Harvest the Sunshine


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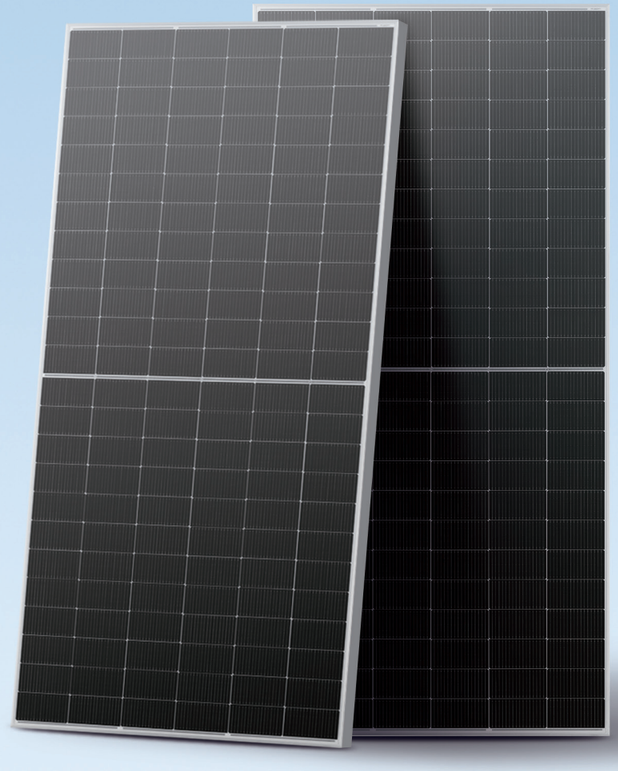
JA SOLAR | DEEP BLUE 4.0 Pro

# DeepBlue 4.0 Pro

## Technical White Paper



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# 01 / Background

## 1.1 PV module development trends

The world is actively shifting towards low-carbon transformation and green development, with new energy sources like photovoltaics (PV) at the forefront of this movement. The PV industry, driven by technology and value, is continually evolving to enhance product quality and efficiency. The synergy between quality and efficiency is fundamental, especially when considering the longevity of PV modules, which can exceed 25 years. The primary objective is to guarantee sustained, dependable, and efficient power generation. LCOE remains the definitive metric for assessing success and signifies the core value delivered to consumers.

Ensuring superior quality in advanced PV products requires adopting increasingly rigorous and expansive reliability tests. To align with emerging standards, cell and module producers are consistently pushing the boundaries through innovative R&D, encompassing new materials, processes, and product designs. To truly understand a module's reliability, performance, and stability, it's crucial to subject them to outdoor field tests across diverse climatic conditions.

Efficiency advancements are primarily realized through refining cell efficiencies, enhancing encapsulation techniques, and augmenting wafer and module dimensions. This evolution of efficiency and power can be visualized in Figure 1. Post-2016 marked a significant stride with the broad-based adoption of PERC cell technology, achieving efficiencies nearing 23% when synergized with half-cell, MBB, and SE technologies, along with high-efficiency BOM materials. By 2022, as PERC cells neared their zenith in production efficiency, TOPCon and HJT cells emerged as the new torchbearers. TOPCon cells were expedited into large-scale production, thanks to their compatibility with PERC production lines, cost-effective equipment investments, and refined processes. These cells have already achieved average efficiencies exceeding 25%. With growing market demand for these high-performance modules, a slew of efficient module technologies and materials have been introduced. Concurrently, wafer size enhancements have been instrumental in elevating module power. Transitioning from square silicon wafers to the prevalent rectangular 182*(182+X) variant, today's modules flaunt efficiencies surpassing 22% and power outputs exceeding 600W, all anchored on 182mm rectangular silicon wafers.





