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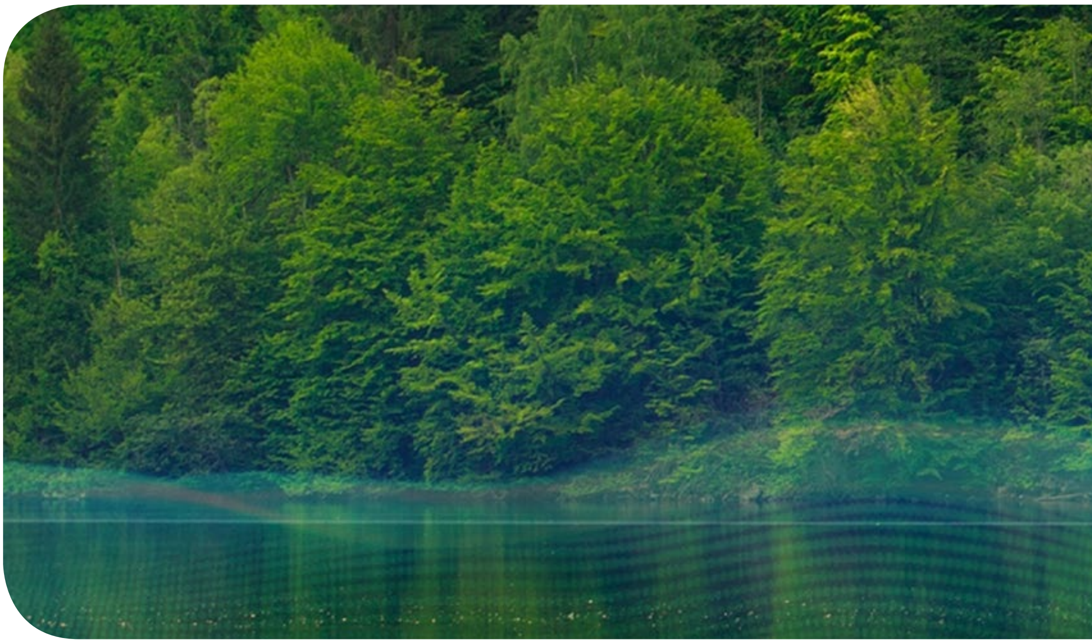
Digital Power 2030

Building a Fully Connected,
Intelligent World



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From the Paris Agreement to COP28 UAE, the global community is accelerating its journey toward carbon neutrality

COP 28 marked the beginning of the end of the fossil fuel era; more than 150 countries have pledged to cut carbon emissions

Since the 18th century, coal, oil, and electricity have been extensively utilized, each playing crucial roles in the first and second industrial revolutions. These energy sources facilitated the transition from an agricultural society into the industrial economy. As a cornerstone of global economic development, energy has consistently driven social progress, reduced poverty, and improved peoples' livelihoods.

However, human activities have clearly impacted the planet's ecosystem with greenhouse gas (GHG) emissions reaching record highs in recent years. According to the United Nations' Intergovernmental Panel on Climate Change (IPCC), human activities generate approximately 23.7 billion tons of carbon dioxide (CO2) annually, with around 20 billion tons resulting from fossil fuel combustion. As a result, the amount of CO2 in the atmosphere now is 27% higher than its average level over the past 650,000 years. The extensive burning of coal during the industrial revolution has resulted in a spike in CO2 levels, putting our ecosystems at unprecedented risk and contributing to severe ecological and economic imbalances. This has prompted discussions on reducing fossil fuel use to lower GHG emissions.

Fortunately, a clearer consensus has been reached among the scientific community and governments on climate change, and the Paris Agreement, signed in 2015, specifies that our most important goal in the global fight against climate change is to achieve carbon neutrality by the middle of the century. The energy development strategies and practices adopted by major economies around the world have proven that reducing our reliance on fossil fuels is one of the best ways to achieve the carbon reduction goals. This requires countries to step up efforts to develop renewables while simultaneously improving energy efficiency and reducing overall consumption of fossil fuels. Multiple countries have put forward targeted energy reform and GHG control goals. At the COP28 UN Climate Change Conference held in Dubai, the United Arab Emirates at the end of 2023, multiple countries and regions reached a consensus on accelerated actions to reduce GHG emissions by 2030. These actions include transitioning from fossil fuels to renewables such as wind and solar, tripling the installed capacity of renewables and doubling the energy efficiency globally by 2030, and phasing out fossil fuels.

As of the first half of 2024, more than 150 countries had pledged to reduce carbon emissions. For instance, China's National Development and Reform Commission and National Energy Administration released the Energy Production and Consumption Revolution Strategy (2016–2030), which specifies that by 2030, China's new energy demand will predominantly be met by clean energy. The strategy proposes reducing total energy consumption to below 6 billion tons of coal equivalent (TCE), with non-fossil fuel making up about 20% of the total primary energy supply by 2030. China has also pledged to achieve its CO2 emissions peak by 2030, if not sooner. The EU's 2030 climate and energy framework aims for net GHG emissions reductions of 55% compared to 1990 levels and an increase in renewable energy consumption to 38–40% by 2030. The US government has also pledged to achieve a 50–52% GHG emissions reduction from 2005 levels by 2030, and one of the most important steps to achieve that goal is to require the US grid to obtain 80% of its electricity from emission-free sources by that year as well.

Global sustainable economic growth requires sustainable energy supplies and renewables will become the most important source of energy

Population growth and national industrialization have driven energy demand to unprecedented levels. Since commercial oil drilling began in the 1850s, experts estimate that the world has harvested more than 135 billion tons of crude oil, with that figure increasing every day. Currently, the global annual consumption of primary energy amounts to approximately 14 billion tons of oil equivalent, which consists of more than 85% fossil fuels. This means that fossil fuels will soon dry up. According to BP Energy Outlook, we will run out of global oil, gas, and coal resources in about 54, 49, and 139 years, respectively, if our current extraction and consumption patterns do not change. This underscores the necessity of advancing renewable energy sources to ensure sustainable development.

According to Goal 7, set in the United Nations 2030 Agenda for Sustainable Development, adopted at the seventieth session of the United Nations General Assembly, the following targets are to be achieved by 2030: ensuring universal access to affordable, reliable, and modern energy services; increasing substantially the share of renewables in the global energy mix; doubling the global rate of improvement in energy efficiency; enhancing international cooperation to facilitate access to clean energy research and technology, including renewables, energy efficiency, and advanced and cleaner fossil fuel technology; promoting investment in energy infrastructure and clean energy technology; and expanding infrastructure and upgrading technology for supplying modern and sustainable energy services for all in developing countries, particularly least developed countries, small island developing states, and land-locked developing countries, in accordance with their respective programs of support.

