

## SHADING-TOLERANT COLORED FAÇADE BIPV MODULES USING BACK-CONTACT CELLS WITH INTEGRATED BYPASS PROTECTION

Marcus Baeckmann)  
 INVITAIC – Invisible Photovoltaic  
 go@invitaic.ch  
 Jiangnan Road 2, Yuhuatai District, Nanjing, China

**ABSTRACT:** Façade-integrated photovoltaics (BIPV) are increasingly recognized as a key contributor to net-zero energy buildings in dense urban environments. However, vertical PV installations are particularly exposed to complex and dynamic shading conditions, leading to disproportionate power losses, accelerated material degradation, and increased system complexity. This paper presents a shading-tolerant colored façade BIPV module platform developed by INVITAIC, based on advanced back-contact (BC) monocrystalline cells with integrated on-cell bypass protection. By embedding shading resilience at cell level, the system significantly reduces energy losses under partial shading while eliminating the need for module-level optimizers or micro-inverters. Combined with color-matched glass laminates, the approach enables architecturally integrated PV façades that behave more like conventional building materials—robust, predictable, and easy to plan. Laboratory measurements and field observations indicate energy yield improvements of 15–25% in shaded façade applications, while simultaneously reducing planning effort, system cost, and lifetime risk.

**Keywords:** Shading Effects, BIPV facades, High-efficiency cells, Color PV, Degradation mechanisms, Module design

### 1 INTRODUCTION

Building-integrated photovoltaics are transitioning from niche architectural elements to core components of urban energy systems. As roof areas in cities become increasingly constrained, façades represent a largely untapped surface for solar electricity generation. At the same time, façade applications impose fundamentally different boundary conditions compared to roof-mounted PV, particularly with respect to shading, orientation, and aesthetic integration.

Unlike rooftops, façades are subject to permanent and transient shading caused by balconies, neighboring buildings, vegetation, and urban infrastructure. Even geometrically simple buildings exhibit complex shading patterns throughout the day and year. Conventional crystalline silicon PV modules react poorly to such conditions, suffering from severe mismatch losses, hotspot formation, and accelerated aging.

This contribution presents a BIPV module platform that addresses shading not at system level, but intrinsically at cell level. By combining back-contact cell architecture with integrated bypass functionality and colored glass laminates, INVITAIC aims to make façade photovoltaics electrically robust, visually adaptable, and economically predictable.

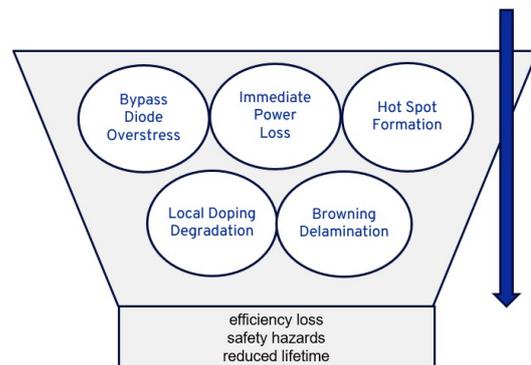
### 2 BACKGROUND: SHADING AS A SYSTEMIC LIMITATION IN FAÇADE BIPV

#### 2.1 Shading Effects in Conventional PV Modules

In standard front-contact PV modules, cells are connected in long series strings. Partial shading of a single cell forces it into reverse bias, causing immediate power loss and local heating. While module-level bypass diodes limit catastrophic failure, they operate at string level and do not prevent localized thermal stress within the cell.

Repeated shading cycles initiate a cascade of degradation mechanisms, including encapsulant

browning, delamination, solder joint fatigue, and diode overstress. Over time, these effects reduce efficiency, compromise electrical safety, and shorten module lifetime.



**Figure 1:** Shading triggers a cascade of degradation effects over time, finally reducing the performance of the module and increasing safety hazards

#### 2.2 Planning and Cost Implications

To mitigate shading losses, conventional BIPV systems often rely on power optimizers, micro-inverters, and detailed 3D shading simulations. While effective, these measures increase system complexity, component count, and interface effort between architects, planners, and electrical engineers. In high-labor-cost regions, engineering and coordination costs increasingly dominate total system cost, offsetting the declining price of PV modules.

