Digital Power
2030

Building a Fully Connected,
Intelligent World

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The next energy transformation: Low-carbon and sustainable energy

Scaling back fossil fuel consumption and greenhouse gas emissions has become an urgent task for the world

Coal, oil, and electricity have been widely used since the 18th century. They played pivotal roles in the first and second industrial revolutions, helping civilization transition from an agricultural society into the industrial economy. As a cornerstone of global economic development, energy has consistently driven social progress, poverty reduction, and improvement of peoples' livelihoods.

However, human activities have clearly impacted the planet's ecology with greenhouse gas (GHG) emissions reaching record highs in recent years. According to the United Nations' Intergovernmental Panel on Climate Change (IPCC), human activities produce about 23.7 billion tons of carbon dioxide (CO_2) every year, of which around 20 billion tons are produced by burning fossil fuels. As a result, the amount of CO_2 in the atmosphere now is 27% higher than its average level over the past 650,000 years. The large amount of coal burnt during the industrial revolutions has resulted in a spike in CO_2 levels, putting our ecosystems at unprecedented risk and contributing to severe ecological and economic imbalances. This has driven people to discuss how to use fewer fossil fuels to reduce GHG emissions.

Fortunately, a clearer consensus has been reached among the scientific community and governments on climate change, and the Paris Agreement specifies that our most important goal in the global fight against climate change

is to achieve carbon neutrality by the middle of the century. Countries around the world are taking action. By the end of 2020, 44 countries and economies had officially declared their own carbon neutral targets. Some of these countries and regions have already achieved their targets, and others have already incorporated their targets into public policy and legislation.

The energy development strategies and practices adopted by major economies around the world have proven that reducing reliance on fossil fuels is one of the best ways to achieve carbon peak and neutrality goals. This requires countries to step up efforts to develop renewable energy while simultaneously improving energy efficiency and reducing overall consumption of fossil fuels.

Multiple countries have put forward targeted energy reform and GHG control goals. For example, China's National Development and Reform Commission and National Energy Administration have released the Energy Production and Consumption Revolution Strategy (2016–2030), which specifies that by 2030, China's new energy demand will mostly be met by clean energy. The strategy proposes reducing total energy consumption to at most 6 billion tons of coal equivalent (tce), with non-fossil fuel only making up about 20% of the total primary energy supply by 2030. China has also pledged to achieve CO_2 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 get 80% of its electricity from emission-free sources by 2030.

Sustainable, renewable energy will play a vital role in driving sustainable development of the world economy

Population growth and national industrialization have driven energy demand to unprecedented levels. Since commercial oil drilling began in the 1850s, experts estimate that we have harvested more than 135 billion tons of crude oil, with that figure increasing every day. Currently, global annual consumption of primary energy amounts to about 14 billion tons of oil equivalent, of which more than 85% is fossil fuels.

This means that fossil fuels will soon run out. According to BP, we will run out of global oil, gas, and coal resources in 50, 53, and 134 years, respectively, if our current extradition and consumption patterns do not change. This makes the development of renewable energy sources imperative to ensure sustainable development. UN Secretary-General António Guterres himself said, "Renewable energy is crucial for building a sustainable, prosperous and peaceful future" at the High-level Dialogue on Energy in March 2021. He also noted, "The year 2021 must be a historic tipping point towards sustainable energy for all."

According to Goal 7, set in the United Nations 2030 Agenda for Sustainable Development that was adopted at the seventieth session of the United Nations General Assembly: By 2030, ensuring universal access to affordable, reliable and modern energy services; by 2030, increasing substantially the share of renewable energy in the global energy mix; by 2030, doubling the global rate of improvement in energy efficiency; by 2030, enhancing international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology; and by 2030, expanding infrastructure and upgrading technology for supplying modern and sustainable energy services for all in developing countries, in particular 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 renewable energy an important part of their future energy strategies. Many countries have formulated specific strategies, plans, targets, regulations, and policies to support the development of renewable energy.

South Korea, for example, has unveiled a new long-term plan for renewable energy that increases the share of renewable energy sources in the electricity supply. According to this plan, by 2034, all coal-burning power plants in South Korea will be shut down and renewable energy will make up 40% of the country's total energy supply, up from their current 15.1%.

France's National Energy Plan 2030 notes that the country will continue to increase the share of renewables, especially wind power, in their power generation in order to achieve an energy transformation. France plans for renewables to account for 40% of its total power generation, with wind power accounting for 20%.