Countries around the world are making the development of renewables an important part of their future energy strategies. Numerous countries have formulated specific strategies, plans, targets, regulations, and policies to support the development of renewables. In 2023, the Indian government released the latest national electricity plan, which unequivocally states that the accumulated installed capacity of renewables will reach 336.6 GW by 2026–2027 and 596.3 GW by 2031–2032. The Vietnamese government predicts that renewables will account for 30.9%–39.2% of the country's power supply by 2030 and 67.5%–71.5% by 2050. The Malaysian government announced a new renewable energy development target, aiming to increase the share of renewables in the country's electricity mix to about 70% by 2050. The United Arab Emirates plans to triple its renewable energy production by 2030, with approximately US$55 billion earmarked for investment in renewables. The Italian government has boosted the country's 2030 renewable capacity goal from 80 GW to 131 GW. The Portuguese government plans to raise the installed capacity of renewables from 27.4 GW to 42.8 GW by 2030. In September 2023, the European Parliament approved a proposal to promote the deployment of renewables. According to the proposal, the share of renewables in the final energy consumption across the EU will increase from 32% to 42.5% by 2030. Additionally, EU countries are urged to strive for a 45% share. We expect that renewables will contribute 65% of global electricity generation by 2030.

Cost-effective wind and solar power will have a share of 70% in renewables by 2030 thanks to rapid development

Fossil fuels continue to dominate the global electricity supply due to their cost competitiveness compared to other energy sources. If we want to transition to a truly decarbonized energy system that primarily relies on renewables, we must ensure that renewables are cheaper than fossil fuels. As an alternative, the global renewable energy industry has emerged as a promising new market in recent decades. Many countries have made wind and solar power generation part of their new energy strategies, and invested significantly in R&D and industrial development in these areas.

Driven by technological innovation, wind and solar power generation is also growing increasingly affordable. Oxford University's Max Roser found that the levelized cost of electricity (LCOE) of utility-scale photovoltaic (PV) plants was US$0.36/kWh in 2009 and that within just one decade the price had declined by 89% to US$0.04/kWh. However, electricity from fossil fuels, especially coal, is not getting cheaper. Coal-burning power plants have a maximum efficiency of 47%, often leaving little room for substantial efficiency improvements. The price of electricity from fossil fuels is also not only based on the cost of technology itself but, to a significant extent, the cost of the fuel. The cost of coal that the power plants burn accounts for around 40% of total costs. This means that even if the cost of constructing a power plant declines, the price of the electricity it generates will not continue to drop until it reaches a certain point. However, each time the cumulative installed capacity doubles, the price of PV modules declines by 20.2%. The LCOE of PV power will continue to drop as new PV module technologies and processes mature.

In addition to these cost benefits, wind and solar power generation is more flexible than traditional fossil fuel power plants. Resource endowments have long influenced domestic energy development and utilization. However, as wind and solar are becoming the preferred new renewable energy sources, they can transcend the limits of resource endowments and produce electricity anywhere as long as their relevant requirements are met. For example, distributed PV has attracted investors from many industries due to its low investment threshold. As wind and solar power generation becomes more affordable and flexible, more users are willing to use distributed PV systems in campuses, industrial complexes, and commercial and industrial (C&I) scenarios, changing how energy is produced and utilized around the world. Offshore wind power is an important type of wind power that occupies zero land space. The power generated from offshore wind turbines is directly delivered to coastal load centers nearby, avoiding the waste that long-distance transmission causes. Because of this, we are currently seeing a shift from onshore wind farms to offshore wind farms. The proportion of distributed PV systems keeps increasing, with C&I distributed PV systems holding a major market share. Floating PV plants have become popular in many regions because they offer larger power generation capacity, no land requirements, and a lower impact on water bodies. According to IRENA, by the end of 2023, the global accumulated installed capacity of wind power and solar power had exceeded 1,000 GW and 1,400 GW, respectively. We expect that the accumulated installed capacity of solar power will approach 6,000 GW by 2030.

Technologies will drive clean energy development and expedite green transitions across industries

New energy systems based on power electronics equipment will drive the future transformation of the energy industry

Power electronics technologies play a key role in electricity generation, distribution, transmission, and consumption. As more electricity is generated from renewables such as wind and solar, energy industry transformation efforts will focus on building an energy system that will be centered on electricity, connected to power grids, and based on power electronics equipment. The inclusive interfaces, fast response times, and high conversion efficiency of power electronics devices are already being widely implemented in electric power generation, transmission, and consumption.

Electric power generation: Power generation systems using renewables, such as wind and solar, cannot directly transmit electricity to local grids like conventional electric generators. Power from these renewables first needs to be converted into frequency-adjustable AC using power electronics technologies to meet the grid transmission requirements. For example, PV inverters and wind power converters can adjust voltage waveforms through power electronics switches to enable the transmission of renewable electricity to local grids, making power generation more efficient.

Electric power transmission: Intelligent power electronics equipment can significantly enhance long-distance power transmission performance, optimize power flow distribution, and improve the reliability of power supply. This strengthens the reliability of electrical grids, thereby making power

transmission over large-scale grids more secure and efficient.

Electric power distribution: Large numbers of distributed power supplies, microgrids, and flexible loads are being connected to power distribution networks, increasing the requirement for plug-and-play power supply and the overall amount of reactive power in the transmission lines. Problems such as voltage spikes and harmonic distortion are also becoming increasingly serious. There are limited ways to improve the power quality and supply stability of traditional distribution networks, meaning these networks alone can no longer meet user requirements for high-quality electricity. Power electronics equipment, such as multi-functional power electronics transformers, DC circuit breakers, and DC switches, can instead be used to guarantee the power quality of different load categories and meet tailored electricity needs.

Electric power consumption: The demand for DC power and proactive source-load interactions is increasing due to the application of distributed power supply and energy storage devices, and the emergence of new types of facilities, such as data centers, communications base stations, electric vehicle (EV) charging stations, computers, and LED lights. Switching power supplies and switchgears with high efficiency, high power density, high reliability, and low cost are meeting the increasingly diverse personalized needs of users and the demand for quality assurance of electric power.

Demand for new types of power semiconductor devices is set to skyrocket. Future energy systems will need to optimize renewable energy resources and maximize energy efficiency. Consequently, the standards for energy transmission and control subsystems will rise significantly in terms of safety, efficiency, and intelligence. We will need entirely new electricity transmission and distribution networks designed specifically for renewables, more efficient terminal systems that work better with other subsystems like distributed power supply and energy storage, and more comprehensive service systems that are integrated with information systems. Changes introduced by these new systems will need to be managed, compensated, or controlled by power electronics equipment, which currently rely on silicon-based components to a large extent. However, the reality is that silicon-based components are going to hit a wall soon. The physical properties of silicon mean that there will no longer be a way to further improve performance. Many are already struggling to further reduce the energy use of silicon-based components. These components simply won't be a good fit for generating, transmitting, consuming, and absorbing clean energy at scale in future energy systems. Third-gen power semiconductor chips and components, based on silicon carbide (SiC), stand out for their high voltage, frequency, temperature, and speed. These SiC components have delivered a huge boost to the reliability, availability, energy density, and energy conversion efficiency of power electronics equipment while simultaneously reducing overall cost and energy loss. SiC components will be widely adopted as they are ideal for sectors with high requirements on energy conversion efficiency, such as electricity generation based on renewables (e.g., solar and wind), ultra high-voltage direct current electricity transmission, new-energy vehicles, rail transportation, industrial power supplies, and home appliances. The high uptake of SiC components in new-energy vehicles, industrial power supplies, and other domains will also help drive down costs. And there will be a new wave of technologies that will enhance the performance and reliability of SiC components. These trends will prime the SiC sector for explosive growth and market development. In 2023, the market value of SiC components reached US$2 billion. McKinsey estimated that the market for SiC components will expand rapidly, reaching US$10 billion to US$14 billion by 2030. It is estimated that by 2030, over 70% of solar inverters will use SiC components. By then, SiC components will most likely be found in more than 80% of the charging infrastructure and EVs, and be widespread in the power systems of communications networks and servers.

