White Paper on Digital Technology for Utility-Scale Clean Energy Plants

2024/08

Continuously supporting the future development of photovoltaic power plants

Foreword I (Yalong Hydro)

China's "Dual Carbon" goals have accelerated the development of a new power system centered on renewable energy. By 2030, the installed capacity of renewable energy, primarily wind and solar power, is expected to reach 1.2 billion kW. As the largest power generation enterprise in Sichuan Province and a leader in the industry, Yalong Hydro is the only entity in China that has fully developed a large river basin by itself. The company will capitalize on its significant advantages, such as river development under a single entity, superior multi-energy complementary conditions, strong regulatory capabilities, and a solid foundation, to speed up the construction of the Yalong River Basin's integrated hydro+PV+wind energy demonstration base. This will contribute to the creation of a new energy system, ensuring national energy security and achieving the "Dual Carbon" goals.

Technological innovation is at the heart of new quality productive forces. We are actively exploring how these forces can drive the transition to clean energy and using digitalization to create a hub for technological innovation. The Yalong River Basin is set to become the world's largest integrated hydro+PV+wind energy demonstration base, characterized by large-scale new energy projects, high altitudes, strict ecological protection requirements, and complex terrain. The planning, construction, operation, and management of such a large base present significant challenges. Therefore, it is crucial to enhance the efficiency of basin development and management and improve decision-making through information technology.

Given the complexities and challenges of the large base in the basin and plateau scenario, which is among the most representative and demanding in the region, we have partnered with Huawei to establish a joint innovation center (JIC). Using the Kela plant and Zhalashan plant as practice bases, we are jointly addressing key technologies in the intelligent design, construction, O&M, and operation of clean energy bases. Our goal is to reduce the lifecycle costs of these projects, maximize the comprehensive benefits of hydro, wind, and PV resources, and promote the digital and intelligent advancement of the energy industry. Through digitalization, we aim to build an open and collaborative innovation ecosystem that facilitates the digital and intelligent upgrade of the energy industry. By providing replicable and scalable experiences in constructing clean energy bases, we hope to drive the intelligent transformation and high-quality development of the energy industry.

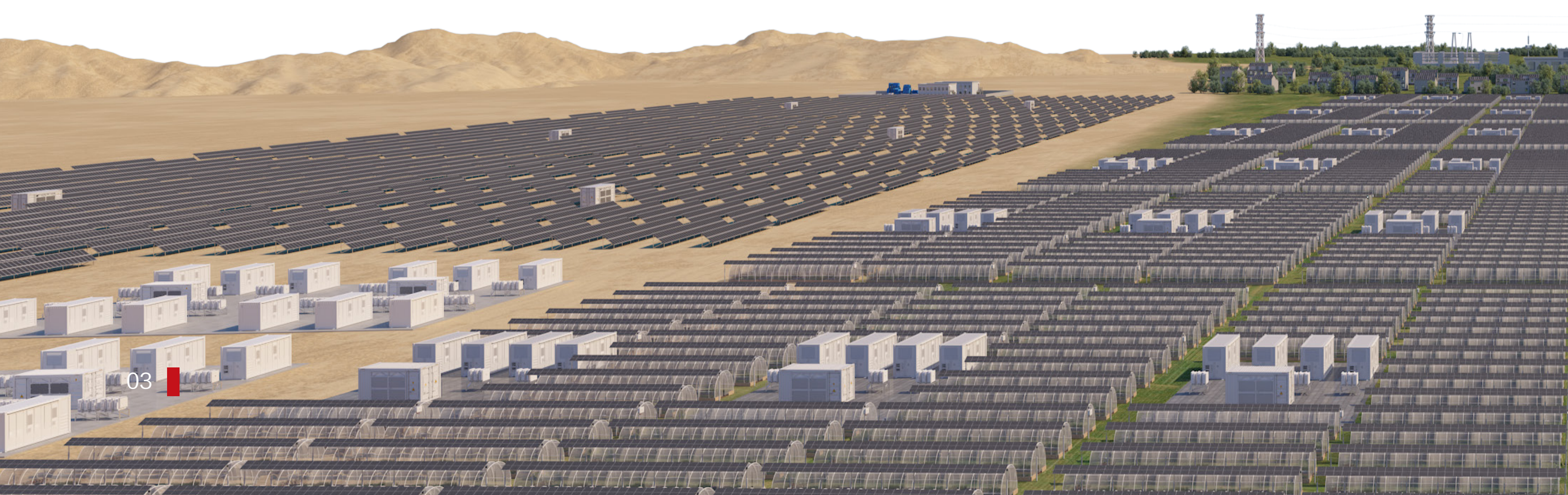
Foreword II (Huawei)

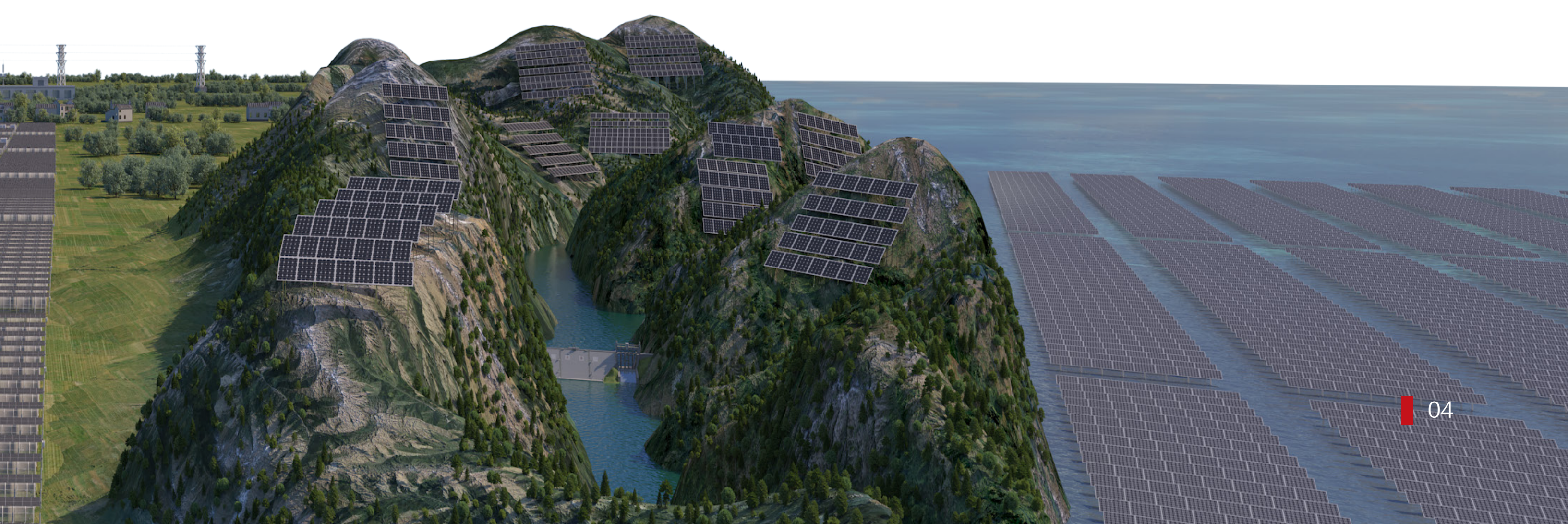
The journey towards carbon neutrality is a major undertaking that is driving significant societal change. The international community is increasingly united in the belief that reducing emissions is essential to addressing global climate change, making green, low-carbon development a key global trend. Solar power, one of the most accessible and cleanest energy sources, is experiencing unprecedented growth. During China's 14th Five-Year Plan, the annual increase in the installed capacity for PV plants in China is expected to exceed 100 GW, with the total capacity across nine major clean energy bases surpassing 600 GW. Solar power is gradually replacing traditional energy sources, emerging as the dominant global power source. According to the forecast of BloombergNEF, the annual average installed capacity worldwide will exceed 700 GW for the period 2025–2030, and the global cumulative installed PV capacity will reach 6.7 TW by 2030.