Germany plans to increase the percentage of renewables in their energy mix to 30% from their current 18%. Chile formally launched a green

hydrogen strategy in November 2020 to promote transformation of the country's energy structure that plans to reduce the amount of coal power to 20% by 2024 while gradually increasing hydropower, wind, photovoltaic (PV), and biomass power generation. Their ultimate goal is to increase the proportion of renewables in the country's total energy supply to 70% by 2030, and shut down all coal-burning power plants by 2040. Brazil has also continued to introduce policies and measures to provide funds and policy support for the development of PV infrastructure and projects. By 2035, total investment in the Brazilian electricity industry will exceed US$30 billion, 70% of which will be used to develop renewable energy technologies such as PV, wind, biomass, and ocean energy.

Cost-effective wind and solar power will drive an energy revolution

The cost of renewable electricity generation is dropping rapidly, even if fossil fuels still dominate the global electricity supply. Coal remains the biggest source of electricity by far, supplying 37% of all electricity, with gas coming in second supplying 24%. This is because fossil fuels are cheaper than other sources of energy. If we want to transition to a truly decarbonized energy system that primarily relies on renewable energy, we must ensure that renewable energy is cheaper than fossil fuels.

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 into supporting 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 Energy (LCOE) of large-scale terrestrial PV plants was US$0.36 per kWh of electricity in 2009 and that within just one decade that price had declined by 89% to US$0.04 per kWh of electricity.

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 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 solar modules declines by 20.2%. Solar power has already become much more affordable in recent years, and this trend will continue 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 plants. Resource endowments have long influenced domestic energy development and utilization. However, as wind and solar are becoming 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 businesses, changing how energy is produced and utilized around the world. By the end of 2020, the global installed capacity of wind power and solar power had exceeded 650 GW and 750 GW, respectively.

Offshore wind power, for example, is an important type of wind power that occupies no 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.

By 2024, distributed PV systems will account for nearly half of the entire solar power market, with industrial and commercial 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 lower impact on water bodies. Over 60 countries have been pushing for wider adoption of floating PV plants, with total power output from floating PV plants expected to reach over 60 GW in the next five years. We expect that the global demand for fossil fuels will also peak in next five years as wind and solar power become more affordable and the installed capacity spikes.

Power electronics and digital technologies are a key driver of energy transformation

Power electronics technologies ensure security and control during energy system transformations

Power electronics technologies play a key role in electricity generation, distribution, transmission, and consumption. As more electricity is generated from renewable energy sources such as wind and solar, energy transformation efforts will focus on building an energy system that will be centered on electricity, connected to power grids, and based on power electronics devices. 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.

a) In electric power generation, power generating systems using renewable energy, 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 converters can adjust voltage waveforms through power electronics switches to enable the transmission of renewable electricity to local grids, making power generation more efficient.

b) In electric power transmission, intelligent power electronics devices can significantly improve long-distance power transmission performance, power flow distribution, and reliability of power supply. This makes electrical grids more secure, thereby making power transmission over large-scale grids more secure, reliable, and efficient.

c) In 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. Power electronics devices, 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.

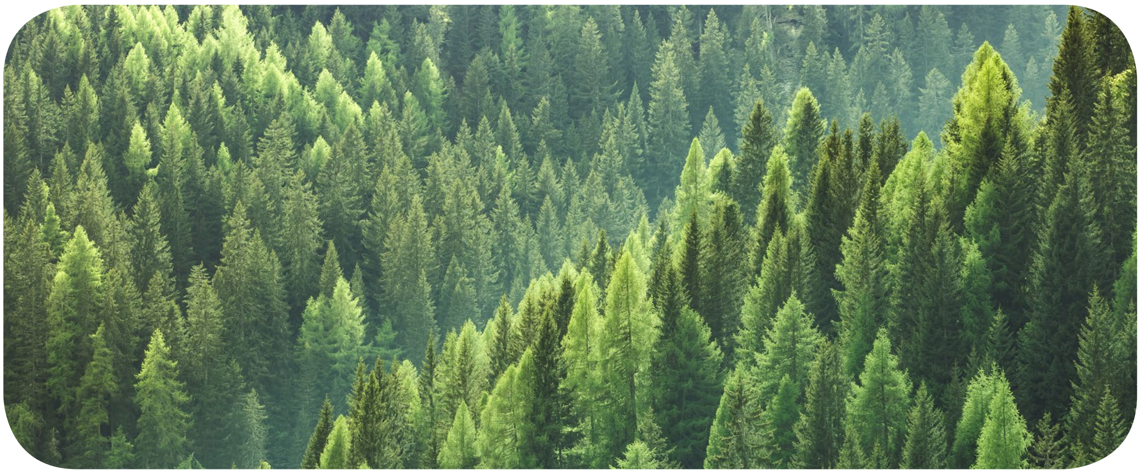
d) In electric power consumption, demand for DC power and proactive source-load interactions are increasing due to the application of distributed power supply and energy storage devices, and the emergence of new types of facilities, such as data centers, communications base stations, electric vehicle (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. Energy systems of the future will need to better utilize renewable energy resources, meaning the bar for energy transmission and control subsystems is going to 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 devices, 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, high operating frequency and temperature, and high speed switch. These SiC components have delivered a huge boost to the reliability, availability, energy density, and energy conversion efficiency of power electronics devices while simultaneously reducing overall cost and energy loss. SiC components 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 next decade will see increased efforts to adopt and further innovate third-gen power semiconductor devices. The substrates used



