial inspection. Small cells are prepared from different locations on the large coating. If the small cells also degrade on the same film, a coating or film issue is likely. If the small cells are good, but the monolithic module is bad, connection and area losses are more likely causes. This distinction directly influences the next experiment.

Comparative experiment. The coating direction is correlated with the PL, thickness, and visual defect map, along with edge and center positions. Scratch isolation and contact resistance are measured on separate samples. The active and aperture area efficiencies of the module are provided together. Power is monitored before and after packaging, preferably on the same samples. The light and temperature history of the sample is maintained at each step.

Decision gate. Before changing the coating method, the dominant loss is localized. If the problem is residual scratches, screening a new absorber composition has low informational value. If the problem is a drying difference along the line, simply changing the cell contact is not sufficient. A large-area target remains a separate performance metric alongside the small-cell record.

Case C: newly calculated absorber candidate

Synthetic beginning. The calculation predicts a suitable band gap and high ideal optical performance. Phase stability has been investigated within a limited set of competing phases; defect passivation and real contacts are not yet known. This could be a worthwhile candidate for further research, although it is not a measured PV device.

Cheapest discriminating sequence. First check computational convergence and coverage of competing phases. Then a small-scale synthesis or growth study tests whether the target phase exists. If it forms, measure optical absorption, chemical stability and basic electrical behavior. Next evaluate photoresponse and charge collection with a simple contact structure. Each stage includes a control that distinguishes the source of failure.

Decision gate. If the target phase is not consistently achieved or if the required processing condition is incompatible with the substrate, the route is changed before proceeding to the full cell optimization. If a candidate is terminated, the reason and the tested conditions are saved. “Not tried” and “failed under these conditions” are distinct types of information. A negative result simplifies the subsequent candidate selection.

A work schedule that can be converted into weeks

The following schedule is not a guarantee; each step must be completed before moving on to the next. If the equipment is ready, the process may take a few weeks; if external services or a new process are required, it may take longer.

Stage	Work	Tangible output.
Start	Selection of literature and references.	Source records, target specification, loss budget
Measurement	Calibration and repetition.	Uncertainty budget, reference control series.

Stage	Work	Tangible output.
Reference	Independent batches	Recipe version, distribution, and failed samples.
Intervention	Controlled factorial study	Effects, interactions, and mechanism measurements.
Approval	New batch and independent measurement.	Reproduced gain or an explicit negative result
Transfer	Area and packaging.	Pilot flow, CTM, and durability file.

Form 1: Pre-experiment record

Research question: Which physical loss should be minimized? Which result would weaken this hypothesis?

Reference: What is the sample architecture, recipe version, raw material lot, and measurement protocol?

Intervention: Which factors are changing? Which factors are kept constant? Is there a control group that does not contain the active ingredient but undergoes the same processing?

Procedure: What is the experimental unit? How were the independent groups, blocks, randomization, and sample size selected?

Answer: What is the primary output and the measurement time? How should steady-state power, area, and uncertainty be reported?

Decision: Which pre-defined condition determines whether the process continues, repeats, changes course, or stops?

Form 2: sample traveler card

The sample tracking card records the sample's identity and history throughout the production process. Each row contains information such as time, process, equipment, recipe version, operator or automated record, input control, and output control. If a deviation occurs, it is recorded not only in the final report but also at the moment it happens. If the same sample is reprocessed, the previous steps are not deleted.

Area	Information to be recorded.
Identity	Program, batch, substrate, cell/module code.
Material	Supplier, lot, certificate of purity, storage history.
Process	Actual time/temperature/flux and equipment record
Wait.	Environment, light, humidity, and duration.

Area	Information to be recorded.
Measurement	Raw file, calibration, area, condition.
Deviation	Unexpected event, reason for exclusion, decision.

Form 3: Results and Evidence Card

The first sentence of a results card states the scope: “In this architecture, under these measurement conditions, and with these independent batches, the following difference was observed.” This is followed by the effect size, uncertainty, distribution, and control results. The mechanism interpretation is provided in a separate paragraph. It is stated which of the alternative explanations were eliminated and which remained open. The final sentence describes the next differentiating experiment.

The raw data files, analysis version, sample list, and sources are attached to the results card. Only screenshots are not provided. The reproduction package should ensure that another researcher can generate the same table from the same data. If the data has been corrected, the old version and the reason for the change are preserved.