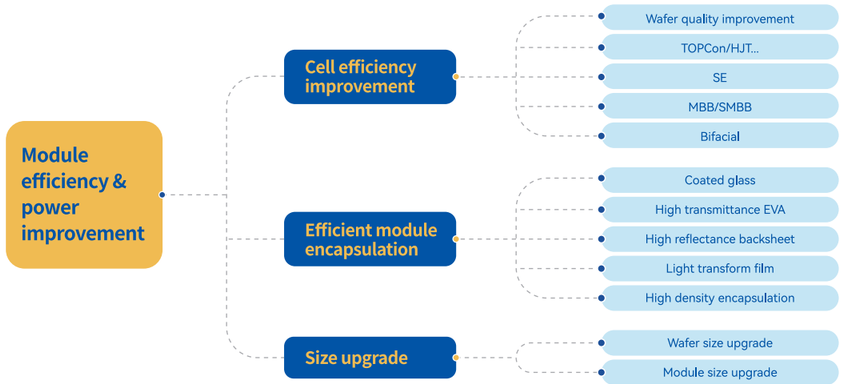



Figure 1 : The main efficiency and power improvement path of PV modules

## 1.2 JA Solar DeepBlue product design concept

JA Solar consistently prioritizes customer value and champions technological innovation. Since 2020, we've significantly ramped up our investment in product research and development. This dedication culminated in the launch of our DeepBlue 3.0 series in 2020. These products, rooted in the 182mm*182mm (M10) silicon wafers and Percium+ cell technology, have garnered widespread acclaim globally. Our product strategy—comprising "one generation for mass production, one for reserve, and one for R&D"—propelled us to debut the DeepBlue 4.0 X in May 2022, recognizing the potential limits of p-type cell efficiency. By May 2023, we unveiled the DeepBlue 4.0 Pro, a new generation of n-type modules, further elevating our commitment to enhancing customer value and promoting industry chain synergies.

September 2021 saw a collaborative initiative with Jinko Solar and LONGi Solar, introducing the standardized size of M10 series modules, encompassing 54/72/78 versions. The 78-cell version, measuring 2465mm1134mm, found substantial application across varied scenarios, marking it a prominent choice for high-power industry products. Nonetheless, this version faced challenges such as the hot spot issue and a high module open circuit voltage, impacting the BOS cost efficiency due to the limited number of modules connected in a single string. The DeepBlue 4.0 Pro, constructed on the industry-standard module size of 2465mm1134mm with 72 cells, carries forward the legacy of high power and efficiency. It diminishes the hot spot risk and optimizes the BOS cost by reducing the module's open-circuit voltage by approximately 7.6%. The DeepBlue series continues its mission with the 4.0 Pro, focusing on our core design philosophy of "Tailored to increase customer value". This commitment ensures superior product quality and performance, offering customers a reduced LCOE, heightened product value, and an enhanced user experience.

# 02 / Core technology

The DeepBlue 4.0 Pro modules primarily intergrated Bycium+ high-efficiency cell technology, advanced efficiency & reliability encapsulation methods, high-density encapsulation techniques, and the innovative rectangular silicon wafer technology.