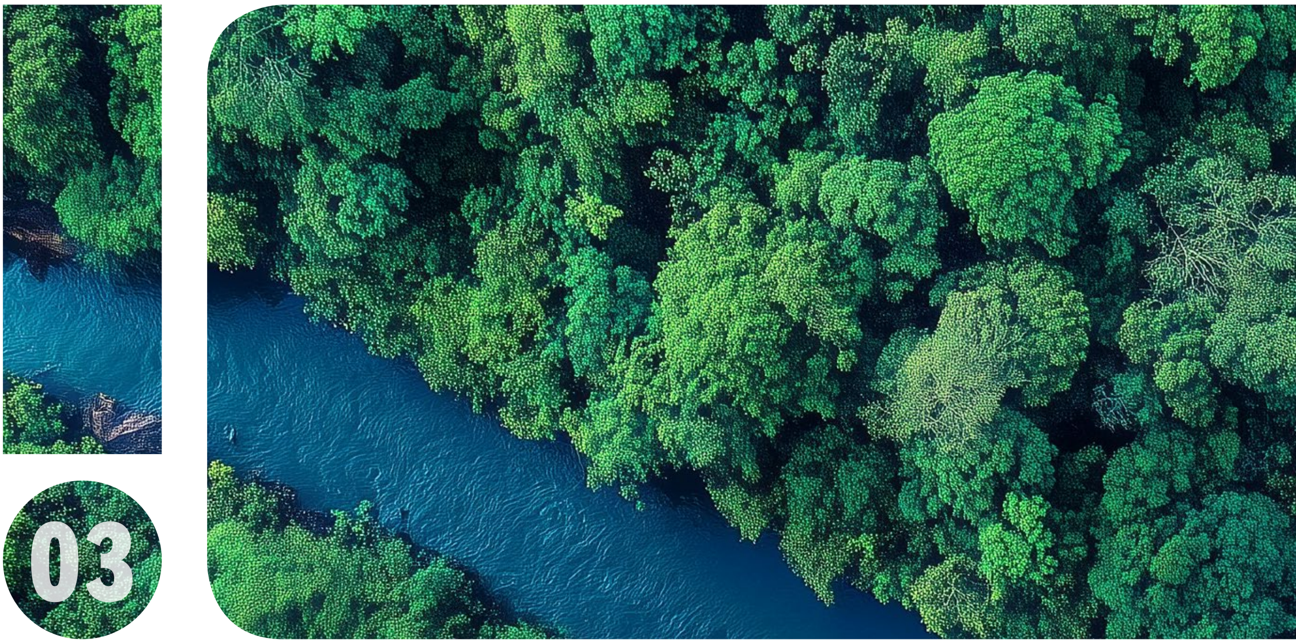
Digital technologies will drive intelligent transformation of energy systems, making renewables smarter, safer, and more efficient

Energy systems will soon become more distributed, thanks to the rapid increase in renewable energy installations (e.g., wind and solar) and the increasing flexibility of applications that support these systems. Energy systems of the future will be decentralized, just like a nebula, with ecosystems made of numerous distributed energy applications. Large power plants, campuses, buildings, households, EVs, and countless other facilities will also develop their own energy systems. These distributed energy systems will not be sustainable if they rely on traditional models. Intelligent connectivity and control powered by digital technologies will make energy systems highly intelligent and connected, which in turn will make them safer and more stable, efficient, affordable, and flexible. They will then be better positioned to reduce carbon emissions and generate clean energy more efficiently.

Advances in emerging technologies, particularly 5G, cloud, AI, big data, and IoT, are ushering all sectors of society into a new digital era. This will be an era where all things can sense, connect, and work intelligently. This vision of ubiquitous connectivity and pervasive intelligence is already becoming a reality. The following new digital technologies are being adopted in the energy sector at an increasing pace and will soon become game changers: Networking: Low-power wide-area networks (LPWANs) are being rapidly commercialized around the world. With wide coverage, low latency, and massive connectivity, 5G is ideal for IoT applications and is permeating a growing array of scenarios that require on-demand, intelligent connections between people, machines, and things. Information processing: Information perception, knowledge representation, and machine learning technologies are advancing rapidly, driving IoT's ability to intelligently process data to levels we have never seen before. IoT virtual platforms, digital twins, and

OSs: Widespread adoption of cloud computing and open-source software is reducing the entry barriers for those who hope to play a part in the energy sector. Cloud computing and open-source software are also boosting the popularity of energy system OSs and digital ecosystems.

As distributed energy systems continue to grow in popularity, users will become prosumers – those who both consume and produce energy. Highly intelligent energy systems can flexibly determine when to switch from generating electricity (when energy prices are high) to storing electricity (when energy prices are low). The systems will leverage generation-grid-load-storage synergy to facilitate energy dispatching and complementation, and they will be able to transfer energy flow to and from each other across time zones and across vast distances. EVs will be able to double as energy storage facilities that feed electricity back into the power grid during peak hours to help meet demand. Data centers will be able to provide heating by reclaiming huge amounts of the residual heat they produce. Intelligent devices for homes will become endpoints that detect, meter, and trade electricity. Distributed energy, energy storage, and the electricity spot market will thrive. There will be an untold number of prosumers that have resources aggregated and controlled through virtual power plants (VPPs), and they will enable energy systems to better respond to demand and provide value-added services. The proportion of PV plants using AI technologies is expected to reach 90% by 2030.



The three pillars of new energy infrastructure will become the foundations for the intelligent era

In the next decade, renewables like wind, solar, and hydro power will replace fossil fuels as the primary sources of electricity. The electrification of power consumption is also on the rise. Technologies for EVs, hydrogen energy, energy storage, heat pumps, and thermal energy storage are advancing rapidly. Transportation, heating, and other energy consuming systems are rapidly transitioning from diesel, petrol, natural gas, and coal towards electricity. Energy systems will soon be embedded with more advanced plug-ins, and be supported by an energy cloud operating system (OS) that integrates information flows and energy flows. The connection between electricity production and consumption will enable two-way, Internet-based interactions among various industry players, encompassing everything from energy sources and power grids to load management, energy storage, and consumption.

Transforming energy systems will unlock vast opportunities for innovation in technology, business models, and operations throughout the energy sector. New power system infrastructure involving renewables, like solar power, will present numerous opportunities. Similarly, the electric mobility sector, primarily driven by EVs, and other new digital industry energy infrastructure sectors, particularly ICT energy infrastructure, will also see significant growth.

In terms of energy generation, it is predicted that renewables will generate more than 65% of the global electricity by 2030, the LCOE of PV power will be as low as US$0.01/kWh, and the global installed capacity of PV power will approach 6000 GW. In terms of energy consumption, the electrification rate will reach 30%, the annual energy charged to EVs will exceed 1.1 trillion kWh, and more than 80% of ICT energy infrastructure will be powered by green energy sources.