in SiC components are currently four to five times more expensive than those used in silicon components, but their costs are expected to break even by 2025. By then, high uptake of SiC components in new-energy vehicles, industrial power supplies, and other domains will help drive down costs. New technologies that will enhance the performance and reliability of SiC components are also expected to emerge. These trends will prime the SiC sector for explosive growth and market development. Yole Développement predicted that the market for SiC components will expand rapidly, from US$600 million in 2020 to US$10 billion by 2030. It is estimated that by 2030, over 70% of solar inverters will use SiC components, compared to the current 2%. By then, SiC components will most likely be found in more than 80% of charging infrastructure and EVs, and be widely used in the power systems of communications networks and servers.

Digital technologies drive intelligent transformation of energy systems for greater value creation

Energy systems will soon become more distributed, thanks to the rapid increase in the number of new renewable energy facilities (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 more effectively generate clean energy.

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 quickly gaining commercial popularity 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 progressing by leaps and bounds, driving IoT's ability to intelligently process data to levels we have never seen before.

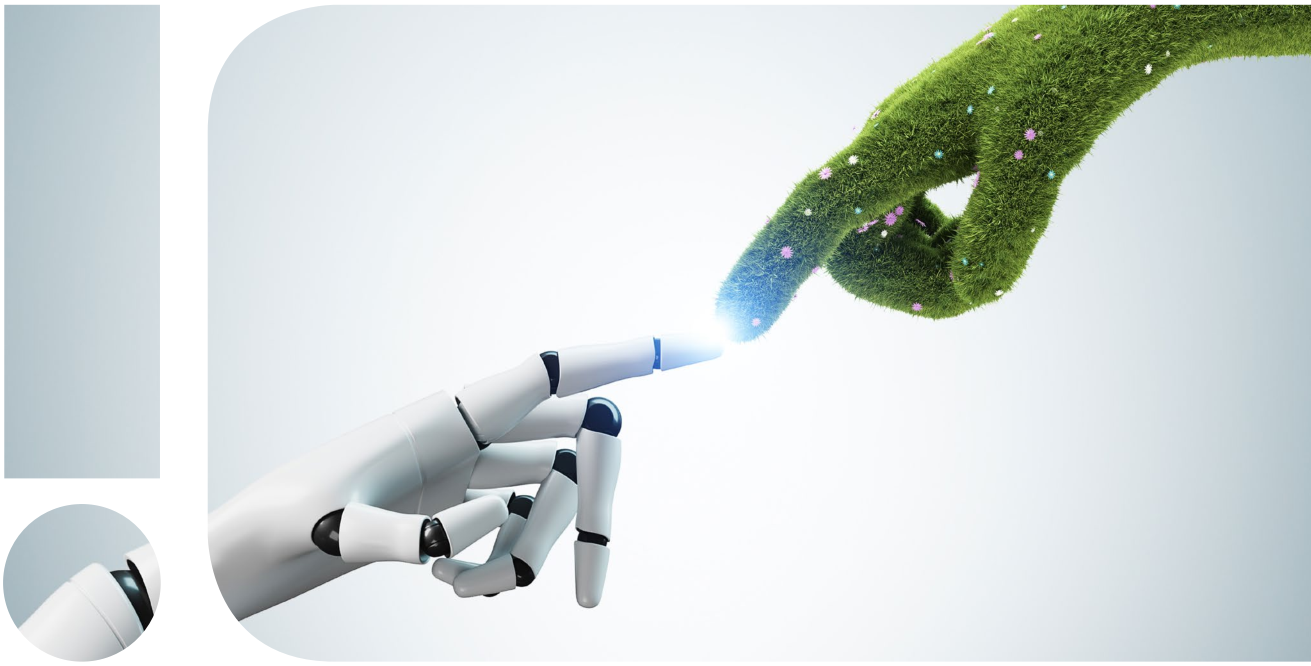
IoT virtual platforms, digital twins, and OSs: Widespread adoption of cloud computing and open-source software is reducing barriers to entry for those who hope to play a part in the energy sector. Cloud computing and open-source software are also boosting the popularity of energy system OSs and digital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

By making energy systems more intelligent, we are moving energy supplies closer to users for better experiences. 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). These energy systems can also adjust energy generation based on the load, and vice versa. This means the systems will be able to transfer energy flow to and from each other across time zones and distances.