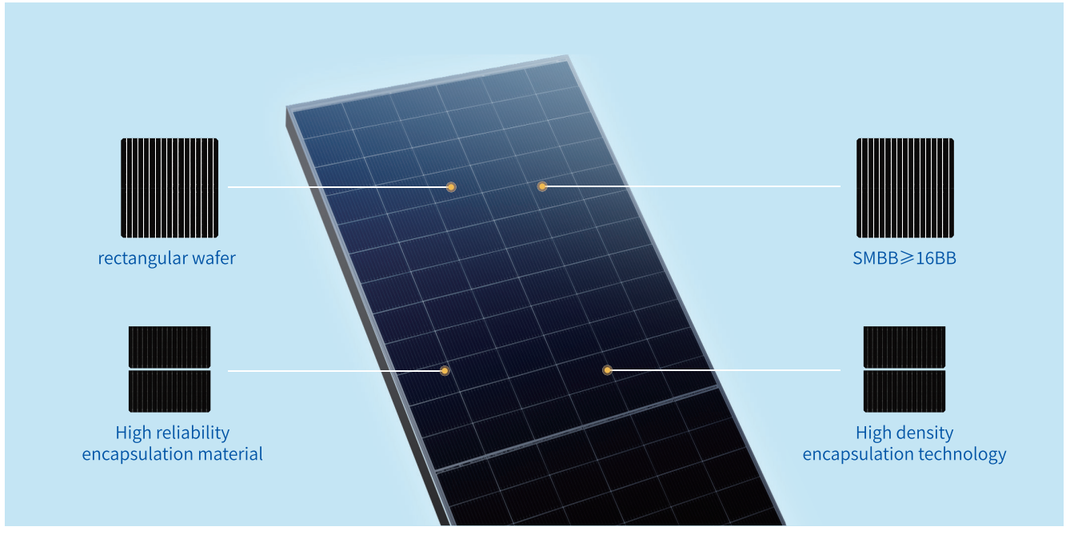



Figure 2 : Some core quality and efficiency improvement technologies for DeepBlue 4.0 Pro modules

## 2.1 Bycium+ high-efficiency cell technology

The Bycium+ cell stands as JA Solar's signature high-efficiency n-type passivated contact cell. Built upon millisecond-level low-oxygen n-type wafer technology, it incorporates optimized passivation  contact technologies, ultra-thin busbar metallization, laser induced firing, and a double-sided anti-reflection film. The cell boasts a Voc reaching up to 740mV, with a mass production efficiency that can hit 26.5%. A detailed structure of the Bycium+ cell can be viewed in Figure 3.





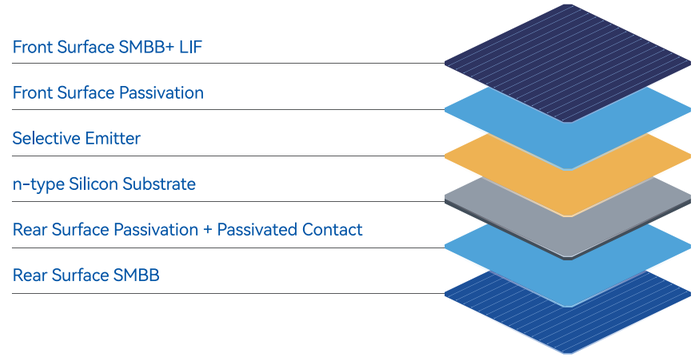



Figure 3 : Bycium+ cell structure diagram

## 2.2 Advanced efficiency & reliability encapsulation methods

In the quest for superior module efficiency and quality assurance, not only is cell efficiency crucial, but high-efficiency and reliable encapsulation technologies are equally vital. SMBB technology amplifies light utilization and current collection, leading to heightened cell efficiency and module power. JA Solar utilizes the industry's leading round welding ribbon, with the number of ribbons being ⩾16, ensuring optimal module power and welding reliability.

For module BOM material, tailored optimization has been executed in line with the module's performance attributes. The DeepBlue 4.0 Pro takes this a notch higher: it bolsters mechanical strength through the enhancement of the frame's aluminum material, an optimized frame cross-sectional design, and the expansion of frame cavities. These enhancements are further complemented by the adoption of non-destructive cutting, SMBB, and other state-of-the-art technologies, bolstering product reliability. Furthermore, the module's anti-PID performance sees improvement using an enhanced encapsulation film.

## 2.3 High-density encapsulation techniques

High-density encapsulation technology focuses on boosting the module's power and efficiency by augmenting the total area of the cells encapsulated per unit module area. This encompasses techniques such as shingle, paving, and gapless encapsulation. The DeepBlue 4.0 Pro product employs the small spacing approach. Compared to other high-density encapsulation methods, this approach balances considerations of cost, power enhancement, production yield, and product reliability. As a result, the small spacing technology is emerging as the predominant choice in high-density encapsulation within the industry and is set to become a standard for high-efficiency module.