Energy infrastructure of new power systems will focus on clean energy, and power generation, grid, load, and storage will be preliminarily integrated

1) As grid parity extends from PV to PV+ESS, the PV industry is entering the PV+ESS era

LCOE is a measure of the average net cost of electricity generation for a PV plant throughout its lifecycle. It is used to compare the electricity generation costs of PV plants with other types of plants. Under a full-lifecycle investment model, the LCOE is determined by a plant's upfront investment, operation & maintenance (O&M) expenses, and the operational lifespan of the system. By 2030, the LCOE of PV plants is expected to plummet, possibly even down to US$0.01/kWh.

PV plants are composed of PV modules and balance of system (BOS) components (such as electrical cables and solar inverters). Generally speaking, about 45% of a PV plant's investment goes into its PV modules. Over the next decade, this percentage is expected to decrease by at least 15 points due to advancements in engineering techniques, reduced manufacturing costs, and the continually increasing efficiency of PV modules. This means more investment will go to BOS components and O&M. On top of this, technological innovations will drive up the overall cost competitiveness of PV plants.

With the rapid advancement of battery and system technologies, the levelized cost of storage (LCOS) for ESSs is decreasing, positioning ESSs to play a significant role in electricity regulation resources within power systems. AS grid parity extends from PV to PV+ESS, the PV industry has entered the PV+ESS era. The ESS industry is thriving thanks to the significant benefits ESSs provide in business scenarios such as renewable energy consumption, power grid peak shaving, and time-of-use arbitration. Simultaneously, other technologies such as long-term energy storage are also rapidly emerging. In China, the proportion of installed capacity for pumped storage decreased from 97% in 2016 to 67% in 2023. Meanwhile, the proportions of lithium-ion batteries, sodium-ion batteries, flow batteries, flywheel energy storage, and hydrogen energy storage have been increasing. It is estimated that by 2030, the annual newly installed capacity of global energy storage will increase from 46 GW to more than 140 GW. As fossil energy generators are gradually phased out, long-term energy storage will play a crucial role in energy regulation for new power systems.

2) Grid-forming technology helps renewables become primary electricity sources

Grid-forming technology has the potential to make power grids more resilient. Due to the significant fluctuations in PV power generation, it can only meet the energy dispatching demands of power grids with the support of regular power supply services such as peak shaving and backup. Consequently, as more electricity generated from wind and solar energy is fed to a power grid, the grid itself will become more vulnerable. For example, the power grid's system inertia may drop, and its ability to regulate frequencies and control system voltage may be compromised. What's more, the characteristics of faults and oscillations on the power grid may change significantly.

Effectively integrating wind power and PV power generators into power grids and harmonizing operations is key to incorporating large amounts of renewable energy into power grids and changing the energy mix. In a power grid, fossil fuel power plants and hydropower plants typically use conventional synchronous generators. These generators employ mechanical structures to provide stable voltage and frequency, facilitating frequency regulation and voltage control. However, as asynchronous generators gradually replace synchronous generators, the fundamental operation of power systems will change. Consequently, renewables-based power systems will need to simulate the technical indicators of synchronous generators to proactively support the grid's frequency and voltage fluctuations. The goal is to enhance the safety and reliability of power grids.

The grid-forming technology combines power electronics, energy storage, and digital technologies to simulate the electromechanical transients of synchronous generators. When connected to power

grids, the grid-forming generators have many of the same external characteristics of synchronous generators, such as inertia, damping, primary frequency regulation, and reactive voltage control. As a result, the grid-forming generators can offer technical specifications that are similar to the synchronous generators used in fossil fuel power plants. The grid-forming generators can proactively support the operations of renewables-based power systems and make them more grid-friendly. This will help renewables become mainstream and provide a solid technical foundation for incorporating them into power grids.

3) Rapidly advancing digital and AI technologies are being widely implemented to develop smart power systems

With the ongoing trends of decarbonization and electrification, power systems are becoming increasingly complex. They now involve trillions of measurement points, tens of thousands of tegawatts of energy for trading, and hundreds of millions of devices. Consequently, there is a growing need for enhanced computing, second-level fast scheduling, and multi-energy comprehensive optimization. In this context, AI has emerged as a crucial technology for energy transformation.

Integrating digital technologies into PV power plants offers a simple, smart, and efficient way of O&M, production management, and asset management, making otherwise "dumb" power plants significantly smarter. AI will play an expert role in enabling PV power plants to achieve autonomous collaboration and optimization. By predicting weather changes and using the smart tracker control algorithm, PV modules, module supports, and solar inverters can collaborate to find the optimal irradiance angle and maximize energy yields. AI can also accurately locate faults, reducing the O&M workload per person from months to minutes, comprehensively improving energy generation efficiency and reconstructing O&M experience to help improve plant productivity and safety. It is estimated that 90% of PV power plants will use AI technologies by 2030.

For power grids, AI algorithms are used to accurately predict the feed-in power and load consumption, improving energy scheduling efficiency. AI models are applied to inspect power transmission lines, improving the operation efficiency 80-fold and significantly reducing the power outage duration.

For energy consumption, AI technologies are adopted in comprehensive energy efficiency management, enhancing the green power application efficiency by more than 15%. In VPPs and electricity trading markets, AI agents can provide optimal solutions for trading entities through swarm intelligence and game intelligence.

4) Energy clouds will intelligently converge energy and information flows to synergize generation, grids, loads, and storage

Energy clouds that converge energy and information flows will function as the OS of the digital power industry. They will direct information flows, regulate energy flows, and spark an energy revolution in which bits can be used to manage watts. In the future, electricity will be the primary energy carrier in energy systems, and digital and power electronics technologies will be leveraged to transform all aspects of power infrastructure, including power generation, transmission, distribution, usage, and storage. Renewable energy will be observably, measurably, controllably, and adjustably enhanced to address the vulnerability of grid integration of renewables and increase renewable energy consumption. Improving the ability to control and regulate extensive terminal systems, like microgrids, integrated energy, and distributed power supply will also enable real-time interaction between power generation units and users. The data generated by these networks will allow power generation units to learn from and adjust to match user consumption habits, improving resource utilization. This will improve the quality, safety, and stability of electricity systems.

- The physical distribution of energy resources is often the inverse of actual energy demand, but the energy cloud will remove these time and distance limitations from energy flows. Take the situation in China, for example. Northwest and Southwest China have abundant wind, solar, and water resources but low demand for power consumption, while Central, East, and South China have high demand but insufficient energy resources. When renewables are centrally connected to local grids, transmission between these regions is further hindered by high randomness and volatility. On the consumer side, the large numbers of user devices and power supplies, such as EVs and distributed power supplies, result in an increased demand for distribution network resources and increased vulnerability in regional power grids. Grids need stronger zoning and interconnection, simplified system operations, and the ability to provide mutual support. Fault isolation also needs to be strengthened to prevent cascading faults that would cause backbone power grids to break down. An energy cloud can facilitate greater sharing of distribution network resources through technologies like active distribution networks and flexible DC distribution networks. This makes it ideal for scenarios such as microgrids, VPPs, and integrated energy systems. By improving the digitalization of transmission and distribution networks, an energy cloud enhances their flexibility, adaptability, and overall control capabilities.