EVs will be able to double as 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. Communications sites will be even more versatile, supporting vehicle-to-infrastructure systems and intelligent "brains" for cities. Intelligent sockets 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, and they will enable energy systems to respond to demand and provide value-added services.

Digital technologies play an essential role in supporting the source-load interaction of energy systems by enabling high-speed and high-frequency computing. Digital technologies are also weaving their way into the fabric of many different sectors. As this happens, data centers, communications base stations, and other types of facilities used for transmitting, computing, and mining information flow will grow in number and consume more energy. This brings us to the question: How can new ICT energy infrastructure reduce its own energy consumption and emissions? We will address this question below in this report.



The era of digital power: Digital and intelligent transformation for integrated information and energy flows, and green and low-carbon operations

In the next decade, renewables like wind, solar, and hydro power will replace fossil fuels as the main sources of electricity. Electrification of consumer terminals on power grids is also increasing. Technologies for EVs, hydrogen energy, energy storage, heat pumps, and thermal energy storage are advancing rapidly. Transportation, heating, and other energy-consuming systems are quickly shifting away from diesel, petrol, natural gas, and coal and towards electricity. Energy systems will soon be embedded with more advanced plug-ins, and be underpinned by an energy cloud OS that integrates information flows and energy flows. Connecting electricity production and consumption will enable two-way, Internet-based interactions between all different types of industry players that handle everything from energy sources and power grids to load management, energy storage, and consumption.

Transforming energy systems will open up enormous opportunities for innovation in technology, business models, and operations in the energy sector. Electricity generation involving renewables (e.g., solar power) in particular will have many opportunities. The same is true in the green mobility sector, which will be driven mainly by EVs, and other energy-consuming sectors, particularly ICT energy infrastructure.

It's predicted that by 2030, renewables will account for over 50% of all electricity generation globally, LCOE of PV plants will reduce to US$0.01 per kWh of electricity, and over 3,000 GW of PV plants will be in place. The proportion of electricity in global energy consumption will increase from the current 20% to 30%. Over 50% of vehicles sold will be electric. Renewable energy will power more than 80% of ICT energy infrastructure.

PV plants will be grid-friendly, intelligent, and convergent, with lower LCOE

LCOE of PV plants may drop to US$0.01 per kWh of electricity by 2030

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, LCOE is determined by a plant's upfront investment, operation & maintenance (O&M) expenses, and the system's useful life. By 2030, LCOE of PV plants is expected to plummet, possibly even down to US$0.01 per kWh of electricity.

PV plants are composed of PV modules and balance of system (BOS) components (such as electrical cables, solar inverters, and wires). Generally speaking, about 45% of a PV plant's investment goes into its PV modules. Over the next decade, this percentage is expected to drop by at least 15 points, because of improved engineering techniques, decreased manufacturing costs, and the ever 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:

a) PV plant systems will be able to support higher voltage. As input voltage increases, so does output voltage. This in turn can reduce line loss in direct current systems and loss in low-voltage transformer winding, significantly increasing the systems' efficiency. In addition, solar inverters and transformers will become more compact, translating into a huge reduction in transportation and O&M workloads. PV plant maintenance will also be automated. Thanks to these trends, by 2030, the system voltage of PV plants will reach 1,500 V or even higher, further slashing LCOE.

b) Solar inverters will deliver higher power density and efficiency because of advanced materials like SiC and gallium nitride (GaN), better heat dissipation in chips, and topology technologies. These materials and technologies increase solar inverters' voltage, operating temperature and frequency, and reduce loss. By

2030, solar inverters will see their power density grow by over 70%.

c) PV plants will use modular, standardized components. For example, solar inverters, power control systems, energy storage, and other key systems will use standard interfaces that allow for flexible capacity expansion and rapid deployment. All internal DC and AC circuit breakers, inverters, controllers, and heat dissipation components will be modularized. This will eliminate the need to enlist experts for maintenance work, slash O&M costs, and enhance system availability. Full modularization at the system and equipment levels will be the future trend.

d) PV plants will be digitalized inside and out. As digital and PV technologies converge, they will make O&M, production, and asset management simpler, more intelligent, and more efficient. With AI, PV plants will transform into intelligent systems. AI will handle the tasks that used to be performed by highly-trained experts, and support autonomous and collaborative optimization inside PV plants. Intelligent tracking algorithms make it possible for PV modules, trackers, and solar inverters to work in tandem to continuously find the maximum power point (MPP) of solar panels, thus maximizing power output. With AI, fault location will be more precise and O&M times can be reduced from months to minutes. Other benefits of AI include higher electricity generation efficiency, better O&M experiences, and greater productivity and safety. By 2030, AI is expected to be used in 90% of PV plants.