# 03 / Product advantages

The DeepBlue 4.0 Pro modules build upon the legacy and strengths of the DeepBlue series. They excel in power generation, characterized by minimized degradation, enhanced high-temperature energy yield, increased bifacial generation benefits, and outstanding performance under low irradiance conditions.

## 3.1 Lower degradation

The n-type wafers' inherent advantages, devoid of B-O complex, ensure reduced power degradation compared to the traditional p-type PERC cell. JA Solar commits to the product's longevity with a 30-year linear power output warranty, guaranteeing less than 1% degradation in its inaugural year, followed by an annual degradation rate of under 0.4% thereafter. This equates to a power generation gain of up to 1.8% over its lifetime, with the first year showcasing gains of up to 1%, illustrated in Figure 4.

In an industry benchmarking field test carried out by JA Solar in collaboration with TÜV NORD, the n-type module with Bycium+ cells displayed an impressive power degradation of just 0.15% in its first year. Such performance is highly esteemed in the industry.

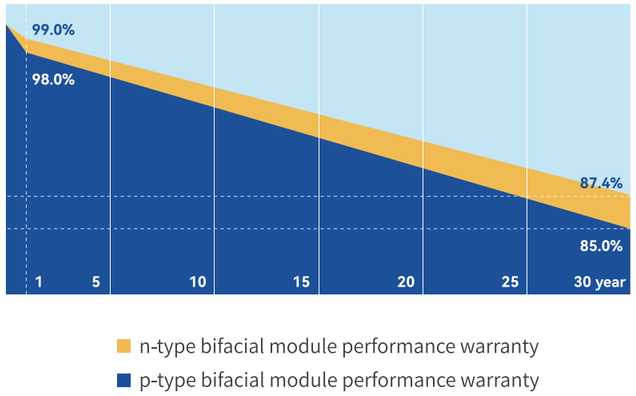



Figure 4 : Power Degradation of n-type and p-type modules





## 3.2 Superior high temperature energy yield performance

High temperature energy yield performance is influenced by the temperature coefficient and the module's operational temperature. A higher cell open-circuit voltage translates to an improved temperature coefficient. The n-type Bycium+ cell boasts an open-circuit voltage of 740mV and a temperature coefficient of -0.29%/°C, outperforming the -0.35%/°C of the p-type PERC cell. On hotter days, with an operational temperature of 55°C, the n-type module's power degradation is 1%-1.8% less than its p-type counterpart. As the module's temperature rises, the n-type module's performance significantly excels.

The n-type module's superior conversion efficiency means less heat conversion from absorbed light, leading to a cooler operational temperature. This is supported by a one-year field test by JA Solar and TÜV NORD. Their findings, illustrated in Figure 5, indicate that the n-type module operates on average 1°C cooler than the p-type module. This, combined with its superior temperature coefficient, allows the n-type module to produce approximately 1.5-2% more power than the p-type PERC module.