- An energy cloud makes the balance between energy production and consumption more flexible. The energy cloud will make the connections between electricity production and consumption more resilient by enabling unified management. Synergy between generation, grids, loads, and storage will automate the distribution of integrated energy resources. Regional nodes will be able to be monitored and managed in real time, and regional energy consumption will be equalized to balance production and consumption. In this way, electricity production and consumption are intelligently aligned and collaboratively operated so as to improve resource utilization. For instance, optimization algorithms can ensure that solar PV and wind power generation and ESSs adapt to their respective power markets. These algorithms also consider local weather forecasts and other factors that influence production. Data integration then ensures the optimal combination of power generation. Flexible interconnection and digital control of multiple integrated energy sources will strike a balance between energy supply and demand over larger networks. This will make energy systems more flexible and better able to meet various objectives, such as cost-effectiveness, carbon emission requirements, and comprehensive energy efficiency. It enables the use of a wider range of energy types to meet complementary demands. Flexible conversion and integrated demand responses from multiple energy sources will enhance the flexibility of power systems, making them more capable of incorporating renewable energy.

New-type EV energy infrastructure, exemplified by smart charging networks, is widely applied to mobility services

1) Transportation will be electrified, with EV sales booming

New energy vehicles (NEVs) have grown beyond expectations, leading to an irreversible trend of mobility electrification. By the end of 2023, the number of NEVs on the road in China had exceeded 18 million and that number is set to rise to 180 million by 2034, marking a 10-fold increase over the next decade. By the end of 2023, the number of commercial NEVs on the road in China had reached 2.44 million and it is expected to surpass 22 million, a 9-fold increase in 10 years. Simply put, mobility electrification has become an irreversible trend.

In 2023, EVs consumed 300 billion kWh of electricity for charging. By 2033, this figure is projected to rise eightfold to 2.4 trillion kWh, accounting for 10% of global electricity consumption. The charging network, a vital part of modern mobility infrastructure, is essential for keeping EVs operational and for developing future cities. Charging availability is a major concern for EV owners. Establishing a comprehensive charging network will not only boost EV adoption but also invigorate local industries and ecosystems. Since the charging network benefits from both land and traffic, investments in this area must support its continuous evolution. As the number of EVs increases, the long-term advantages will become more apparent.

The rapid rise of EVs is reshaping the ownership balance, where passenger EV owners are replacing commercial EV owners as the main consumers, accounting for 87% of all types. In light of these changes, the mainstream charging preference shifts from low cost to optimal experience. The existing chargers are still plagued with on-going problems such as poor EV-charger matching, loud charging noise, and major safety concerns: The first-attempt charging success rate of most chargers is still less than 85%; the loud noise of air-cooled chargers brings a bad charging experience to EV owners; more than 50% of thermal runaways still occur during charging or a few hours after charging, which causes buyers to hesitate due to the significant risks involved. Accelerating the construction of charging infrastructure is an important measure to improve user experience and develop the EV industry.

2) Ultra-fast, liquid-cooled, intelligent charging networks are widespread, promoting high-quality and collaborative development of EVs and charging facilities

Comprehensive ultra-fast charging is the future. Technically, third-generation semiconductors like SiC and GaN are now mass-produced for commercial use, enhancing energy efficiency and supporting higher-voltage operations for EVs. The evolution of high-voltage EV architecture allows EVs to support low-current, high-power charging, further promoting ultra-fast charging applications. As one of the core components of EVs, traction batteries have also been upgraded. In these systems, cells determine the charging power. Since 2023, 4C cells have been mass-produced, with prices decreasing to match those of lower-C-rate cells. This price drop motivates automakers to develop ultra-fast charging EV models. Driven by technical and economic benefits, ultra-fast charging will soon be widespread. In 2021, only eight EV models supported ultra-fast charging, but by the end of 2023, that number grew to 113 at an automobile expo in Guangzhou, China. Ultra-fast charging is no longer restricted to high-end EV models, but can also be applied to mid-range and low-end ones, and the number of ultra-fast charging EVs will skyrocket in the future. Ultra-fast charging offers immense value to commercial vehicles, especially where time is money. The time saved translates to lower operational costs and higher revenue. With the trend towards high-voltage and ultra-fast charging, it is estimated that over 60% of EV models on the road will support ultra-fast charging by 2030.

The operation and maintenance of chargers are facing greater challenges due to the emergence of diverse charging scenarios, such as the deployments in tropical regions, coastal areas, and mining sites. At the same time, working conditions are increasingly complex, requiring chargers to work properly in hot, humid, salty, or dusty environments. Traditional chargers adopt air cooling or semi-liquid cooling. As the protection capability is weak, the circuit boards and power components in the charging modules are directly exposed to the external environment. Therefore, the annual failure rate of the modules can be 3%–8% or even higher due to humid air, dust, or heat, reducing the service life of chargers to only 3–5 years. Moreover, fans for the power units and charging modules are vulnerable mechanical components, which require frequent cleaning and maintenance onsite at least four times per year, significantly increasing the O&M costs of charging stations. To overcome these difficulties, the cooling method of chargers is transitioning to fully liquid cooling, covering the charging dispensers, charging modules, and power units. Fully liquid-cooled devices are protected to IP55 or higher, completely isolated from external corrosive materials, and enjoy a longer service life. In addition, during high-current charging, heat generated by charging connector ports is efficiently dissipated by liquid cooling cables, ensuring rapid cooling. Similarly, the heat from power components is managed in real-time by liquid pipes. The system intelligently adjusts the flow rate based on cooling needs, ensuring precise temperature control. The fully liquid cooling architecture offers numerous advantages, including high quality, long service life, wide application scenarios, and easy and cost-effective O&M. The annual failure rate of charging modules can be reduced to less than 5‰ and they can work for one decade or longer in most scenarios.

The lack of advanced digital charging networks results in the isolated management of networks, charging stations, chargers, and EVs. To change this and achieve all intelligence in the future, these isolated parties will be deeply integrated to create the following benefits:

First, EVs and chargers will collaborate more effectively. The head unit in an EV helps the EV communicate with a charger in real time to generate the optimal charging solution and map out the navigation route for the EV owner based on information such as the battery state-of-charge (SOC), EV location, and destination. Technologies like wireless charging, automatic plug-in, and autonomous driving can simplify charging operations, allowing robots to handle the process. After charging, EV owners can pay bills easily and securely using technologies such as blockchain and facial recognition.

Second, the grid-friendly charging networks will support the grid with millisecond-level demand response and high-precision intelligent scheduling. According to the loads and electricity price of the grid, the operation strategy of the charging stations can be dynamically adjusted to balance and optimize the charging demand and power supply.

Third, all-digital O&M of the charging networks will be achieved by using technologies such as cloud management, remote fault diagnosis, and automatic fault recovery. These technologies will detect, locate, and handle charging network faults and exceptions in a timely manner, reducing manual inspection and maintenance, improving the grid connection rate and service quality of the charging networks, and helping operators cut business costs and expand their service range.

3) EVs can collaborate deeply with various energy systems, serving as crucial regulation resources

EVs will become fully involved in interactions with energy systems as important regulators in energy flow control. The large-scale promotion of EVs and renewable energy creates opportunities for EV-grid synergy. There is increasing demand for a large number of flexible power sources on the power generation side and for adjustable load resources on the consumption side. Unlike more common electrical loads such as household appliances, EVs are highly flexible and adjustable. As wireless charging, smart charging, and autonomous driving technologies mature and are widely adopted, EV users will be free to choose when to charge, discharge, and swap batteries, participating in the electricity spot market and ancillary service market based on their individual needs. This will reduce the impact of EV charging on the power grid, provide new resources for the power system to schedule, and avoid a large amount of wasted investment in the power grid and power supply.