Form 4: Transfer card from the literature

The article title, DOI or permanent link, and access scope are recorded. Device structure, area definition, measurement conditions, steady-state power, sample size, and aging method are recorded as separate fields. If the details of an inaccessible method are unavailable, they are not filled in with estimations. It is stated which mechanism the study supports and in what aspects the results differ from those obtained with your sample.

In a company announcement, the same card includes information on the product or pilot status, the date of the announcement, and the scope of independent verification. Resources need to be updated regularly; however, an up-to-date record table does not replace the learning of fundamental physics and methods. When these two books are used together, the first book provides the rationale, and the second book provides measurable steps for improvement. The test of learning is the ability to explain why a particular experiment was chosen in response to a new problem.

Book II · References and access notes

D codes identify methodological and infrastructure sources; C codes identify company sources. Company statements are not the same type of evidence as independent experimental validation. Access to a catalogue does not imply that the full text of a standard was reviewed.

[D01] Solar Photovoltaic Manufacturing Basics
U.S. Department of Energy (2021).
https://www.energy.gov/cmei/systems/solar-photovoltaic-manufacturing-basics
A corporate training resource regarding the wafer and thin film production chain; the page content was reviewed.

[D02] Photovoltaics Report, 14 July 2026
Fraunhofer ISE; PSE Projects (2026).
https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/photovoltaics-report.html
Official publication page for the current report. Used for market and technology context; separate performance categories are maintained.

[D03] Snapshot of Global PV Markets 2026: Fact Sheet
IEA PVPS (2026).
https://iea-pvps.org/fact-sheets/fs-snapshot-2026/
The 2026 publication regarding the 2025 end-of-year market indicates that capacity and shipments are not the same.

[D04] Status and perspective of industrial TOPCon solar cell development at Fraunhofer ISE
S. Mack and others. (2022).
https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/conference-paper/wcpec-8/Mack_1AO63.pdf
An open-access, six-page conference paper was reviewed. It describes the process of a specific research approach; it is not a universal fabrication recipe.

[D05] ForTeS: Passivated Contacts for High-Efficiency Silicon Solar Cells
Fraunhofer ISE (undated).
https://www.ise.fraunhofer.de/en/research-projects/fortes.html
This is the project page where the institution presents its own TOPCon research. The historical experiments were not presented as the current production record.

[D06] Alkaline texturing
UNSW / PV-Manufacturing.org (undated).
https://pv-manufacturing.org/alkaline-texturing/
Educational page on crystal orientation, texture, and wetting; previous market share data was not used.

[D07] Diffusion basics; tube diffusion
UNSW / PV-Manufacturing.org (undated).
https://pv-manufacturing.org/solar-cell-manufacturing/diffusion-basics/
A basic explanation of diffusion. The sign error in the second Fick's law, as presented on the source page, was not carried over; instead, the physical diffusion equation with a positive D was used in the book.

[D08] Cz Monocrystalline Silicon Production
UNSW / PV-Manufacturing.org (undated).
https://pv-manufacturing.org/silicon-production/cz-monocrystalline-silicon-production/
CZ and impurity segregation were used; the historical market percentages on the page were not taken as current data.

[D09] Only 4 Steps! Witness the Birth of a Huasun Heterojunction Solar Cell
Huasun (2024-05-09).
https://www.huasunsolar.com/news/only-4-steps-witness-the-birth-of-a-huasun-heterojunction-solar-cell.html
The manufacturer’s description of the main process groups. Marketing language and efficiency claims were not considered as independent verification.

[D10] Silicon heterojunction solar cell with interdigitated back contacts for a photoconversion efficiency over 26%
K. Yoshikawa and others. (2017).
https://www.nature.com/articles/nenergy201732
The publisher's summary and the article record were reviewed; this provides a historical example of the combination of HJT and IBC technologies.

[D11] Low-loss contacts on textured substrates for inverted perovskite solar cells
S. M. Park and others. (2023).
https://www.nature.com/articles/s41586-023-06745-7
The publisher's summary, figure captions, and data access note were reviewed; the full text available through subscription was not considered to be fully reviewed.

[D12] Efficient planar heterojunction perovskite solar cells by vapour deposition
M. Liu; M. B. Johnston; H. J. Snaith (2013).
https://www.nature.com/articles/nature12509
Based on the publisher's summary, an early vacuum deposition process was demonstrated; however, the specific recipe was not disclosed.

[D13] Surfactant-controlled ink drying enables high-speed deposition of perovskite films for efficient photovoltaic modules
Y. Deng et al. (2018).
https://www.nature.com/articles/s41560-018-0153-9
The publisher's summary was reviewed. The results for small cells and modules with different aperture areas were analyzed separately.