PV generators ensure stable operations of power grids through proactive support for frequency and voltage fluctuations

PV power generation technologies have the potential to make power grids more resilient. PV power generation fluctuates wildly over time, so 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. Therefore, as more PV generators are brought into 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 suffer. What's more, the characteristics of faults and oscillations on the power grid may change significantly.

Effectively integrating PV 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 synchronous generators utilize mechanical structures to provide stable voltage and frequency, thus facilitating frequency regulation and voltage control. However, as asynchronous generators gradually displace synchronous generators in power grids, the way power systems work will change fundamentally. In response, renewables-based power systems will need to simulate the technical indicators of synchronous generators, in order to proactively support the grid's frequency and voltage fluctuations. The goal will be to help power grids become safer and more reliable.

PV power generation technologies combine power electronics, energy storage, and digital technologies to simulate the electromechanical transients of synchronous generators. When connected to power grids, PV 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, PV generators can offer technical specifications that are similar to the synchronous generators used in fossil fuel power plants. PV power generation technologies 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 renewables into power grids.

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 main 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. New energy will be observably, measurably, controllably, and adjustably enhanced to address the vulnerability of new energy access systems and increase new 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 user consumption habits, improving resource utilization. This will improve the quality, safety, and stability of electricity systems.

a) 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 new energy sources are centrally accessed over 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, results 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 arrange for more sharing of distribution network resources with technologies such as active distribution networks and flexible DC distribution networks, making it perfect for scenarios like microgrids, virtual power plants, and integrated energy systems. An energy cloud will improve the digitalization of transmission and distribution networks, make their operations more flexible and adaptable, and enhance overall network control capabilities.

b) In conventional power grids, over the entire process from electricity production to consumption, more than 50% of resources are wasted. An 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 example, optimization algorithms can ensure that solar PV and wind power generation and storage can adapt to their power market, and take into account the local weather forecast 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 different objectives like cost-effectiveness, carbon emission requirements, and comprehensive energy efficiency. This makes it possible to use a wider range of energy types to meet complementary types of demand. Flexible conversion and integrated demand responses from multiple energy sources will make electric power systems more flexible and ready to take on more renewable energy.

Transportation will be electrified, with sales of EVs catching up with combustion-engine vehicles by 2030

Currently, the transportation industry is highly dependent on fossil fuels like petroleum, and the transportation sector is responsible for about a quarter of all energy-related carbon emissions. In Europe, transportation is the second largest carbon emitter, right after electricity generation. In the United States, transportation is the single largest source of GHG emissions. The transportation industry is primarily centered around four methods of transport – road, rail, aviation, and shipping – each of which has different requirements for green fuel. The rapid advancements in battery technologies and the growth of comprehensive electricity infrastructure have made electricity the most important clean energy alternative in road and rail transportation. Interaction between electricity systems and transportation systems is increasing, and the two are becoming more integrated. EVs, for example involve transportation, power consumption, and energy storage. EVs and their charging or power facilities will become critical hubs for the integration of electricity systems and transportation systems.

Many countries have already begun to promote EV development in recent years. Large-scale investment in electrification, intelligent driving, and Internet of Vehicles (IoV) technologies have greatly improved the competitiveness of EVs. Consumers are also turning to EVs in increasing numbers because of their energy-saving, eco-friendly, intelligent, and high-tech features. Though the global automobile industry as a whole is still suffering from the fallout of COVID-19, EV sales rose by 41% in 2020, with sales exceeding 3 million vehicles, achieving a market share of 4%. EV sales exceeded 1 million in Europe, 1.3 million in China, and 250,000 in the United States. As battery costs decline, performance improves, and autonomous vehicle technologies evolve, EVs are expected

to become as cost effective as combustion-engine vehicles by 2025, and the EV market growth will increase. More than 40 million EVs are expected to be sold globally by 2030, tying with combustion-engine vehicle sales. Adequate charging facilities will be needed to support this development. According to the International Energy Agency (IEA), by 2030, the global number of private charging piles is expected to reach 100 million, collectively delivering a total charging power of 1,500 GW and a total charging capacity of 800 TWh. The number of public charging piles is expected to reach 20 million, with a total charging power of 1,800 GW and a total charging capacity of 1,200 TWh.