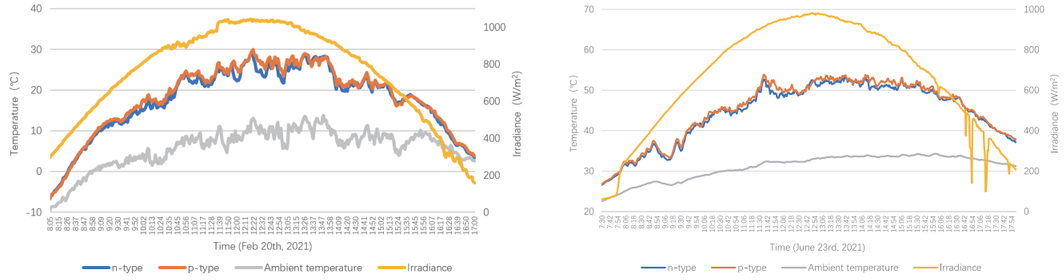



Figure 5 : Operational temperature comparison of n-type and p-type PERC modules

## 3.3 Higher bifacial generation gain

For bifacial generation, the n-type module boasts an 80% bifaciality, outpacing the 70% of p-type PERC modules. Given a rear-side irradiance of 100-150 W/m$^2$, this 10% edge can translate to a 1%-1.5% power surge for the n-type module. Taking into account varied ground conditions, rack specifications, and shadowing, PVsyst simulations suggest that DeepBlue 4.0 Pro modules can achieve power gains ranging from 0.8% to 1.2%.

## 3.4 Excellent low irradiance energy yield performance

DeepBlue 4.0 Pro's performance in low irradiance conditions is a testament to its advanced design. Three primary factors underscore its efficiency:

**Minority Carrier Lifetime:** Enhanced in DeepBlue 4.0 Pro, a longer lifetime means better efficiency.
**Open-Circuit Voltage (Voc):** The module's higher Voc, thanks to Bycium+ cells, ensures optimal power generation even under subdued sunlight.
**Sheet Resistance:** Optimized in this module, lower resistance translates to efficient electricity conversion.

In practical terms, during early mornings or late evenings with around 600W/m² irradiance, DeepBlue 4.0 Pro showcases an energy yield gain of approximately 0.2%. This illustrates consistent performance, ensuring maximum energy harnessing even under varying sunlight conditions.

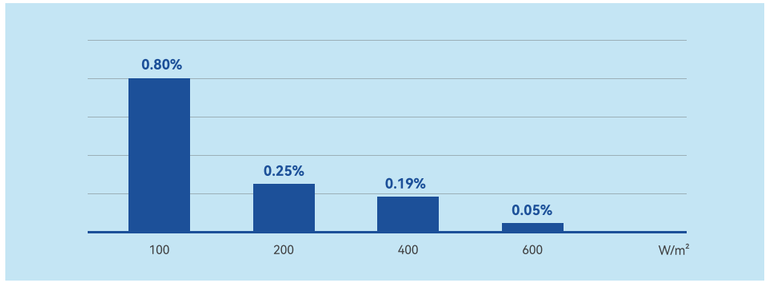
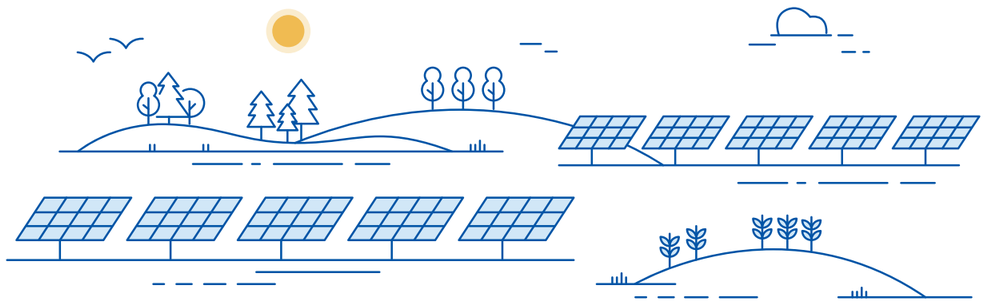



Figure 6 : DeepBlue 4.0 Pro module low irradiance power generation gain







# 04 / Excellent reliability

The reliability of a module underpins its power generation capabilities. Typically assessed through accelerated aging tests, the DeepBlue 4.0 Pro modules exemplify this reliability, consistent with the entire DeepBlue series. Meeting IEC standards, they have undergone rigorous testing and certifications from leading industry authorities, ensuring their performance, safety, and reliability across various applications.