Electrification, digitalization, and intelligence are the three key pathways for carbon neutrality. In many countries, the construction of clean energy bases, with capacities at more than 100 MW or even GW level, has become a clear trend. These bases, characterized by large footprint, remote locations, and numerous pieces of equipment, face a range of challenges throughout their lifecycle, from planning and construction to O&M and operation. On the fast track to digitalization and intelligence, technologies such as 5G, AI, cloud computing, big data, and IoT have experienced exponential development. Managing watts with bits has been widely accepted in the industry. This has created a growing demand for the digitalization of plants throughout their lifecycle. We are integrating energy flows with information flows to build a robust digital platform. This platform focuses on six key areas: data collection, data analysis, data governance, digital visualization, data operation, and data O&M. By applying the information technology, sensor technology, AI, and control technology, we aim to achieve full lifecycle visibility, management, control, and optimization of energy bases, ensuring that plants operate intelligently, safely, reliably, and efficiently.

Based on the joint innovation and application of Huawei and Yalong Hydro, the White Paper on Digital Technology for Utility-Scale Clean Energy Plants systematically introduces the latest technologies and practices of utility-scale PV plant digitalization, aiming to facilitate the application of PV plant digital technologies, accelerate the transition to the digital, intelligent, and automatic PV plant management, jointly explore innovative paths for digital transformation of the industry, and help achieve the "Dual Carbon" goals.

CONTENTS





01 Background and Challenges of Plant Digitalization

The digitalization of PV plants first emerged in the plant O&M sector. By extensively collecting production and alarm data from equipment, Huawei established a data platform. When combined with work order and two-ticket systems inherited from hydro and thermal power projects, this platform enabled basic O&M management functions. As data accumulated, by 2014, the industry had developed mature methods for identifying faulty equipment through basic statistical analysis, marking the early stages of PV plant digitalization. Starting in 2017, more advanced fault detection technologies for tasks such as site inspections, fault identification, and dust cleaning using intelligent cameras, drones, robots, and AI analysis algorithms, began entering the market.

As the adoption of new energy sources continues to grow, plants are becoming larger and their operating environments more complex. The plateau and basin scenarios, with their intricate terrain and harsh conditions, are among the most challenging. The rugged landscape, harsh weather, and extensive power generation equipment not only heighten O&M challenges but also introduce new difficulties in the optimal planning and design, high-quality construction, stable grid connection, efficient operation, and safe operation of plants. In this context, digitalization has become an essential solution for the development of utility-scale plants.

1.1 Challenges in Plant Planning and Design

Utility-scale clean energy plants are typically constructed in remote areas like deserts, wastelands, plateaus, and basins, where meteorological conditions are complex. These geographical and geological environments also lead to insufficient historical data in related areas, making it challenging to provide effective guidance for plant planning and design. In certain scenarios, such as the basin utility-scale plants in Southeast China and offshore in coastal region of East China, the limited experience with PV plant construction further complicates the planning and design phases.

•**Complex terrain and difficult site selection:** Designing utility-scale plants, which can cover tens of square kilometers, requires selecting optimal locations within the available land area to minimize the impact of mountainous obstructions. This presents a significant challenge for the industry.

> Identify PV deployment areas based on mountain shelters

•**Lack of reliable data:** Most plants are built in uninhabited regions with sparse geological data, leading to potential discrepancies between actual land conditions and design assumptions.

> Lack of geological information, terrain subsidence during construction

•**Heavy design workload:** As the plant scale increases, the reliance on manual experience for the drawing design and plan optimization becomes inefficient and insufficient to meet the growing demands.

1.2 Challenges in Plant Construction

The short construction timelines for PV plants present significant challenges in managing and overseeing construction sites. Key challenges during the construction phase include:

- **Difficulty in monitoring construction progress:** Harsh natural environments, low labor efficiency, large project volumes, and tight schedules make it difficult to effectively track and analyze construction data and manage construction site progress using manual methods.

- **Difficulty in ensuring construction quality:** The reliance on temporary workers with varying skill levels often results in inconsistent quality management. Once construction is complete, conducting comprehensive inspections is challenging, complicating the assessment of construction quality during project acceptance.

- **Difficulty in supervising construction safety:** During peak construction periods, the large number of workers and the presence of heavy equipment increase the difficulty of ensuring safety. The absence of monitoring equipment in the early stages of construction further complicates the task of managing worker safety.

1.3 Challenges in Plant O&M for Troubleshooting

Utility-scale PV plants are marked by their extensive land coverage, numerous equipment, and remote locations, often experiencing harsh environmental and climatic conditions. These factors pose significant challenges for daily O&M, including:

•**Difficulty in detecting faults:** Manual inspections can only spot obvious issues like major module breakage or shadings. Hidden problems, such as diode faults or gradual land subsidence, are harder to detect. Manual checks are inefficient and typically only cover a fraction of the site. For mountain plants with modules installed more than 1.8 meters high or in steep terrains, it is even more difficult for manual checks to identify module issues, raising safety concerns.

•**Difficulty in planning for troubleshooting:** With a large number of equipment units, a plant can generate dozens or even hundreds of alarms and issues daily. O&M personnel often have to rely on their experience to decide which faults to rectify first, without clear insight into which faults will most impact power generation or offer the greatest benefit when resolved.

•**Difficulty in locating equipment:** Equipment locating is challenging due to the vast area of PV plants, long distances between arrays and from the booster station to the PV zone, and the lack of navigation systems for self-built internal roads. When an alarm is generated by the equipment, it is hard to pinpoint the exact location of the fault based on inverter or string/module numbers alone, resulting in wasted time.

•**Non-standardized troubleshooting:** Non-standardized troubleshooting practices can lead to safety risks or additional equipment issues, causing greater losses. Therefore, standardizing operations through technologies is essential for timely fault detection, quick locating, and efficient rectification.