New materials and digitalization will redefine the EV experience and safety

Extensive application of wide-bandgap semiconductor materials and digital control technologies will collaboratively be used to help EVs achieve an optimal energy efficiency ratio. As power components, topologies, and control algorithms related to power electronics advance, power devices will deliver record high efficiency. The application of new technologies and materials such as silicon carbide will increase bandgap width almost threefold and electric field strength 15 fold, double electron saturation rates, and triple thermal conductivity when compared with traditional silicon. An E2E architecture covering charging, driving conditions, power transmission, power conversion, heating, cooling, and energy recovery will be constructed and continually upgraded to deliver system-level efficiency optimal for EVs. Powered by digital technologies, intelligent electrothermal synergy, intelligent torque distribution algorithms, and intelligent electro-hydraulic braking distribution will be used to achieve high efficiency at every level from components to systems and from the power domain to vehicle operation. To further save energy and maximize EV range, a hyper-converged and domain-based control architecture will be used to implement multi-energy scheduling through coordinated control of electric energy, kinetic energy, thermal energy, and energy recovery, achieving a high vehicle-level efficiency in all aspects such as power charging, storage, and consumption. Intelligent electrothermal synergy will allow the heat from the motor and inverter to be intelligently recaptured through the heat pump system to the passenger compartment for heating. Drive torque can be intelligently distributed to balance braking ability and energy recovery. Other technologies such as optimal distribution between motor braking and hydraulic braking will also extend EV range.

Digitalization is redefining EV experience. EVs are delivering better driving experiences

than combustion-engine vehicles in terms of acceleration, control, and intelligence as battery energy density increases, battery management improves, and the electric control systems become increasingly precise in calibration. High-power EVs with fast acceleration are becoming more and more common. 300 kW, 400 kW, 600 kW, and 800 kW EVs now regularly outperform combustion-engine vehicles. Distributed electric drives are replacing mechanical limited-slip differentials (LSDs) in combustion-engine vehicles to archive faster acceleration at curves and better off-road driving, making EVs more enjoyable to drive. In terms of innovative intelligent features, the service oriented architecture (SOA) and centralized electrical and electronic architecture (EEA) allow software features to be kept up-to-date over the lifetime of an EV's power domain, and intelligent remaining range estimation lets drivers hit the road without worrying about how much charge they have left. EVs operating in smart track mode can adjust their thermal systems to boost power and control front and rear drive torque to drive for more fun. Intelligent accelerators and converged drive and brake give drivers more control. The motor itself will monitor the tire slip and adjust torque in real time to prevent hydroplaning on wet or snowy roads, greatly improving driver control and safety.

The energy cloud will improve vehicle energy efficiency management at the cluster level and make periodic service experience all-online. In an era of intelligent EVs, the diversity of the market and customers' personalized needs will more heavily influence automotive R&D, launch, and lifecycle requirements. These changes will lead to manufacturing and product service model innovation, driving a digital transformation of the entire automotive industry. For example, digital twin technology for the power domain of alternative fuel vehicles is based on vehicle power system digitalization and IoV technologies. With this technology, real-time operating data of vehicles and their components is continuously collected through sensors and fed to a digital twin created on the cloud. This data is then synchronously fed into a digital model on the cloud. The cloud generates data for real objects monitoring their real-time operating status and power domain status, and then enables real-time interactions to ensure that the EV power system works reliably and efficiently. Cloud computing brings natural advantages in terms of computing power, algorithms, model training, big data storage and analytics, and ecosystem partner participation. Digital modeling on the cloud can therefore be achieved based on the real-time data of vehicle components such as batteries, motors, and electric controllers. The cloud can build fault prediction analysis algorithms, parameters for efficient operating status, device aging models, intelligent fault rectification algorithms, and intelligent calibration algorithms. It remotely diagnoses and rectifies faults, and enables OEMs and service providers to proactively optimize product design based on actual end user requirements. These features improve service efficiency, reduce vehicle use costs, and enhance user experience.

Kilovolt flash charging will be widely applied to supplement energy supplies

As ranges increase and charging becomes easier, more and more customers are choosing EVs. From a technical perspective, EV range is being increased by improving battery energy density, and fast charging is becoming more common by increasing battery voltage for fast charging. Take electric passenger cars, for example. Average battery capacity is expected to increase from 60 kWh to 100 kWh by 2025, and mainstream charging voltage is expected to rise from 500 V to 1,000 V by 2030, bringing the EV industry into the kilovolt era. Each charging gun will be able to deliver 480 kW of power, up from the current 60 kW and charging will speed up — today a full charge takes about an hour, but this could be brought down to less than 10 minutes in a few years. This is almost comparable to how long it takes to refuel a combustion-engine vehicle. We will also have kilovolt-level EV power systems that are intensive, integrated, and well-coordinated, helping to decrease current and reduce energy loss. High-voltage platforms and precise high-rate charge/discharge curve design will enable efficient coordination between charging, discharge in driving, and kinetic energy recovery. High-voltage technologies will be widely used in charging infrastructure systems. For example, high-voltage silicon carbide technology will promote high-efficiency and high-density application and support the evolution of high-voltage platforms. Based on the ChaoJi charging technology roadmap, a 1,000 (1,500) V charging voltage platform will support a maximum charging power of 900 kW. This type of supercharging technology will be widely deployed on intercity highways.