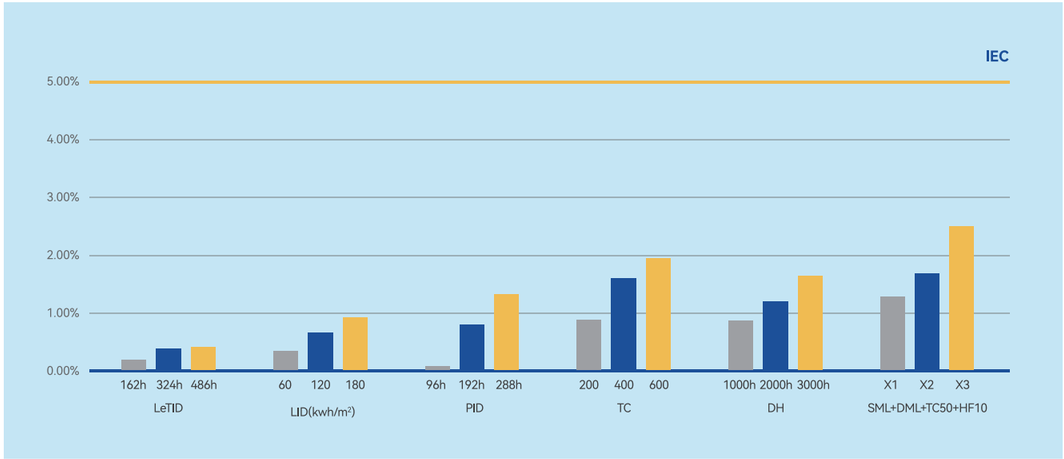



Figure 7 : DeepBlue 4.0 Pro module reliability test results

# 05 / Product parameters and application scenarios

The DeepBlue 4.0 Pro series epitomizes a seamless fusion of efficiency, power, and adaptability. These modules come in four distinct designs: 54-cell (1762mm)、72cell (2278mm)、66-cell (2382mm)、72-cell (2465mm) , tailored for varied applications, as detailed in Table 1. The compact 54-cell version suits European and American rooftop projects, while the other designs cater to global industrial, commercial rooftops, and large-scale utility projects. Specifically in China, the 72-cell module (2465mm*1134mm) emerges as a high-power leader, ideal for distributed projects and diverse applications.

Table 1 : DeepBlue 4.0 Pro module main technical parameters

| Module type/ technical parameters | JAM54D40-460/LB | JAM72D40-595/MB | JAM66D45-620/LB | JAM72D42-640/LB |
|---|---|---|---|---|
| Pmax [W] | 460 | 595 | 620 | 640 |
| Vmpp [V] | 33.17 | 44.64 | 40.21 | 44.29 |
| Impp [A] | 13.87 | 13.33 | 15.42 | 14.45 |
| Voc [V] | 39.70 | 52.58 | 48.50 | 52.87 |
| Isc [A] | 14.64 | 13.99 | 16.13 | 15.31 |
| Module efficiency | 23.0% | 23.0% | 23.0% | 22.9% |
| Temperature coefficient of Isc | +0.045%/°C | | | |
| Temperature coefficient of Voc | -0.250%/°C | | | |
| Temperature coefficient of Pmax | -0.290%/°C | | | |
| Dimensions | 1762*1134*30(mm) | 2278*1134*30(mm) | 2382*1134*30(mm) | 2465*1134*30(mm) |
| Weight | 22.0kg | 31.8kg | 33.1kg | 34.6kg |
| Warranty | 1% 1st-year degradation, 0.4% annual degradation over 30 years | | | |





# 06 / Customer value

LCOE is a core measure of customer value. Modules with high power, high efficiency, high energy generation capacity, and high reliability can bring customers more value and improve overall revenue.

## 6.1 Field test - high power generation performance

Field tests are instrumental in evaluating and verifying the performance of PV modules and systems. JA Solar emphasizes this by rigorously testing all its new products across diverse climatic conditions to guarantee that they offer customers the most dependable and efficient module solutions.