1.4 Challenges in Plant Production and Operation

Once a PV plant is up and running, it encounters various challenges over its 25-year lifecycle, affecting power generation, grid connection, and safety:

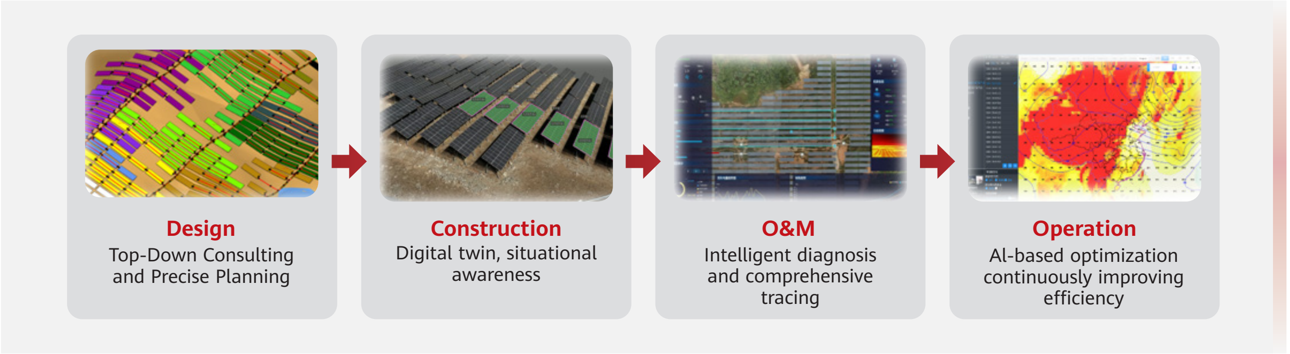
•**Decline in energy yield efficiency:** As time goes by, factors like equipment faults, module aging, dust buildup on modules, and aging equipment can cause the plant's performance ratio (PR) to fall short of its design expectations, resulting in notable energy yield losses.

•**Difficulties in forecasting and scheduling:** PV power generation is inherently variable, with fluctuations and intermittency. Accurate power forecasting involves integrating complex meteorological data, which can be quite challenging. The precision of these forecasts is crucial for grid scheduling and can impact issues like frequency oscillations or transient overvoltage. For utility-scale multi-energy plants, forecasting accuracy also affects scheduling efficiency. Inaccurate PV power forecasting can disrupt the energy yield plans of other energy sources like hydro or thermal power, ultimately impacting the overall revenue.

Given these challenges, digital technology offers significant potential to enhance every aspect of utility-scale PV plants, such as design, construction, O&M, and operation. Applying digital technology through the plant lifecycle can improve site survey accuracy, design quality, construction efficiency, and cost-effectiveness, as well as boost O&M efficiency and safety, supporting the successful development of utility-scale multi-energy plants.

02 Applications of Digital Technologies in Plants

Digital technologies are crucial at all four main stages of the plant lifecycle: design, construction, O&M, and operation. The four stages include site survey, simulation design, construction progress management, construction quality management, site safety management, equipment O&M management, plant operation assurance, intelligent plant control, multi-energy collaboration, auxiliary decision-making, and plant operation management.

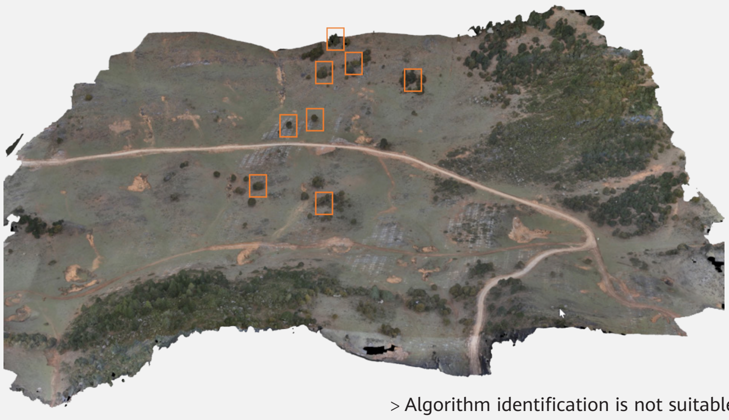


2.1 Digital Design of Plants

In the design phase of plants, 3D modeling and design software are used for site selection, modeling, drawing, and simulation, enhancing site selection accuracy and streamlining the process. This approach boosts design efficiency, reduces errors, and ensures high-quality construction.

Site Survey

During the planning stage, drones equipped with cameras and lidar complement the GIS system by creating high-precision 3D models. These models provide design teams with centimeter-level geological data cost-effectively, meeting early design needs. In addition, AI algorithms automate detailed data analysis, identifying unsuitable construction areas before the design phase, which helps avoid land use issues and environmental constraints during actual construction.



> Algorithm identification is not suitable for construction areas

Design and Simulation

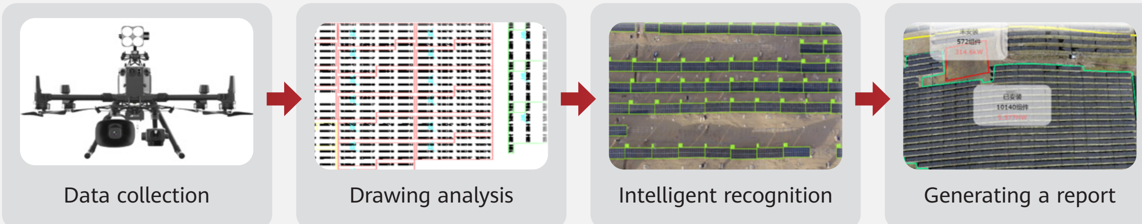
The 3D design software enables the creation of detailed plant models with automatic PV module layout and connection, greatly improving design and solution optimization efficiency of the design institute. In addition, simulation software can incorporate factors like weather and temperature to model the received irradiance of PV panels at different times, providing more accurate energy yield forecasts and supporting efficient, high-quality plant design.

2.2 Digital Construction of Plants

During construction, where basic monitoring and communication infrastructure may be lacking, drones offer a more effective and economical way to oversee the construction progress, quality, and safety.

Construction Progress Management

Effective progress monitoring ensures timely project completion and helps prevent errors such as incorrect or incomplete construction caused by human factors. Drones equipped with cameras and LiDAR capture high-precision 3D data of the site, which is then sent back to the data middle-end for analysis through the LAN. The orthophoto and tilt images of the plant are collected and processed by using technologies such as drone-based surveying, image processing, and deep learning technologies. Then, the results are compared with the corresponding targets in the CAD design drawing. This process allows for bulk recognition of construction structures in different positions in drone-captured images, calculation of the number of piles, supports, and PV modules installed, and precise monitoring of the construction progress.

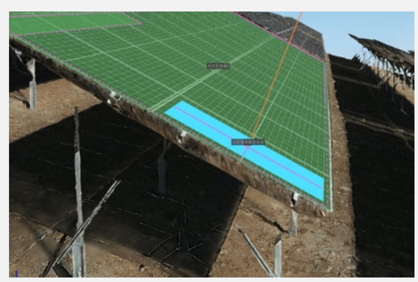


Construction Quality Monitoring

After a detailed 3D model of the plant is created using large-scale 3D reconstruction and incremental modeling, intelligent image processing techniques are employed to segment and identify key modules of the model, such as PV panels and pile foundations. Vector inclination and verticality algorithms are then used to verify whether the installation angles and vertical alignment of modules meet design specifications. This method also reveals discrepancies between the actual construction and the design plan, greatly enhancing quality control throughout the PV plant's construction.