[D14] Choosing an experimental design
NIST/SEMATECH (undated).
https://www.itl.nist.gov/div898/handbook/pri/section3/pri3.htm
Framework for selecting the design of experiments. The PV examples in the book are original educational designs.

[D15] What is Process Capability?
NIST/SEMATECH (undated).
https://www.itl.nist.gov/div898/handbook/pmc/section1/pmc16.htm
The process stability, distribution, and capability indices were used for the assumptions.

[D16] Gauge R&R studies
NIST/SEMATECH (undated).
https://www.itl.nist.gov/div898/handbook/mpc/section4/mpc4.htm
The framework for measurement repeatability and reproducibility is specific to the photovoltaic measurement design presented in this book.

[D17] Consensus statement for stability assessment and reporting for perovskite photovoltaics based on ISOS procedures
M. V. Khenkin and others. (2020).
https://www.nature.com/articles/s41560-019-0529-5
The open-circuit agreement was used to determine the operating condition, MPP, and to differentiate between internal and external stress.

[D18] Degradation and Failure Modes in New Photovoltaic Cell and Module Technologies
IEA PVPS Task 13 (2025).
https://iea-pvps.org/key-topics/degradation-failure-modes-new-cell-module-technologies/
Official report page and summary. The diagnostic tables in the book do not provide a definitive diagnosis for individual faults.

[D19] IEC 60904-1-1:2017
IEC (2017).
https://webstore.iec.ch/en/publication/29335
The official catalog scope was reviewed; not all clauses of the paid standard were copied or considered as reviewed.

[D20] IEC 60904-9:2020
IEC (2020).
https://webstore.iec.ch/en/publication/28973
The official scope of the simulator classification does not imply that the class certificate signifies zero spectral error for a specific device.

[D21] IEC 61215-1:2021
IEC (2021).
https://webstore.iec.ch/en/publication/61345
The scope of design qualification includes the statement that the tests do not provide a quantitative lifetime prediction.

[D22] IEC 61730-1:2023
IEC (2023).
https://webstore.iec.ch/en/publication/59803
Official scope regarding the safety adequacy of the module structure.

[D23] IEC TS 62915:2023
IEC (2023).
https://webstore.iec.ch/en/publication/66172
The scope regarding re-testing evaluations for design or material changes will be specified in the July 2024 revision of the catalog.

[D24] Phase Diagrams (PDs)
Materials Project (Accessed in 2026).
https://docs.materialsproject.org/methodology/materials-methodology/thermodynamic-stability/phase-diagrams-pds
Definition and scope of the phase envelope.

[D25] SCAPS: Solar Cell Capacitance Simulator
Ghent University / Marc Burgelman (Accessed in 2026).
https://scaps.elis.ugent.be/
Official tools and algorithms are not a means of experimentally verifying the software output.

[D31] Large Area TOPCon Cells Realized By a PECVD Tube Process
F. Feldmann and others. (2019).
https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/conference-paper/36-eupvsec-2019/Feldmann_2EO14.pdf
Open conference paper; specific experimental example related to annealing/hydrogenation and contact measurement.

[D32] Silicon heterojunction solar cells with up to 26.81% efficiency achieved by electrically optimized nanocrystalline-silicon hole contact layers
H. Lin et al. (2023).
https://www.nature.com/articles/s41560-023-01255-2
An open-access article, focusing on the results and methods sections, was analyzed. It was confirmed that the highest fill factor (FF) and highest efficiency were obtained from different cells.

[D33] The first demonstration of entirely roll-to-roll fabricated perovskite solar cell modules under ambient room conditions
H. C. Weerasinghe et al. (2024).
https://www.nature.com/articles/s41467-024-46016-1
Openly accessible primary research; the 11% module result with approximately 50 cm^2 of active area was not treated as comparable to a small-area record.

[D34] Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency
Sahli et al. (2018).
https://www.nature.com/articles/s41563-018-0115-4
The publisher's summary and figure captions were accessed; the complete methodology text behind the subscription was not considered for review.

[D35] Highly Efficient Perovskite Solar Modules by Scalable Fabrication and Interconnection Optimization
M. Yang et al. (2018).
https://pubs.acs.org/doi/10.1021/acsenergylett.7b01221
Publisher's summary and supporting information description; an example of the distinction between interconnection resistance and area definition.

[D36] Doping with phosphorus reduces anion vacancy disorder in CdSeTe semiconductors enabling higher solar cell efficiency
Kuciauskas et al. (2025).
https://www.nature.com/articles/s41467-025-63589-7
Open access original study. The potential of 25% in the model was separated from the measured 20.2%.