For instance, in an outdoor field test spanning one year (from February 2021 to February 2022) conducted in partnership with TÜV NORD at CPVT's Yinchuan National PV Field Test Base – a region known for its dry and hot climatic conditions – it was observed that n-type modules, particularly those integrating Bycium+ cells, produced approximately 3.9% more power than their p-type counterparts. This is visually represented in Figure 8.

Similarly, in a contrasting setting characterized by hot and humid conditions, JA Solar collaborated with TÜV Rheinland for another year-long outdoor field test (from February 2023 to January 2024) in Qionghai, Hainan. The test data indicates that n-type modules leveraging Bycium+ cells outperform p-type modules by around 3.5%, as illustrated in Figure 9.

Further emphasizing its commitment to thorough testing, JA Solar has extended its field tests to challenging environments, including maritime regions and extreme cold conditions, to comprehensively assess the power generation capabilities of its modules.

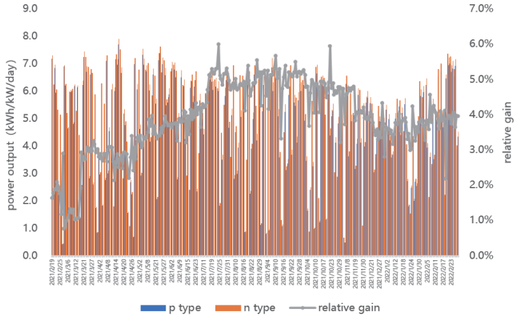



Figure 8 : Data compared between n-type module and p-type PERC module in Yinchuan base

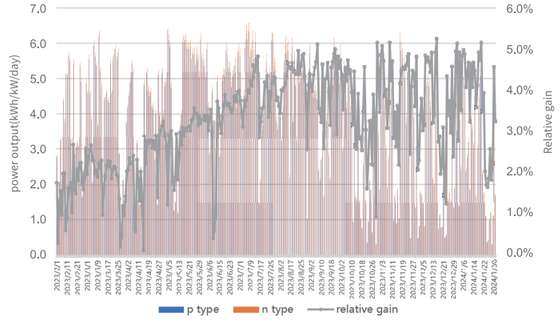



Figure 9 : Data compared between n-type module and p-type PERC module in Hainan base

Power generation performance of n-type modules varies across different climatic and environmental conditions, in comparison to p-type modules. In the full-year test period, the analysis reveals that the average daily power generation for n-type modules in the Yinchuan and Hainan projects stands at 5.03kWh/kW and 3.92kWh/kW, respectively. Yinchuan's power generation surpassed Hainan's by approximately 28%, a disparity largely attributable to variations in irradiance resources between these locales.

To further explore the impact of irradiance differences on n-type modules' performance, we juxtaposed power generation data from a high irradiance day (July 13) and a low irradiance day (April 12) in the Hainan field test project. As demonstrated in Fig. 10:
On high irradiance days, like July 13, the n-type module achieves a substantial power generation gain, registering at 4.06%. Conversely, on low irradiance days, exemplified by April 12, the power generation gain diminishes to 1.32%.

This trend indicates that in scenarios of heightened irradiance, and when other variables remain constant, n-type modules consistently yield higher energy gains. It's notable that ground albedo and array heights in both the Yinchuan and Hainan tests are virtually identical. Thus, any discrepancy in energy yield gains hinges predominantly on irradiance intensity. Such comparative data underscores the superior power generation capabilities of n-type modules.






Figure 10: Power energy yield gain data of n-type modules under different irradiance in Hainan field test project

## 6.2 System calculation- lower BOS cost and LCOE

When evaluating BOS (Balance of System) cost and LCOE (Levelized Cost of Electricity), various factors come into play, including installation methods, project types, and specific application scenarios. Considering costs related to racking, foundation, cabling, installation, and land utilization, the DeepBlue 4.0 Pro series modules offer significant advantages over their counterparts:

Comparison with p-type modules: The BOS cost of DeepBlue 4.0 Pro modules can be reduced by approximately 2%-4.5%, leading to a decrease in LCOE by around 2.5%-6%.
Comparison with traditional n-type modules: When juxtaposed against n-type modules of standard dimensions, DeepBlue 4.0 Pro's BOS cost can be curtailed by roughly 1.4%-2.8%, resulting in an LCOE reduction of about 0.7%-1.6%.