Comparison of PV module tilt detection

> Manual inspection



> Intelligent identification of PV module tilt angles

Comparison of Pile foundation verticality detection

> Manual inspection

> Intelligent identification of pile foundation verticality

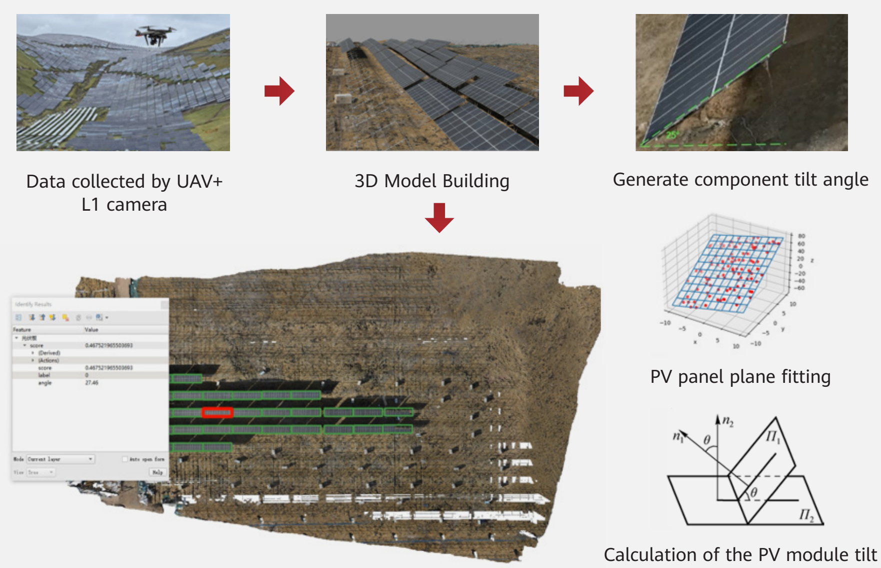
Construction Safety Supervision

The four-camera PTZ drone equipped with infrared, visible light, lidar, and wide-angle lens is used for live broadcast through the RTP video streaming media service to effectively monitor the construction site. These drones use specialized recognition modes and models to address the complex and changing risks on site. The machine vision technology automatically detects unsafe practices, such as unauthorized entry into hazardous areas, workers not wearing safety helmets, or those working at heights without safety ropes. Additionally, drones can use public address systems to direct or evacuate non-compliant personnel.

> UAV identify identify failure to wear a helmet

> UAV identify hazardous area intrusions

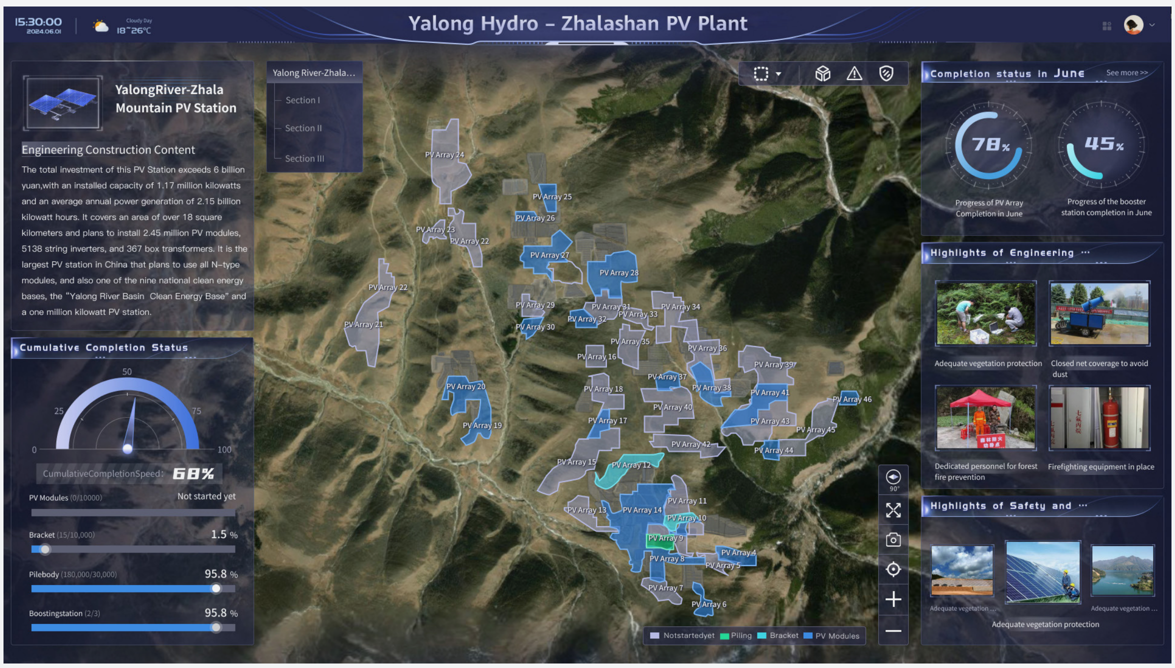
Furthermore, drones can be customized with specific recognition patterns and rules for different scenarios to monitor and protect the surrounding ecological environment, roads, and other infrastructure. By analyzing changes in the 3D structure of modules, drones can detect ground subsidence, identify landslide risks, and generate warnings.



> Detecting the tilt angle of the PV module to identify the risk of terrain settlement

Joint Innovation in Digital Engineering Construction

The Zhalashan PV plant, situated in Yanyuan County, Liangshan Prefecture, Sichuan Province, lies at elevations between 3200 and 4200 meters. Spanning roughly 18 square kilometers with a total installed capacity of 1.17 million kW, the plant commenced construction on August 25, 2023, with a target to achieve full-capacity grid connection by 2025. Once operational, the plant is projected to save around 650,000 tons of standard coal annually and cut CO2 emissions by approximately 1.8 million tons.



In a pioneering collaboration, Yalong Hydro and Huawei have worked with solution ecosystem partners to design, develop, and deploy an intelligent construction management platform for the Zhalashan PV plant for the first time. This platform leverages centimeter-level real-world modeling technology to create accurate 3D topographical maps of the site. It enables real-time tracking of construction progress and the intelligent detection of construction errors and omissions. Utilizing high-precision tilt/verticality recognition algorithms, the platform monitors the quality of pile foundations and module strings with 99% accuracy. The algorithms are developed and optimized for the platform. This cutting-edge technology helps reduce construction errors by 30–40%, enhancing both the quality of construction and the efficiency of energy yield.