The number of EVs worldwide could exceed 150 million by 2030. Ideally, by that time, the energy storage capacity should be 40 times as large as the energy storage capacity installed in 2020, with the potential to serve as an adjustable load and a flexible power source. EVs perform orderly charging as a way to contribute to local peak shaving, bringing about huge economic benefits. In the future, EVs participating in the frequency regulation ancillary service market will have higher value. EVs will be able to take full advantage of their role as flexible loads and perform orderly charging as a way to contribute to user-side applications such as peak shaving, distributed PV charging, demand response, peak staggering ancillary services, and spot market balancing.

Charging infrastructure connects EVs, transportation systems, and mobile lifestyles, as well as diverse energy use scenarios. It is the point of convergence for energy and transportation, in terms of transactions, interaction, behavior, and information. It is one of the important enabling components of the energy cloud.

Large-scale construction of charging networks and the development of technologies such as digitalization, IoT, cloud computing, big data, and AI bring about multilevel improvements in intelligence: Intelligent charging infrastructure will make charging networks visible, manageable, controllable, and optimizable, significantly reducing O&M costs and increasing efficiency and revenue. As a data interface, chargers can be utilized to build a smart charging network that integrates EVs, chargers, power grids, the Internet, and value-added services. This network will leverage chargers' strengths in terms of scale, integration, data, and connectivity, create multiple new business models, and generate a virtuous cycle of economic and social benefits. Chargers enable charging facility operators to provide data consulting services to support business district construction, real estate development, dealership store planning, second-hand car trading, digital payments, and e-commerce operations as a way to monetize, expand sources of revenue, and improve market operation capabilities. For local governments, chargers can provide data support for urban planning, power dispatching, everyday services, and infrastructure construction, making charging infrastructure an important part of smart cities. It is estimated that by 2030, the annual energy charged to EVs will exceed 1.1 trillion kWh.

Empowering the digital age: green, simple, smart, and reliable energy infrastructure

Consumer data traffic from cellular networks and fixed broadband will grow at a compound annual growth rate of 29% in 2024, increasing from 1.3 million PB in 2018 to 5.8 million PB in 2024. This rapid growth poses significant challenges to existing ICT infrastructure, including data centers, data center interconnection networks, and Internet access networks. To meet these new demands, operators, cloud vendors, and Internet enterprises are upgrading, expanding, and scaling up their data centers. However, data centers consume substantial amounts of electricity to process service loads, resulting in considerable indirect carbon emissions. Building efficient and low-carbon communications networks and data centers is not only an operational necessity for enterprises, but also their civic duty. Leading operators worldwide have made carbon reduction commitments and launched various initiatives. Vodafone and Orange aim to achieve net zero emissions by 2040, while Telefónica has set its target for 2030. Google plans to power all its operations, including data centers and campuses worldwide, entirely with carbon-free energy by 2030. Microsoft has pledged to be carbon negative by 2030, and to remove all the CO2 it has ever emitted, either directly or through electricity use since its founding in 1975, by 2050. Additionally, the municipal government of Beijing mandates that data centers be built with their own distributed renewable energy facilities and be powered 100% by clean energy by 2030. Key players in Europe's cloud infrastructure and data centers have developed a self-regulatory initiative, the Climate Neutral Data Centre Pact.

It is not only crucial to make data centers to be green and low-carbon, but also their significant responsibility as infrastructure to drive the rapid digital and low-carbon transformation of the energy-intensive industries. In the digital economy, the consumption of energy will bring "overlaid returns." Each kilowatt-hour of electricity used in a data center contributes to not only the business value of this data center, but also those of various industries whose applications, including cloud computing, big data, and Internet services, run on these services. Estimates suggest that every ton of standard coal consumed can directly generate CNY11,000 for a data center, contribute CNY888,000 to the added value of the digital industry, and indirectly create a digital market worth CNY3.605 million (excluding parts not directly related to the data center). According to the Global Enabling Sustainability Initiative (GeSI), the ICT sector's carbon emissions will account for 1.97% of global carbon emissions by 2030. However, by enabling

other industries, the ICT sector will help reduce global carbon emissions by 20%, which is 10 times its own emissions. This positive impact is known as the "carbon handprint." Therefore, building green and low-carbon data centers not only promotes the high-quality development of the ICT sector but also enables traditional energy-intensive industries. Through actions such as "migrating to cloud, using digital tools and enabling intelligence," one industry can empower various industries, leading to significant reductions in energy consumption and substantial improvements in productivity and total factor productivity.

We predict that the ICT energy infrastructure will develop in the following directions in the next decade. And more than 80% of the ICT energy infrastructure will be powered by green energy.

1) Green electricity will bring more green computing power

As digitalization progresses globally, the ICT sector has increasingly become energy-intensive. Driven by the carbon reduction targets, the shift toward green energy supply for ICT infrastructure is inevitable. Clean energy sources such as PV, wind, and hydrogen will be integrated into ICT energy infrastructure. Due to their cost-effectiveness and flexibility, more than 80% of power supply systems in ICT infrastructure are expected to incorporate distributed green energy within the next decade. For telecom sites with low power consumption, distributed PV may become the primary power source, enabling zero-carbon telecom networks. Unlike conventional power purchase agreement (PPA) for renewables and renewable energy certificates, data centers will adopt a direct supply of clean energy. This includes building distributed PV plants on data center campuses and rooftops, or building utility-scale PV, wind, and other clean energy plants in nearby areas to directly supply power to data centers. With intelligent control, these distributed energy systems will no longer provide unidirectional power supply but will also participate in ancillary services markets such as power grid peak shaving. This helps smooth out the random and intermittent output of wind power and PV. Consequently, this approach enhances the power supply benefits of ICT infrastructure, maximizes the business value of basic resources, and improves the stability and reliability of the entire energy system.

2) Reliability is the most essential requirement of ICT infrastructure

ICT infrastructure forms the physical backbone for handling vast amounts of data and serves as the core resource for centralized information processing, computing, storage, transmission, exchange, and management. It is vital for the smooth functioning of society and the economy. Consequently, reliability is the lifeline of data centers, yet it often remains the weakest link. Implementing a comprehensive end-to-end assurance mechanism provides the most robust foundation for the reliable and stable operation of infrastructure throughout its lifecycle.

Ensuring the reliable and stable operation of the infrastructure hinges on highly dependable products and professional services. Each infrastructure comprises of tens of millions of components, necessitating an end-to-end full-link assurance mechanism that spans from product inherent reliability to design and O&M by expert teams. Take lithium-ion batteries as an example. During the planning phase, considerations should include remote deployment or separate compartment design with a water fire suppression system for lithium-ion battery rooms. In the construction phase, selecting highly reliable products is crucial. Additionally, strict control over transportation, warehousing, and installation specifications, along with a robust O&M inspection mechanism, is essential to build emergency response capabilities. These comprehensive measures ensure the reliable operation of data centers.