[D37] High-concentration silver alloying and steep back-contact gallium grading enabling copper indium gallium selenide solar cell with 23.6% efficiency
Keller et al. (2024).
https://www.nature.com/articles/s41560-024-01472-3
Open-access original study; certified 23.64%, Uppsala team. No claim of a new record was made.

[D38] Products and manufacturing technology
AZUR SPACE (Accessed in 2026).
https://www.azurspace.com/en/products/
MOVPE and the III-V compound family are not equivalent when comparing space AM0 conditions with terrestrial AM1.5G conditions.

[D39] Equally high efficiencies of organic solar cells processed from different solvents reveal key factors for morphology control
Zhang et al. (2024 online; 2025 journal volume).
https://www.nature.com/articles/s41560-024-01678-5
An example of an open-access method: molecule-solvent interactions and morphology.

[D40] Mixed-quantum-dot solar cells
Yang et al. (2017).
https://www.nature.com/articles/s41467-017-01362-1
An example of an open-access historical method; it was not presented as the current record.

[D41] Orthogonal colloidal quantum dot inks enable efficient multilayer optoelectronic devices
Authors of the original paper (2020).
https://www.nature.com/articles/s41467-020-18655-7
The publisher search excerpt was accessed; a direct-opening error prevented detailed methods or record performance values from being incorporated.

[D42] PV-TEC: Photovoltaic Technology Evaluation Center
Fraunhofer ISE (Accessed in 2026).
https://www.ise.fraunhofer.de/de/fue-infrastruktur/tecs/pv-tec.html
The definition of corporate infrastructure does not assume the acceptance of any specific external service.

[D43] Perovskite Tandem Solar Cells
Helmholtz-Zentrum Berlin (Accessed in 2026).
https://www.helmholtz-berlin.de/forschung/oe/se/perovskite-tandemsolarcells/index_de.html
Official research group definition.

[D44] Corporate highlights 2025
CSEM (2025).
https://www.csem.ch/en/annual-report/2025/corporate-2025/
In the context of solar research and technology transfer to industry, historical collaborative projects were reviewed, specifically D34.

[D45] The tandem module, a unique opportunity to reboost EU PV industry
imec (2020).
https://www.imec-int.com/en/imec-magazine/imec-magazine-june-2020/the-tandem-module-a-unique-opportunity-to-reboost-eu-pv-industry
The historical institutional approach/roadmap did not consider future targets as having been achieved.

[D46] Materials and Devices: Photovoltaic Research
National Laboratory of the Rockies (Accessed in 2026).
https://www.nlr.gov/pv/materials-devices
The current institutional website; in older publications, the name NREL is preserved in its historical form.

[D47] Laboratory for Thin Films and Photovoltaics
Empa (Accessed in 2026).
https://www.empa.ch/en/web/s207
Areas of corporate research.

[D49] Photovoltaics coating systems
VON ARDENNE (Accessed in 2026).
https://vonardenne.com/fileadmin/user_upload/brochures/VA_Photovoltaics/VONARDENNE_PV_eng.pdf
This is an official equipment brochure; it does not constitute a specific performance or purchasing recommendation.

[D50] Photovoltaics
centrotherm (Accessed in 2026).
https://www.centrotherm.de/en/industry-solutions/photovoltaics
Official definition of the thermal and coating equipment families.

[D51] Green Energy
RENA (Accessed in 2026).
https://www.rena.com/en/products/green-energy
Wet chemical surface treatments; supplier ranking was not performed.

[D52] InnoLas companies and laser applications
InnoLas (Accessed in 2026).
https://www.innolas.com/
InnoLas Solutions' PV micro-processing field does not assume a specific device specification.

[D53] CalLab PV Modules
Fraunhofer ISE (Accessed in 2026).
https://www.ise.fraunhofer.de/en/rd-infrastructure/accredited-labs/callab/callab-pv-modules.html
The institutional definition of the module calibration laboratory encompasses the scope and uncertainty, which depend on the sample condition.

[C01] Hi-MO X10 module featuring HPBC 2.0 cell technology
LONGi (2024-10-14).
https://www.longi.com/en/news/longi-hpbc-2-new-product-hi-mo-x10-launch/
Product launch: HPBC 2.0, manufacturer's performance claims. Company comparisons were not considered as independent results.