DeepBlue 4.0 Pro **VS** p-type module

2%–4.5% BOS cost reduction

2.5%–6% LCOE reduction

DeepBlue 4.0 Pro **VS** n-type module with original dimension

1.4%–2.8% BOS cost reduction

0.7%–1.6% LCOE reduction

Simultaneously, a comprehensive analysis of data from several leading n-type high-power modules, across different application scenarios, has been conducted. Notably, the JAM72D42/LB model, measuring 2465mm x 1134mm, stands out as a flagship high-power product within the DeepBlue 4.0 Pro series. This module presents an optimal solution for various applications, including residential rooftops, industrial and commercial rooftops, and large-scale utility projects.

Table 2 : System data for different application scenarios of DeepBlue 4.0 Pro modules

**Utility scale PV plant**
**Location:**Northwest China

| Item | 182-72n-2278 | 182-66n-2382 | JAM72D42/LB |
|---|---|---|---|
| Module power (W) | 590 | 620 | 640 |
| Module dimensions(L*W*H)(mm) | 2278x1134x30 | 2382x1134x30 | 2465x1134x30 |
| Installed capacity(MWp) | 100.0168 | 100.02832 | 100.03968 |
| Mounting system | 2P fixed tilt,38° | 2P fixed tilt,38° | 2P fixed tilt,38° |
| String number per racking (string) | 2 | 2 | 2 |
| Total number of modules (PCS) | 169520 | 161336 | 156312 |
| BOS cost | baseline | ↓1.17% | ↓1.42% |
| LCOE | baseline | ↓0.54% | ↓0.64% |





**C&I plant**
**location:**East China

| Item | 182-72n-2278 | 182-66n-2382 | JAM72D42/LB |
|---|---|---|---|
| Module power (W) | 590 | 620 | 640 |
| Module dimensions(L*W*H)(mm) | 2278x1134x30 | 2382x1134x30 | 2465x1134x30 |
| Installed capacity(MWp) | 6.17848 | 6.2496 | 6.28992 |
| Mounting system | Aluminum alloy guide rail, tiled | 铝合金导轨，平铺 | 铝合金导轨，平铺 |
| number of modules per string(PCS) | 28 | 30 | 28 |
| Total number of modules (PCS) | 10472 | 10080 | 9828 |
| BOS cost | baseline | ↓1.10% | ↓2.73% |
| LCOE | baseline | ↓0.79% | ↓1.74% |

**Residential rooftop**
**location:**East China

| Item | 182-72n-2278 | 182-66n-2382 | JAM72D42/LB |
|---|---|---|---|
| Module power (W) | 590 | 620 | 640 |
| Module dimensions(L*W*H)(mm) | 2278x1134x30 | 2382x1134x30 | 2465x1134x30 |
| Installed capacity(MWp) | 20.06 | 21.08 | 21.76 |
| Mounting system | 铝合金导轨，平铺 | 铝合金导轨，平铺 | 铝合金导轨，平铺 |
| Total number of modules (PCS) | 34 | 34 | 34 |
| BOS cost | baseline | ↓4.83% | ↓7.81% |
| LCOE | baseline | ↓3.32% | ↓5.35% |

# Customer value

The Levelized Cost of Electricity (LCOE) serves as a pivotal gauge of customer value.

Modules boasting high power, efficiency, generation capacity,

and reliability offer superior value, optimizing revenues.

DeepBlue 4.0 Pro series modules, a novel addition to n-type PV products,

are ideally suited for diverse application scenarios.

They offer unparalleled value, epitomizing our product design philosophy:

“DeepBlue - Tailored to Increase Customer Value”.