EVs can collaborate with various energy systems to become regulators of energy flows

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 vehicle-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 vehicle 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 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 power grid and power supply.

The number of EVs worldwide could exceed 150 million by 2030. Ideally, by that time, the energy storage capacity could 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. In the future, EVs participating in the frequency-modulation ancillary service market will have higher value. By 2025, 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 load shaving, distributed PV charging, demand response, peak clipping ancillary services, and spot market balancing. As the cost of power batteries decreases and their service life increases over the course of the decade, EVs will become increasingly capable of serving as distributed power sources. With the support of platforms such as microgrids and virtual power plants, EVs will be able to provide services like frequency modulation and spot power balancing through both charging and discharging.

Charging infrastructure connects vehicles, 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 multi-level improvements in intelligence: Intelligent charging infrastructure will make charging networks visible, manageable, controllable, and optimizable, greatly reducing maintenance and operation costs and increasing efficiency and revenue. As a data interface, charging piles can be utilized to build a smart charging network that integrates vehicles, charging piles, power grids, the Internet, and value-added services. This network will leverage charging piles' strengths in terms of scale, integration, data, and connectivity, create multiple new business models, and generate a virtuous cycle of economic and social benefits. Charging piles enable charging facility operators to provide data consulting services to support business

district construction, real estate development, 4S store planning, the second-hand car market, digital payment, and e-commerce operations as a way to monetize, expand sources of revenue, and improve market operation capabilities. For local governments, charging piles can provide data support for urban planning, power dispatching, everyday services, and infrastructure construction, making charging infrastructure an important part of smart cities.

ICT energy infrastructure is going green

A decade from now, there will be hundreds of billions of connections, the total amount of general computing will have increased 10-fold, and the total amount of AI computing will have increased 500-fold. ICT technologies will empower other industries to reduce their carbon emissions, and a global reduction of emissions by 20% is predicted. Construction of related infrastructure will increase. For example, the number of telecom sites will increase from 10 million to 55 million, and the number of data center racks will increase from 4.2 million to 10 million. ICT will account for 4% of global power consumption, up from less than 2% today. Building efficient and low-carbon communications networks and data centers will not just be an operational necessity for enterprises, but their civic duty.

In addition to providing high-quality ICT services, leading operators worldwide have made carbon-neutrality declarations and launched various initiatives. Vodafone and Orange have proposed to achieve net zero emissions by 2040, while Telefónica has brought its carbon-neutrality target forward to 2030. In addition, Google has set the goal to power its operations — across all of its 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 CO_2 Microsoft has ever emitted, either directly or through electricity use since the company was founded in 1975, from the environment by 2050. The municipal government of Beijing has required 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. Japan plans for its data center industry to become carbon neutral by 2040. It is predicted that, over the next decade, the ICT energy infrastructure will evolve in a number of directions that will be discussed in the following sections.

Comprehensive architecture refactoring is making ICT energy infrastructure simple, converged, flexible, and efficient

Networks and data centers will become 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 rent. The way in which data centers are built will also change rapidly. Traditional concrete buildings usually take more than 20 months to build, and concrete is 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 greatly reduces onsite construction and maintenance. This way, a data center housing 1,000 cabinets 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 converged into a blade form factor. Power supply, energy storage, temperature control, and power distribution are being integrated into a single module, and on-demand evolution is being enabled to support cross-generational network evolution. All data center power supply links, including transformers, uninterruptible power systems (UPSs), and power distribution, will be converged to reduce footprint. All backup power will be based on lithium batteries to support intelligent collaboration between electric power generation, storage, and consumption, reducing the required configuration capacity of the data center UPS, and reducing the footprint and construction costs of data centers.