2.3 Digital Plant O&M

PV O&M is a key step in ensuring the stable and efficient operation of a PV plant. It includes routine inspection, periodic maintenance, and troubleshooting. Intelligent plant O&M has become a mature feature of digital PV plants. The earliest O&M is performed only within a single PV plant. However, with the rapid development of the PV industry, more and more PV plants are built. On the one hand, the power generation group requires unified management of all its subordinate power plants. On the other hand, the industry urgently needs to get rid of its dependence on experienced engineers. PV plant O&M is gradually shifting from single-point decentralization to multi-point centralization. Plant O&M now can be classified into intra-plant O&M and centralized O&M. As renewable energy plants move toward "unattended O&M" and "the separation of O&M and inspection", the ideal solution is as follows: The site is unattended and the production system automatically reports the running status to the centralized control and O&M center. The centralized O&M center then analyzes, compares and displays the data reported by the site in a unified manner. When a fault is detected, a work order is sent to the regional maintenance center, which will send engineers to the site for troubleshooting. The idea has not been fully realized, as most PV plants have few on-duty personnel, but the key to an efficient digital PV plant O&M solution is now evident. First, the site should sense, collect, and transmit a large amount of running and inspection information to the centralized O&M center. Second, the centralized O&M center must be able to extract, process, and analyze the data, thereby identifying the most important O&M tasks and making proper planning to reduce manpower waste. Finally, after the processing result is returned to the site, the O&M personnel must be able to quickly locate the fault for troubleshooting to ensure the normal operation of devices.

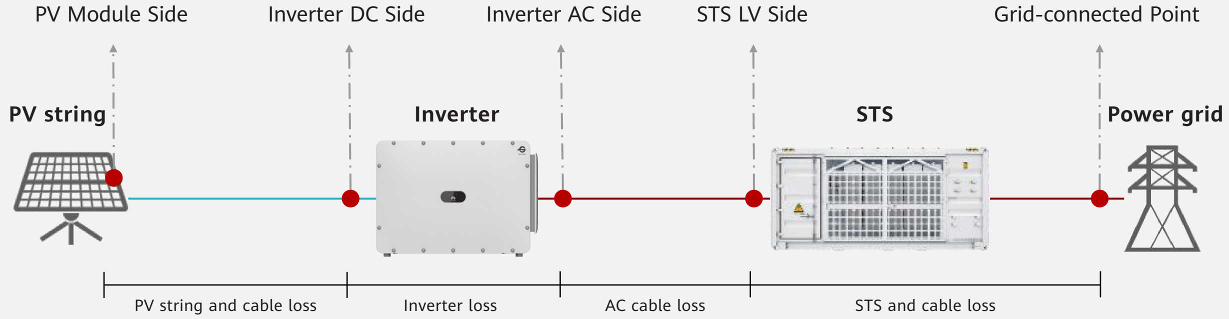
Digital methods are then used to consolidate the O&M process. Sites and centralized O&M centers cooperate with each other to integrate inspection, analysis, diagnosis, fault locating, and troubleshooting, building an efficient one-stop comprehensive O&M management platform that covers the entire O&M process. This will be the trend of PV O&M in the next few years.

Digital Twins for PV Plants

The digital twin technology builds a virtual management space based on the physical world to enable O&M management throughout the PV plant lifecycle. As an intelligent interconnection platform between services, personnel, and devices, a PV plant digital twin integrates information such as terrain, plant layout, device model, energy yield data, safety data, and management data into a 3D plant to show the plant running status and details, and provides a virtual environment container for functions such as real-time monitoring and device positioning, enabling "bits to sense watts". It serves as a visualized and efficient operation platform for intelligent PV plant O&M tools.

Full-Link Fault Diagnosis

Full-link fault diagnosis is developed based on the traditional "five points and four sections" loss analysis. By collecting and analyzing the energy yield, alarm, and diagnosis data of the PV modules, inverter DC side, inverter AC side, transformer station low-voltage side, and power grid side, full-link fault diagnosis can accurately identify the losses of four sections and also display the running status and energy yield efficiency of the entire link, helping quickly detecting safety risks.



•Coefficient of Variation Analysis

Coefficient of Variation Analysis is a widely used performance analysis method in PV plants. It mathematically identifies energy yield units whose deviations are far from the average value, indicating that the energy yield units may be faulty. This method can be applied to string inverters or a single PV string, with advantages including high efficiency and ease of use for quick analysis. However, it is difficult for the method to accurately identify whether the abnormal energy yield is caused by a specific fault. Personnel are required to manually check PV strings whose deviation exceeds a certain value one by one, which is inefficient for large PV plants.

•Smart I-V Curve Diagnosis


鉴衡认证
CHINA GENERAL CERTIFICATION

Certificate for Photovoltaic Product

——PV string I-V scanning and Intelligent diagnostic
Performance grade certification（PV inverter）

Certificate No.: CGC234698013R0M

Applicant:	Manufacturer:	Factory:
Huawei Technologies Co.,Ltd.	Huawei Technologies Co.,Ltd.	Huawei Machines Co.,Ltd.
Address: Huawei Base, Bantian, Longgang District, Shenzhen, China	Address: Huawei Base, Bantian, Longgang District, Shenzhen, China	Address: 2 Xincheng Avenue, Songshan Lake Science and Technology Industrial Park, Dongguan

>>> Product information
Product: PV inverter
Model: See Annex 1

>>> Trademark
HUAWEI

>>> Certification mark
光伏领跑者
FRONTRUNNER

>>> Certification Mode
Technical evaluation + Type test + Field test + Surveillance

>>> Certification result
Level 4

>>> Standard and Technical Requirements
1. CGC/GF 180: 2020A Technical Specification for evaluation of PV string I-V scan and Intelligent diagnostic
2. CGC-R460305:2020A Implementing Rules of PV string I-V scanning and Intelligent diagnostic performance grade certification（PV inverter）

Note:
- The test results and product information are shown in Annex 1.
- The grading standards are shown in Annex 2.
- This certificate is valid for use together with the Annex and the certificate retention notice for the current year. Any change in product design and manufacturing by the certified enterprise shall be approved by our organization, otherwise this certificate will be invalid.

Signature:
Date of Issue: 2023-10-02
Valid Until: 2026-10-01

China General Certification Center
Address:Room 301, 3/F., Building 26, No.6, Hepingli North Street , Dongcheng District, Beijing, China
Website: www.cgc.org.cn

Huawei's Smart I-V Curve Diagnosis makes full use of the string current and voltage data collected by string inverters, conducts in-depth study on possible faults of PV strings in PV plant application scenarios, and establishes fault identification and diagnosis models for different faults. Different types of PV module faults leave different signals on the I-V curve. After models are built, the PV string information can be identified based on the analysis of the PV string I-V curve to determine whether a PV string is abnormal. Its advantages include fast scanning speed, identification of fault types, and calculation of energy yield losses to help O&M personnel prioritize O&M tasks.

Huawei's Smart I-V Curve Diagnosis has the highest accuracy, consistency, and fault identification rate in the industry, and has passed the highest China General Certification Center (CGC) L4 certification.

•Smart Co-Diagnosis

As PV plants grow in scale, module-level O&M conflicts become prominent. The camera and sensor installed on the drone are used to collect images and model information and capture the surface details and temperature data of PV modules. With advanced image recognition and data analysis technologies, fault types are accurately identified, facilitating the comprehensive diagnosis of PV modules. However, because the battery life of the drone is limited and a full inspection is time-consuming, the impact of faults on energy yield remains unknown.