[C02] N-Type ABC Technology
AIKO (undated).
https://aikosolar.com/en/techbreakthroughs/
Company statement on ABC, back contacts and silver-free metallization; dated roadmap items must be read in the context of their respective years.

[C03] Second Quarter 2026 Financial Results
JinkoSolar (2026).
https://ir.jinkosolar.com/news-releases/news-release-details/jinkosolar-announces-second-quarter-2026-financial-results
The capacity target for TOPCon 3.0 by the end of 2026 has been designated as a forward-looking statement and is not considered realized production.

[C04] Trinasolar Advances TOPCon 2.0 Era With Global Delivery
Trinasolar (2025).
https://www.trinasolar.com/us/resources/newsroom/Trinasolar-Advances-TOPCon-2.0-Era-With-Global-Delivery/
Vertex N / TOPCon Ultra product and delivery description; the individual record was not equalized with the production average.

[C05] 2024 Annual Report of JA Solar Technology Co., Ltd.
JA Solar (2025).
https://disc.static.szse.cn/disc/disk03/finalpage/2025-06-27/3270832f-a5b8-4d88-a684-be133b31da39.PDF
The activity report from the official stock exchange archive was used for the Bycium+ and DeepBlue 5.0 product lines.

[C06] REC Alpha Pure-RX
REC Group (undated).
https://www.recgroup.com/en/rec-alpha-pure-rx
HJT residential module and interconnection design. Warranty conditions were not presented as measured field lifetime.

[C07] Huasun HJT products and manufacturing
Huasun (Accessed in 2026).
https://www.huasunsolar.com/
The HJT product family and the manufacturer's capacity/shipment statements were reviewed, covering 2026 pages.

[C08] New-generation TNC high-efficiency cell manufacturing technology
Tongwei (2026-06-05).
https://www.tongwei.com/news/detail/170975.html
The TNC 3.0 product page on the manufacturer's website describes edge passivation and patterning; the promotional claims listed in the source are not independently verified.

[C09] 2025 Annual Report
First Solar (2026).
https://s202.q4cdn.com/499595574/files/doc_events/2026/May/13/FSLR-2025-Annual-Report-web.pdf
The technology and production-related sections of the 143-page report were reviewed; the CuRe dissemination plan was not considered a completed global transformation.

[C10] Perovskite tandem panels: first commercial shipment
Oxford PV (2024-09-05).
https://www.oxfordpv.com/press-releases/oxford-pv-solar-technology-patent
The company's initial announcement regarding commercial shipments did not include the total production volume or evidence of decades of field testing.

[C11] Key Tandem Solar Module Stability Milestone
Qcells (2025-05-14).
https://us.qcells.com/blog/qcells-achieves-key-tandem-solar-module-stability-milestone/
Test description for M10-based pilot line modules; this does not constitute proof of series shipment or full lifetime.

[C12] GW-Scale Perovskite Industrial Base Commences Production in Kunshan
GCL Technology (2025-06-24).
https://www.gcltech.com/en/about/newsinfo/973.html
The company announcement regarding the commissioning of the production facility states that the capacity indicated on the nameplate is not the actual annual yield of good products.

[C13] Silicon Today, Tandems Tomorrow
Swift Solar (2026-03-12).
https://www.swiftsolar.com/news/silicon-today-tandems-tomorrow
The acquisition of Meyer Burger's production assets and intellectual property; the US factory and tandem expansion were planned as separate projects.

[C14] Roll-to-Roll Series Production
Heliatek (Accessed in 2026).
https://www.heliatek.com/en/technology/roll-to-roll-series-production/
Continuous production flow using vacuum evaporation for organic PV. Declared capacity does not represent actual production.

[C15] Completion of the G12R TOPConPlus solar cell investment.
Kalyon PV (2026-05-07).
https://www.kap.org.tr/tr/Bildirim/1602169
The company’s announcement on KAP: the commissioning of the production line and the commencement of production were not interpreted as realized annual capacity.

[C16] Acceptance of the entire Niğde Bor Solar Power Plant; use of panels with domestically produced cells.
Smart Güneş Teknolojileri (2026-03-10).
https://www.kap.org.tr/en/Bildirim/1569417
Smart Güneş’s company statement indicates local cell and panel production in Aliağa; however, it differs from the previous report, which only mentioned module compatibility.

[C17] Explanation regarding showroom agreements and production infrastructure in the USA.
CW Enerji (2026-08-12).
https://www.kap.org.tr/tr/Bildirim/1648411
The company’s identity was verified on a full page: CW Energy. The first phase was separated from the second phase, which involved the capacity decision.