As the power density of ICT infrastructure increases, the time available for emergency handling significantly decreases, presenting greater challenges for maintenance. AI technologies enable risk prediction and data center infrastructure management. AI algorithms can learn from historical and real-time data to predict and identify abnormal patterns. This shift from passive reaction to proactive prevention enhances the reliability of ICT infrastructure through improved O&M.

3) Comprehensive architecture refactoring is making ICT energy infrastructure simple, converged, smart, and efficient

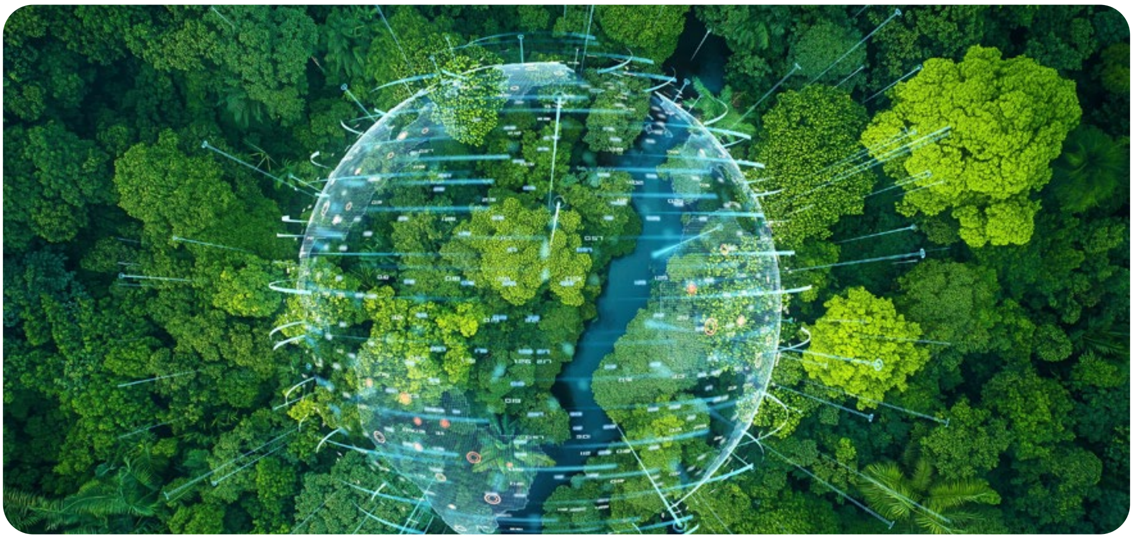
Networks and data centers are becoming larger and more complex. The ongoing pursuit of simplicity is driving the development of ICT energy infrastructure architecture toward greater convergence. Most of today's telecom sites are built indoors, and traditional air conditioners are used for cooling. The overall energy efficiency of these sites is only 60%. Conventional power supply solutions typically use multiple sets of power supply equipment, each supporting a different voltage system, which complicates deployment. We believe that the form of telecom sites will change dramatically in the next decade. What once filled an equipment room can now be squeezed into a cabinet, and what once filled a cabinet can now be mounted on a pole. Sites are becoming simpler and more reliable, with smaller footprints and lower leases. The way in which data centers are built will also change rapidly. Traditional concrete buildings usually take more than 20 months to build, and the building materials are neither environmentally friendly nor recyclable. Prefabricated modular data centers will become increasingly common over the next decade. Prefabrication reduces the use of high-carbon-emission materials, such as concrete, rubber, and rock wool sandwich panels, and dramatically reduces onsite construction and maintenance. This way, a data center housing 1,000 racks can be built in only a few months, meeting the requirements for rapid service rollout. In terms of network and data center power supply solutions, power supply link convergence will become a major trend. Adapting to more renewable energy sources, ensuring compatibility with multiple energy supplies, and being ready for smooth evolution are the directions in which the power supply architecture will evolve. Examples include multi-mode scheduling control and management, modular overlay evolution, and the convergence of different services and devices across multiple scenarios. With this converged architecture, power supplies and batteries of telecom sites are being integrated into a blade form factor. This approach develops power supply, energy storage, temperature control, and power distribution into individual modules, enabling on-demand evolution to support cross-generational network advancements. All data center power supply links, including transformers, uninterruptible power systems (UPSs), and power distribution, will be converged to reduce the installation footprint. Backup power will rely on lithium-ion batteries, facilitating intelligent collaboration between power generation, storage, and consumption. This reduces the required capacity of the data center UPS, as well as the footprint and construction costs of data centers.

4) DC for AI, AI for DC

With the continuous progress of AI technologies, the operation of data centers is undergoing a revolutionary transformation. AI technologies not only help improve the energy efficiency of data centers and reduce operation costs, but also play a key role in ensuring data center reliability.

In terms of reliability, advanced AI prediction and analysis technologies can predict the service life of key devices such as capacitors and fans in the UPS. In addition, outlier algorithms can identify potential faults of lithium-ion batteries in advance, implementing early fault detection and prevention, which is similar to the concept of "prevention is better than cure" proposed by Bian Que, a famous doctor in ancient China. In terms of energy saving, the AI energy saving algorithms will optimize the cooling system of a data center through real-time analysis and adjustment. Compared with traditional manual optimization, AI algorithms automatically adjust parameters based on real-time weather changes, significantly improving the overall cooling efficiency by an estimated 8%–15%. In terms of simple O&M, AI technologies significantly reduce the workload and difficulty of routine O&M. Traditionally, inspecting the power supply and distribution system requires 6 to 12 onsite meter readings daily. However, with AI technologies, inspecting 2,000 cabinets can be completed in just 5 minutes. Additionally, the AI O&M assistant can monitor devices 24/7, receive real-time device alarms, and provide corresponding solutions. Monthly health reports are automatically generated, offering robust data support for service decision-making.

The application of AI technologies in data centers improves operation efficiency, reduces energy consumption, and enhances data center reliability. With the further development of technologies, we believe that AI will become an indispensable part of data center operations, enabling them to become greener, simpler, and more reliable.



Quality and safety will become key challenges for renewables

The extensive use of power electronics devices presents significant challenges to the grid connection and operational safety of renewable energy plants.

As high proportions of renewables and power electronics devices including power supplies, loads, and ESSs with different electrical characteristics, are integrated into existing power systems, the strength of the power grid is significantly reduced. This reduction is due to issues such as voltage instability, frequency instability, power angle instability, and wideband oscillation. Renewable energy devices have poor voltage tolerance capabilities. When a fault occurs, they can provide only 1.1 times the rated current for dynamic voltage support. Traditional thermal power can provide 5–10 times the rated current. In addition, renewable output requires voltage boosts by several stages before being fed into the power grid, and the electrical distance from the grid connection point is 2–3 times that of a common generation unit. With a low short circuit ratio (SCR), a renewable plant may not provide sufficient voltage support for the power grid. Devices such as renewable grid-tied inverters and converters do not have the inertia response capability. As a result, the overall inertia of the power grid is low and the system frequency regulation capability is reduced. The low inertia of renewable generation units also causes the amplitude to decrease for the power angle curve, resulting in power angle instability. The rapid response feature of renewable generation units also causes new problems of wideband oscillations in medium and high frequency bands.