### 3 TECHNOLOGY PLATFORM: BACK-CONTACT CELLS WITH INTEGRATED SHADING PROTECTION

#### 3.1 Evolution of Shading-Tolerant Cell Architectures

INVITAIC builds upon technology developed within the AE Solar Group. Early shading-robust modules employed discrete surface-mounted bypass diodes on each cell, significantly improving partial shading

behavior compared to conventional designs. This approach demonstrated the feasibility of distributing bypass functionality beyond the module junction box.

The current generation advances this concept further by integrating bypass structures directly into the semiconductor architecture of back-contact cells. Local parallel current paths are formed via engineered P/N junction arrangements on the rear side of the cell.

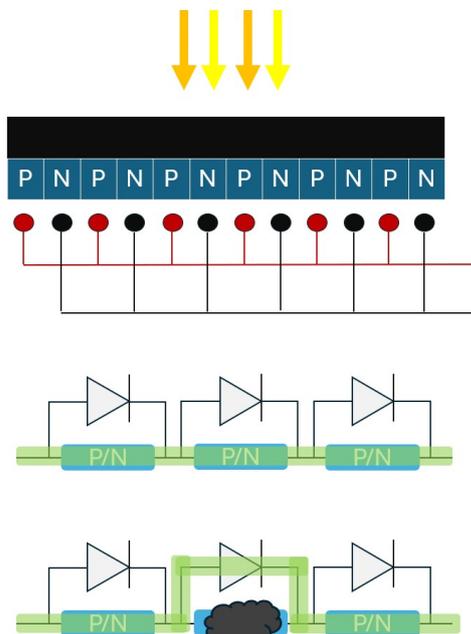
### 3.2 Functional Principle

In normal operation, current flows uniformly through the back-contact grid without front-side metallization. Under partial shading, the locally shaded region activates its embedded bypass path, allowing current to circumvent the affected area without forcing the cell into destructive reverse bias.

This distributed protection mechanism reduces hotspot risk, stabilizes operating temperature, and preserves output under non-uniform illumination.

## 4 ELECTRICAL PERFORMANCE UNDER PARTIAL SHADING

Laboratory tests and outdoor demonstrations confirm the effectiveness of the cell-level shading concept. Under partial shading conditions of 30–50% active area obstruction, back-contact modules with integrated bypass protection retain approximately 90% of nominal output. Comparable conventional modules typically drop below 80% under identical conditions.



**Figure 3:** The backside junctions form a diode grid which allows the current to flow even with partial shadings

Field simulations across typical urban façade geometries indicate annual energy yield gains of 15–25%, depending on shading frequency and orientation. Importantly, these gains are achieved without active electronics at module or string level.

## 5 AESTHETICS AND ARCHITECTURAL INTEGRATION

Beyond electrical performance, façade PV must meet architectural expectations. Back-contact cells inherently eliminate front-side busbars, resulting in a uniform, homogeneous appearance. This visual neutrality forms an ideal substrate for colored glass solutions.

INVITAIC employs ceramic coloration and digitally printed glass layers to achieve façade-compatible surfaces resembling stone, metal, or composite panels. These layers maintain sufficient optical transmittance while visually integrating PV into the building envelope.



**Figure 3:** Especially colored BIPV gains additional aesthetics when there are no visible busbars on the front

The resulting modules can be mounted using standard façade substructures, with either visible or concealed fixations, allowing seamless integration into conventional construction workflows.

## 6 SYSTEM-LEVEL BENEFITS AND SUSTAINABILITY IMPACT

Embedding shading tolerance at cell level shifts complexity away from system design toward intrinsic material behavior. This approach reduces the need for detailed shading simulations, minimizes wiring segmentation, and eliminates active power electronics in many applications.

The reduction in components improves system reliability and simplifies maintenance, while lower engineering effort shortens project timelines. For small and medium-sized façade projects in particular, these factors significantly improve economic viability.

From a sustainability perspective, longer module lifetime and reduced balance-of-system components lower the overall environmental footprint per kilowatt-hour generated.

## 7 CONCLUSION

Shading represents one of the most persistent barriers to widespread adoption of façade-integrated photovoltaics. By addressing this challenge at the cell level rather than through external system components, INVITAIC's back-contact BIPV modules offer a fundamentally robust solution.

The combination of intrinsic shading tolerance, architectural flexibility, and simplified system design enables façade PV systems that are easier to plan, safer to operate, and more predictable over their lifetime. As cities increasingly rely on vertical surfaces for renewable energy generation, such technologies will be essential to

scaling BIPV from bespoke projects to mainstream building practice

## 8 REFERENCES

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## 9 LOGO SPACE