The Smart Co-Diagnosis integrates two core technologies: I-V scanning and drone AI-based image recognition. It is the first efficient module-level fault diagnosis solution jointly developed by

Huawei and partners. First, Huawei Smart I-V Curve Diagnosis diagnoses the area to be detected and locates the faulty PV string. Then the drone checks the faulty PV string for a second time and further locates the faulty PV module. The integrated solution not only realizes module-level fault location, but also reduces the flight range and solves the battery life problem of drones. In normal cases, a 1 GW PV plant can complete full diagnosis within one week without manual site visits.

Advantages:

Accurate: The two diagnosis modes are cross-verified, and the PV module fault identification accuracy exceeds 96%.

Efficient: After the fault scope is determined, only faults that affect energy yield are handled, improving fault locating efficiency by 80%.

Easy-to-use: Remote one-click operations eliminate the need of manual site visits. RAT+BeiDou navigation helps rectify faults in a closed-loop manner.

Intelligent Operation Route Planning and Navigation

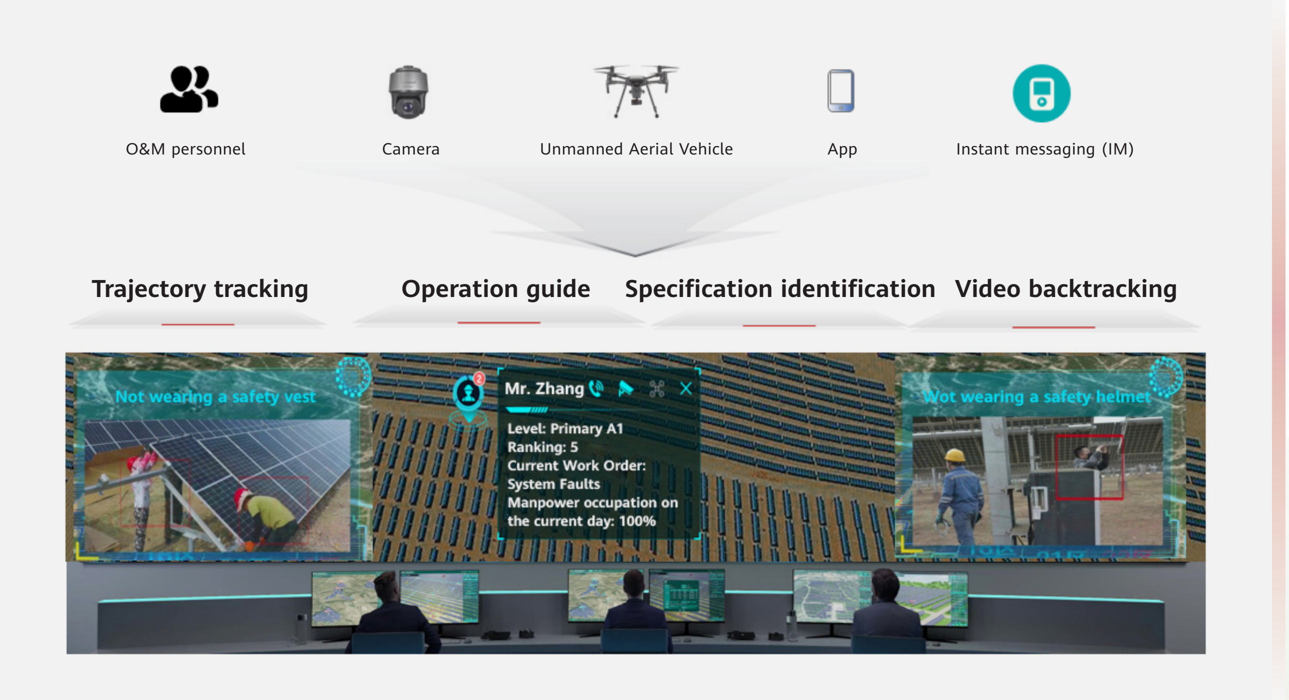
Proper operation route planning can effectively improve fault rectification efficiency. It is necessary to consider economic indicators such as energy yield loss, labor cost, spare parts cost, alarm density, and alarm clearance duration during route planning. This helps O&M administrators choose an O&M solution with optimal cost-effectiveness. Through the digital twin technology, road networks of sites are drawn to optimize routes in advance based on information such as cost-effectiveness and geographical location, eliminating multiple faults at once in an orderly manner.

Due to the lack of inverter location information, common navigation cannot effectively guide intra-plant O&M. Therefore, integrating the GPS positioning technology, site construction drawings, and intra-plant navigation is also an indispensable method in the O&M phase, which effectively shortens the time for locating faulty devices and greatly improves the troubleshooting efficiency. With mobile applications, O&M personnel can obtain intra-plant navigation information, and on-duty personnel can view the actual routes of O&M personnel in 3D scenarios.

Full-Process Operation Management

O&M operations of PV plants are usually performed in outdoor and electrical environments, which poses certain risks and places higher demand on the management of standard operations. The application of digital technologies, especially the cooperation of mobile communication technologies and AI cameras, can standardize the management of PV plant operations. Facial recognition and AI recognition technologies are used in the operation area of PV plants to authenticate operators' qualifications to avoid non-compliant operations and monitor foreign object intrusion and personal protective equipment.

The intra-plant GPS positioning system is deployed to track the movement of O&M personnel. When O&M personnel arrive at the coverage area of cameras, cameras automatically start to record and save the operation process for backtracking. In this way, standard operations including fault rectification and maintenance can be ensured, and warning is generated to protect the safety of O&M personnel in PV plants. And the full-process traceability mechanism can be used to control and manage outsourced operations.