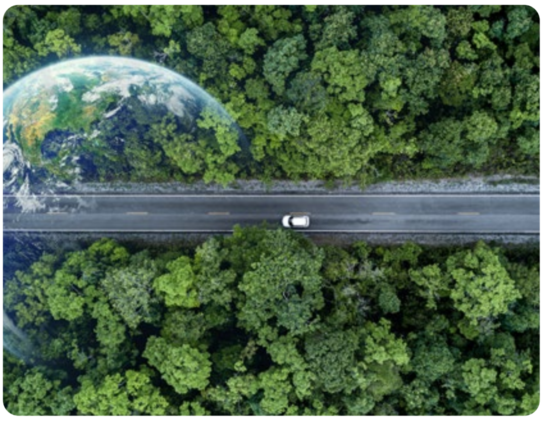
O&M for utility-scale renewable plants are challenging due to their large footprints, high capacities, and numerous devices. For instance, a simple inspection of a 100 MW plant can take at least five person-days. Additionally, most utility-scale projects are situated in remote areas with harsh environments, such as hot deserts with heavy sandstorms, seas with high humidity and salinity, or extremely cold high-altitude plains. These adverse conditions significantly impact the quality and reliability of devices, posing serious threats to the operational safety of the power plant.

For a distributed PV system, more and more devices are deployed in buildings, campuses, and homes, which are closely related to daily production and life. Once an accident occurs in a rooftop PV system, personal and property safety will be seriously threatened. DC arcs have been proved to be a major fire risk in rooftop PV plants. Arcs may occur due to poor contact in PV module weld joints, aging cables, and loose terminal connections. In rooftop PV projects, the DC voltage of PV modules can reach 600–1000 V as long as there is sunlight, even if the equipment is shut down. This poses potential risks to construction workers, O&M personnel, and plant owners. During emergencies such as fires, rescue personnel face significant challenges. They cannot access the rooftop or use water to extinguish the fire due to the high voltage present in the PV array. Consequently, they often have to "let it burn," waiting until all PV modules are burnt before intervening. This approach significantly hampers the rescue process, leading to greater personal and property losses.

Firstly, to cope with these challenges, we should focus on the quality of devices initially. The industry should reach a consensus on the importance of quality and ensure product safety and reliability by using high-quality hardware and software. Secondly, we need to integrate individual technologies such as PV modules, ESS, grid forming, digitalization, and intelligence to develop innovative renewable solutions which shift from grid following to grid forming, achieve intelligent DC safety diagnosis, warning, and protection in system O&M, and ensure personal and asset safety in various scenarios.

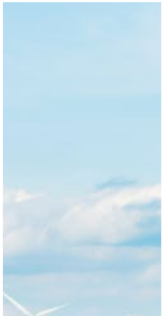
Extensive deployment of ESS presents huge challenges such as the risks of carrying massive energy, thermal runaway, and control difficulty in case of fire carrying massive energy, thermal runaway, and control difficulty in case of fire

With the rapid and extensive application of ESSs, numerous serious incidents have occurred in ESS plants, resulting in significant economic losses and casualties. In May 2024, a fire broke out at the world's largest energy storage plant at the time, with a capacity of 250 MWh, in San Diego, California. The fire reignited multiple times and lasted for 11 days, causing severe losses and environmental impacts. According to incomplete statistics, 65 major energy storage fire accidents occurred worldwide from 2019 to 2023. Of these, 27 were utility-scale and C&I energy storage accidents caused by battery quality issues such as process defects and uneven copper foil coating. Twelve were residential energy storage accidents due to battery quality problems like iron shavings falling into the module. Seven were data center accidents caused by water intrusion, management system faults, and battery quality issues. Nineteen were attributed to other quality problems, including improper battery securing methods and insulation faults. Moreover, there are no mature standards and specifications for the design, construction, commissioning, operation, and maintenance of energy storage plants. The management, operation, and maintenance of these plants need to be conducted with greater professionalism. As a new component of the power system, the energy storage industry is still in the exploration phase, and safety has become a significant challenge for its development.



As a kind of regulation resource of an energy system, the ESS is becoming increasingly prevalent. The scale of a lithium-ion battery site is increasing to GWh-level. The large-capacity ESS is developing from 2 MWh per cabinet to 5 MWh+ per cabinet, boasting higher energy densities. Additionally, the adoption of diverse new technologies, such as sodium-ion batteries, flow batteries, and supercapacitor batteries, is on the rise. Consequently, this technological advancement brings about more complex safety risks in energy storage plants.

To mitigate the safety risks associated with energy storage plants, ensuring the high quality of energy storage products is essential. By addressing potential issues from the ESS architecture design, accidents can be prevented before they occur. The manufacturing and usage of key components such as battery cells are important to ensure body safety. Proper heat insulation and flame-retardant materials should be selected. Heat dissipation, smoke exhaust, and fire suppression systems are designed to improve passive safety, while online monitoring, intelligent control, and safety warning technologies are developed to ensure active safety. Safety principles and management should be implemented throughout the entire lifecycle of an energy storage plant, spanning from planning and design, equipment selection, manufacturing, acceptance, transportation, delivery, onsite installation, system commissioning, operation control, repair and maintenance, and plant retirement. Furthermore, relevant safety standards and regulations should be developed and implemented based on industry practices, and consolidated by policies and regulations to promote the high-quality development of the industry.



Conclusion

The energy sector has made remarkable strides, evidenced by the convergence of renewable energy, digital technologies, and power electronics. In the future, electricity-based energy systems will resemble ICT networks, with power grids acting as the backbone, power electronics devices as gateways, and the energy cloud as the operating system. This evolution will transform how energy flows are processed, moved, and stored. We are on the brink of large-scale development and utilization of clean, low-carbon energy. Multi-level energy networks will be widely connected, enabling both active and passive participation from various loads. Collaborative decision-making and operation across multiple service logics will become a reality. Over the next decade, the integration of energy and information flows will deepen, supporting each other and marking a key transition period for comprehensive energy transformation. This shift will shape the energy landscape for the next century. As we enter the intelligent age, technological innovations in information and energy flows are becoming increasingly synchronized. The focus of innovation is shifting from individual devices and scenarios to entire systems and industries. Energy networks are expanding from local to global scales, and operations are transitioning from device-based to cloud-based. Energy systems are becoming more visible, measurable, and controllable on a broader scale. The convergence of energy and information flows is amplifying the value of energy systems, making them more economical, cleaner, and safer to operate. New models of electricity production, transmission, storage, and consumption are emerging, heralding a new era in the energy sector. The integration of energy systems with information and commercial systems is transforming the energy landscape. Energy networks are evolving from standalone entities into critical infrastructure platforms that interconnect with transportation, carbon footprint, and information networks. This collaborative control across industries enhances the scope and method of energy cloud management, extending beyond individual devices and systems.

Technological advancements and energy transformations are mutually reinforcing, profoundly shaping the future of the energy sector. By recognizing major trends, we can better address future challenges and seize current opportunities. In this emerging digital power era, collaboration is key. Building new alliances and exploring innovative ways to collaborate across value chains and ecosystems will drive global energy innovation and development. Together, we can propel energy transformation, creating low-carbon, electrified, digital, and intelligent energy systems. This collective effort will make the world a greener, better place for all.

HUAWEI TECHNOLOGIES CO., LTD.
Huawei Industrial Base
Bantian Longgang
Shenzhen 518129, P. R. China
Tel: +86-755-28780808
www.huawei.com