Green energy is becoming mainstream in ICT energy supply

The global trend of digitalization is turning ICT into an energy-intensive industry. Driven by the goal of carbon neutrality, ICT infrastructure providers are increasingly turning to clean energy sources such as PV, wind, and hydrogen. With the cost effectiveness and flexibility of these distributed energy sources, over 80% of ICT infrastructure power systems will use distributed green energy over the next decade. As the power consumption of individual telecom sites is low, distributed PV systems are likely to become a major power supply solution, helping to make zero-carbon communications networks a reality. Instead of taking the traditional approach of signing renewable-energy power purchase agreements (PPAs) and purchasing green certificates, sources of clean power will be integrated into the design of data centers themselves. For example, distributed PV plants are built on data center campuses and rooftops, and large-scale terrestrial PV plants, wind farms, and other types of clean-energy structures are built in surrounding areas to directly supply data centers. With lithium batteries replacing lead-acid batteries, the backup power of telecom base stations and data centers will soon be fully lithium battery based. With intelligent regulation, these traditional unidirectional distributed energy systems will participate in the ancillary service market which includes services like power grid peak clipping. This will allow the systems to help address

the unpredictability and intermittency of wind power and solar power. Therefore, the revenue coming from ICT infrastructure power supply will increase, maximizing the commercial value of basic resources. The stability and reliability of the entire energy system will also improve.

ICT energy infrastructure O&M is moving toward full automation

Over the next ten years, ICT energy infrastructure O&M will gradually become more autonomous, thanks to technologies such as neural networks, knowledge graphs, and domain shift. The combination of AI with other technologies will greatly improve O&M efficiency, eliminate a large amount of repetitive and complex manual work, and improve the fault prevention and prediction capabilities of energy infrastructure using big data. Data-driven differentiated service models will enable highly automated and intelligent operations of ICT energy infrastructure, profoundly changing how O&M is performed.

a) From manual operations to autonomous system operations: Operations involving inefficient and repetitive work (for example, configuration delivery, change, and upgrade) will be automated. The role of O&M personnel will change from in-the-loop intervention to on-the-loop management, greatly improving operation efficiency and addressing the pressure of intensive maintenance in the future. This significantly shortens the time needed for construction and service rollout.

b) From manual decision-making to machine-assisted and even autonomous decision-making: Traditional O&M approaches that rely on expert experience will change. Driven by data, AI machine learning can be leveraged to assist in or even automate decision-making under human supervision. This enhances the system's ability to cope with complexity and uncertainty, and greatly improves the response speed, resource efficiency, and energy efficiency of energy infrastructure.

c) From open-loop operation management to closed-loop guaranteed operations: The automation of ICT energy infrastructure will streamline data flows from end to end and make closed-loop autonomy a reality. Closed-loop autonomy will be implemented based on predefined SLA policies during construction, maintenance, and optimization to ensure manageable and guaranteed electricity production and consumption policies. This enables differentiated services for ICT energy infrastructure, more efficient resource utilization, higher revenue, and differentiated business innovations.

Conclusion

How advanced the energy sector has become can be seen in the extent to which renewable energy, digital technologies, and power electronics technologies have developed and converged. In the future electricity-based energy sector, power grids will be like the backbone networks in ICT, power electronics devices will be like gateways, and the energy cloud will be like the OS. The way in which energy flows are processed, moved, and stored will also change. As a result, the large-scale development and utilization of clean and low-carbon energy, wide connection of multi-level energy networks, active and passive participation of multiple loads, and collaborative decision-making and operation of multiple service logics will become a reality. Energy flows and information flows will be deeply integrated and support each other over the next decade. This will be a key transition period for a comprehensive energy transformation that will impact the development of energy landscapes over the next century.

The energy sector is now entering the digital age. Technological innovation regarding information flows and energy flows is becoming increasingly synchronized, shifting the focus of innovation from individual devices and scenarios to systems and industries as a whole. Energy networks are expanding from local networks into global networks, and operations are changing from device-based to cloud-based. Energy systems are becoming visible, measurable, and controllable on a wider scale. The convergence of energy flows and information flows is extending on a larger scale across time and space, further amplifying the value of energy systems. Energy systems are becoming more economical, cleaner, and safer to operate, while new models of electricity production, transmission, storage, and consumption are being promoted. All of this facilitates the deep integration of energy systems with information systems and even commercial systems. An energy system will no longer be a simple standalone energy network; it will also be a critical infrastructure platform that co-exists with other networks, such as transportation networks, carbon footprint networks, and information networks, which are collaboratively controlled across industries. The method and scope of energy cloud management collaboration are not limited to individual devices, systems, or industries in the energy system.

Technological advancement and energy transformation mutually catalyze each other and have profound implications for the future of the energy sector. Only by recognizing the major trends can we better address the challenges of the future, and only by focusing on today's realities can we seize the opportunities of the times. In the emerging digital power era, we must all work together to build new alliances, explore new ways to collaborate across value chains and ecosystems, and contribute to energy innovation and development worldwide. Only together can we drive energy transformation, build low-carbon, electrified, and intelligent energy systems, and make the world a greener, better place for all.

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