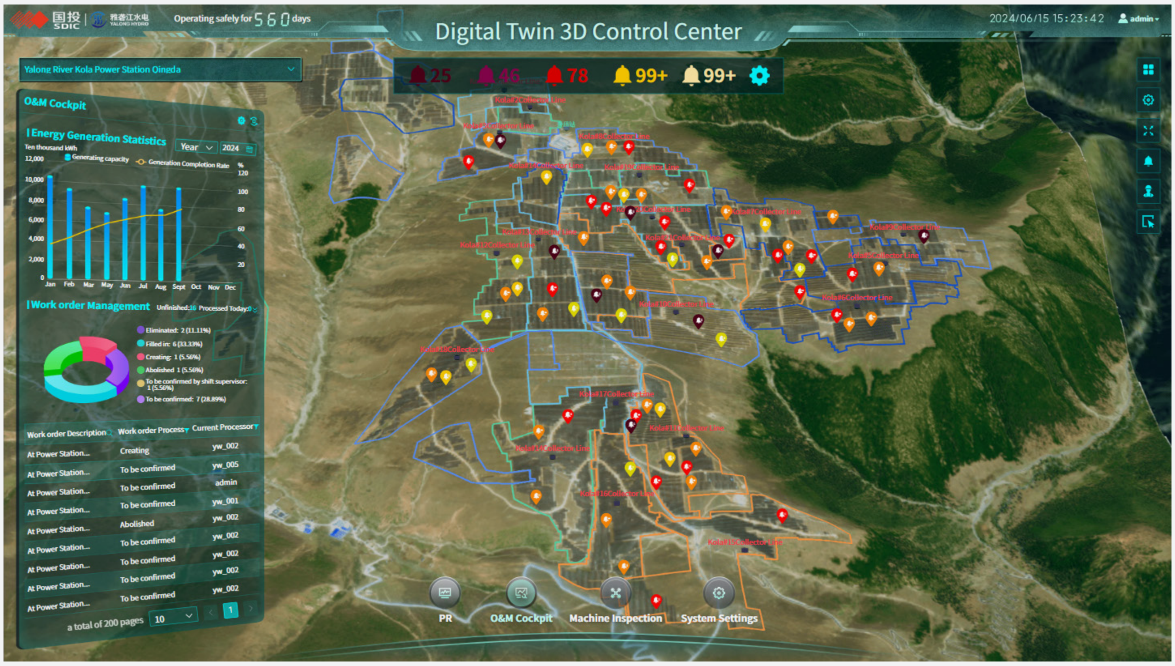


Joint Innovation Practice of Digital Plant O&M

Located at an altitude of 4000 m to 4600 m on the Sichuan-Tibet Plateau, the Kela PV Plant project along the Yalong River in Yajiang County, Ganzi Prefecture, Sichuan Province, China covers an area of about 16 square kilometers, equivalent to that of 80 Bird's Nest Stadiums. With over 2 million PV modules, the plant has an installed capacity of 1 million kW.

Using the Kela PV plant as a practice base, Huawei has worked with partners to build an "Intelligent O&M Cockpit" that covers the entire process for Yalong Hydro. As a data foundation for the plant, Huawei's Smart PV Plant Management System (Smart PVMS) collects energy yield and alarm data, and comprehensively diagnoses the plant through Coefficient of Variation Analysis, Smart I-V Curve Diagnosis, and Smart Co-Diagnosis technologies. The alarm and diagnosis information is sent to the fault pool of the centralized O&M system provided

by the solution ecosystem partner. The system then analyzes the O&M cost-effectiveness and automatically plans O&M routes based on the priorities and distribution of faults. Drawn through road network modeling, the intra-plant navigation system can quickly guide O&M personnel to faulty devices. In addition, the system can be linked to Yalong Hydro's work order system to implement fault closure.



According to onsite tests, intra-plant navigation can shorten the inverter positioning time by more than 30%, significantly reducing the distance traveled by O&M personnel and the risk to personnel working at high altitudes. The O&M Cockpit covers the entire O&M process and improves the overall O&M efficiency by 50%, effectively reducing the O&M pressure on high-altitude PV plants and accelerating the transition to plant automation.

2.4 Digital Plant Operations

During the 25-year lifecycle, a PV plant faces many challenges, including efficiency degradation, grid integration issues, device safety, and network security. In addition to troubleshooting, it is also critical to use advanced digital and intelligent technologies to promote grid integration, increase energy yields throughout the lifecycle, improve plant safety, and reduce device safety and network security risks.

In-Depth PR Analysis

The performance ratio (PR) of a PV system is a key indicator for evaluating the energy yield efficiency of a PV plant. It reflects the plant's energy yield capability and indicates its quality. The PR is affected by many factors, such as plant location, technology roadmap, construction quality, device performance, O&M timeliness, and weather. Its value is the ratio of the actual electric energy input to the power grid, after all losses are subtracted, to the theoretical electric energy yield.

$$PR^{*} = \left(\frac{E_{OUT.\tau}}{CI}\right) / \left(\frac{G}{G_0}\right)$$

PR : performance ratio

$E_{OUT.\tau}$: total energy yield of a PV plant during the period of τ

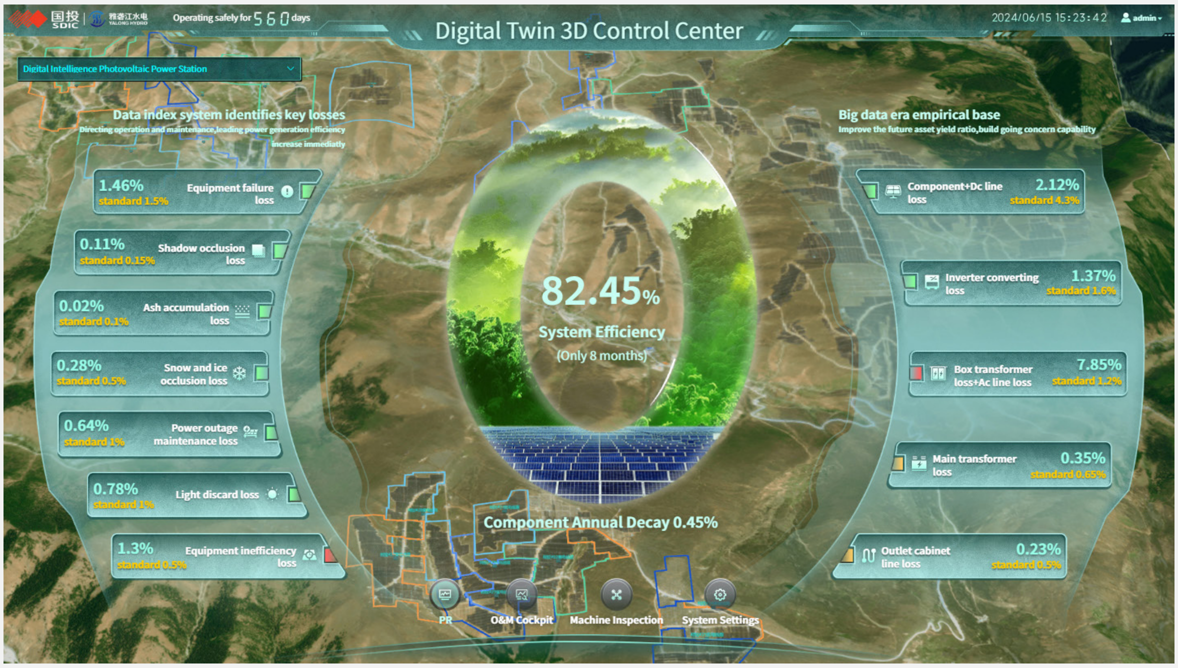
CI : installed capacity of a PV plant

G : total irradiance per unit area of the PV array inclined plane during the period of τ

G_0 : irradiance under standard conditions

*The PR calculation method is quoted from GB/T 39854 Specification of performance evaluation for photovoltaic power station.

In fact, the PR usually fails to meet the original design because losses occur due to various factors during the operation of a PV plant. The in-depth PR analysis solution jointly developed by Huawei and its partners can help users deeply analyze various types of energy yield losses and find out the key factors affecting PR. It analyzes losses caused by collector line faults, tracker faults, inverter faults, transformer station faults, shadow shading, snow shading, low-efficiency devices, and others. Based on the horizontal comparison of losses of each segment in different PV plants and the vertical comparison of losses in different periods, the in-depth PR analysis can find out segments with great losses, provide O&M experts with reference for decision-making, and guide timely, efficient, and accurate O&M to increase the energy yield and revenue of PV plants. It can also provide data support for new PV plants, helping customers continuously build more efficient and high-quality PV plants.



High-Precision PV Power Prediction

PV energy yield is random, fluctuating, and intermittent. Inaccurate predictions affect power grid scheduling and renewable energy integration. Meteorological forecasts are an important input for power prediction. Deviations in meteorological forecasts will have a severe impact on PV power predictions. Currently, the sources of meteorological forecasts are mainly numerical results. The most authoritative sources include data from the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Global Forecast System (GFS) data from the US National Weather Service (NWS). However, the technology roadmap requires high computing power and is time-consuming and infrequently updated. In practice, the interval between the latest valid time and the start time of forecasts exceeds 24 hours, resulting in poor forecast precision.

During actual operation, PV plants may fail to generate electricity according to the rated power in a short time due to unexpected maintenance or device damage. Such historical data also affects the accuracy of power prediction. In the industry, abnormal energy yield data is manually corrected, resulting in poor accuracy, which directly affects the training effect of prediction models.

PV power prediction is affected not only by deviations in meteorological forecasts and emergencies, but also by PV modules, device degradation, and seasonal changes. The change of energy yield characteristics is a long-term and slow process, and its impact cannot be fully and accurately predicted. Typically, industry peers adjust their prediction models after the prediction precision decreases due to changes of energy yield characteristics. As a result, the model optimization is delayed for at least three to five days, impacting the prediction precision.

Precise PV power prediction can reduce appraisal penalties, improve renewable energy integration, facilitate multi-energy complementation and power trading, and assist in formulating more reasonable O&M plans. Huawei combines the meteorological model with the AI irradiance-to-power algorithm to implement high-precision hour-level rolling PV power prediction for plant areas. In addition, Huawei uses data governance and model self-updating technologies to correct the prediction model in a timely manner, ensuring the accuracy of short-term and ultra-short term PV power prediction.

•Meteorological Model

The meteorological model developed by Huawei uses the 3D Earth-specific Transformer that adapts to the Earth coordinate system as the basic framework. After global high-altitude variables and surface variables are input, it outputs the future weather status of the same shape.

Compared to the traditional numerical weather forecast, the meteorological model has better prediction performance and a faster inference speed. It outperforms the ECMWF Integrated Forecasting System (IFS) in prediction results, with an inference speed of more than 10,000 times, achieving the calculation of 24-hour prediction in seconds.

Thanks to the powerful data fusion capability of AI models, the regional meteorological model integrates real-time plant data, high-precision satellite data, global large model inference data, numerical weather forecast data, and observation data near the plant for model training and inference. In this way, fast iteration, low-delay prediction, and renewable energy plant customization can be realized. The data closer to the forecast target time can be used for service forecasting, and region-specific customized prediction optimization can be achieved to further improve the prediction precision.

•Data Governance

Data quality is another important factor that affects the quality of prediction models. Based on the characteristics of meteorological forecast and PV energy yield, Huawei integrates more than 10 data governance methods, including missing value processing and abnormal value processing, to control data quality in each phase of power prediction.

Thousands of alarm signals are sorted out and normalized to create an "alarm signal - energy yield restriction" mapping model for inverters to the entire plant. Based on the maximum energy yield capability data of Huawei inverters, the power prediction model implements minute-level energy yield capability correction responses. The data quality is then improved in a timely and effective manner, improving the model training effect. Without external intervention, the mapping model can quickly detect the change of the maximum energy yield capacity of the plant and remind personnel to adjust the prediction model, thus reducing the impact of shutdown and maintenance caused by certain faults on the PV power prediction precision.

•Model Self-Updating Technology

Huawei-developed model self-updating technology works with the cloud-based collaborative deployment solution to ensure model stability and implement 15-minute rolling forecast update, effectively coping with the impact of changes in energy yield characteristics caused by environmental factors such as temperature changes or PV module attenuation during long-term operation of plants. Generally, it takes three to five days later for a cloud-based solution to correct the model. In contrast, Huawei's model self-updating technology has advantages in short-term and ultra-short term prediction precision. It effectively handles the impact of mid- and long-term irreversible changes in the energy yield characteristics of plants.

Joint Innovation Practice of Digital Plant Operations

In the first half of 2024, the Kela PV Plant alongside the Yalong River deployed the PR in-depth analysis system. The system not only displays the energy yield efficiency of the entire plant and single arrays, but also analyzes the energy yield data of each component to provide 13 types of energy yield losses, including PV module loss, low-efficiency device loss, DC cable loss, transformer station loss, AC cable loss, device failure loss, and dust/ice/snow loss. By viewing the distribution of energy yield losses on the PR dashboard, personnel can quickly identify the problems that affect energy yield the most. The system assists O&M personnel in formulating O&M plans and improving the energy yield efficiency of the Kela PV Plant, and helps the customer gain experience in plant construction and device selection through horizontal comparison with other PV plants in the future, enabling sustainable and high-quality plant construction.

The Kela PV Plant is also a hydro-solar hybrid power plant. It is connected to the Lianghekou Hydropower Plant through the 500 kV power transmission line to output stable hydro-solar hybrid power. Since water levels are high in summer and low in winter, solar power and hydropower complement each other to maximize economic benefits, while this places higher demands on the accuracy of PV power prediction. In response, Huawei innovatively applies the meteorological model to the PV field and refines the grid of the meteorological model to better match the meteorological conditions of the PV plant. In addition, the data governance and model self-updating technologies are combined with AI algorithms to create a more accurate irradiance-to-power conversion technology. As a result, the combination of the large model and AI technologies enables the average short-term PV power prediction accuracy of the plant to reach 91%, significantly reducing situations with prediction accuracy lower than 85%. This reduces the amount of electricity to be evaluated, improves the plant revenue, and helps achieve more efficient hydro-solar complementation.

03 Summary

The integration of renewable energy with digital and power electronics technologies has become an inevitable trend. Over the past decade, PV plants have gradually moved from basic data monitoring and collection to intelligent analysis and policy optimization, and from single-device and single-plant maintenance to multi-plant and centralized O&M. However, the development so far is only the beginning. According to the current industry trend and the outlook of future technology development, the integration of information flow and energy flow will reach a whole new level in the next decade. Digital plants will evolve from "digital maintenance" to "digital O&M" and then to a next stage throughout the lifecycle of "planning, construction, maintenance, and operation". More than a simple technological pursuit, the journey embodies a practice of sustainable development.

Scientific and technological progress and the energy transition are mutually reinforcing and profoundly changing the prospects for energy development. The development of 5G and IoT technologies expands the scope of sensing and collection from data streams to video streams. The use of big data, AI, and GPS navigation brings plant O&M management from analyzing and diagnosing the device running status to end-to-end O&M and management. The use of cloud technologies and large models not only promotes the integration of the physical and digital worlds, but also enables PV plants to learn and iterate autonomously. "Bits" sense and manage "watts", and moreover, optimize and predict "watts."

Future PV plants will be digital throughout their lifecycle. Future PV plants with core characteristics including digitalization, intelligence, automation can better interact with power grids and meet the needs of other energy sources and users to create an efficient, flexible, and sustainable energy production and supply system. Through the development and application of such technologies, PV plants will play an increasingly important role in the transition of the global energy mix. Huawei will work with more solution ecosystem partners, such as Pinnet Technologies and SNEGRID, to continuously promote the development of PV plant technologies and build a greener and smarter future with the industry.

Compiling team

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