Received November 25, 2019, accepted December 3, 2019, date of publication December 13, 2019, date of current version December 23, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2959309

An Overview of the Photovoltaic Industry Status and Perspective in China

MEIQI YAO AND XU CAI
Wind Power Research Center, School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
Corresponding author: Xu Cai (xucai@sjtu.edu.cn)

ABSTRACT Photovoltaic (PV) is developing rapidly in China, and the installed capacity and PV module shipping capacity are the first in the world. However, with the changes in the global economic environment and the uncertainty of China's PV policy, especially after the 531 new policy, China PV has started a new cycle. To understand the laws of the development of photovoltaics in China better, the article first introduces the distribution of China's solar resources, sorts out the development process of China's PV, focuses on the development of China's PV Top-runner project, and emphasizes the role of advanced technology in the application of the Top-runner project for grid parity and industrial development. Then it expounds the evolution of PV module technology, inverter technology and System design technology, and analyzes the development status of photovoltaic industry chain and production of Chinese PV enterprises. Finally, it summarizes and predicts the development trend of China's PV industry and gives recommendations for China's PV development.

INDEX TERMS Levelized cost of energy (LCOE), grid parity, top runner Project, bright project, high efficiency module, bifacial module, PV poverty alleviation program.

I. INTRODUCTION

Solar energy resources are abundant and widely distributed throughout the world, and PV power generation technology is the most promising technology of renewable energy power generation technology. PV is a technology that directly converts solar energy into electricity by using the photovoltaic effect of semiconductor interface. It is safe, clean and efficient. With worsening global energy shortage and environmental pollution, global PV power generation evolves into large-scale development stage, Europe, Australia and other traditional markets continue to maintain steady growth trend, India, South America, southeast Asia and other emerging markets also quick start, photovoltaic power generation has been increasingly widely used in the whole world, PV industry gradually evolved into many countries important industry. The total installed capacity of PV increased from 1.3GW in 2000 to 306.5GW in 2016, with a compound annual growth rate of 40.7%. The annual installed capacity of PV increased significantly. The annual installed capacity increased from 0.3GW in 2000 to 76.6GW in 2016, with an annual compound growth rate of 41.4%.In 2016, the annual installed capacity of global PV power generation increased by 51.4% compared with 2015, and the market capacity continued to increase [1], [2]. China's new installed capacity of 34.54GW ranked first [3], while US's new added installed capacity of 14.7GW was second. Since 2011, installed capacity in the United States, China and other regions and countries such as the Asia-pacific region has surpassed the traditional European PV market.

Driven by various factors such as "630", "930", the policy of PV poverty alleviation, and the expected reduction of the electricity price of distributed PV, Chinese PV market will increase the installed capacity over 50GW, with a year-on-year growth of over 45%, and it will continue to be the first in the world. The cumulative installed capacity is expected to exceed 127GW [4]–[8], ranking the first in the world. Looking forward to 2018, China's PV enterprises will further consolidate their global competitiveness, continuously improve their technological level, and further reduce their product cost.

However, they are also faced with challenges such as uncertain polices. For example, China's "531" policy was announced by the National Development and Reform Commission, the Ministry of Finance, and the National Energy Administration without warning on May 31(hence

The associate editor coordinating the review of this manuscript and approving it for publication was Nataraj Prabaharan.

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see http://creativecommons.org/licenses/by/4.0/

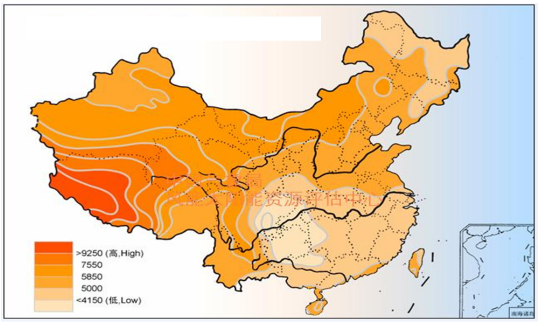

FIGURE 1. China solar resource distribution.

the "531" name) [9]–[11]. The policy is designed to control breakneck growth in the solar sector, principally by accelerating the phase-out of subsidies. Moreover, there are still some problems in the development of China's photovoltaic industry, such as large subsidy gap, increasing curtailment of PV power generation, lack of competitiveness in manufacturing industry, high land tax and cost of photovoltaic power stations, and imperfect standard system.

This paper first comprehensively reviews the literature related to China PV industry, and finds that there are many reviews on wind power in the aspect of new energy, but few on PV. The literatures give different perspectives of PV development. [3] introduces the PV market development in China in 2017. [4]–[6] present PV industry policy evolution. [7], [9] make the comparison between the development of wind power and PV in China. [8] focuses on large scale PV integration into grid.

It is very necessary for a systematic review of the development status of China's PV industry, including comprehensive analysis and summary of market, technology, production and manufacturing, and it is of guiding significance in judging the development trend of China's photovoltaic products, formulating relevant industrial policies and positioning and layout of industrial products.

The article is organized as follows: The second part introduces the development history of the entire Chinese PV market, sorts out the policy of PV development, and emphasizes the important role of the Top-runner projects on promoting the development of the PV market. The third part is a compilation of the development of PV technology in China, including solar modules, inverters and system design technology. The fourth part describes the development of the PV industry chain, especially Chinese PV manufactures production. Finally, the fifth part summarizes the full text and gives suggestions for the development of PV in China.

II. DEVELOPMENT OF CHINA'S PV MARKET

A. CHINA SOLAR RESOURCE DISTRIBUTION

China is one of the countries rich in solar energy resources. The annual sunshine hours in areas with a total area of more than 2/3 of the country are more than 2,000 hours and the annual radiation quantity is over $5000 MJ/m^2$ (Figure 1). According to statistical data analysis, the annual solar radiation received by China's land area is $3.3 * 10^3 \sim 8.4 * 10^3 MJ/m^2$, equivalent to $2.4 * 10^3$ billion tons of standard coal reserves [10], [11]. According to the classification standard of wind and solar energy evaluation center of national meteorological administration, China's solar energy resources are divided into the following four categories, as Table 1 shown.

TABLE 1. The definition of Solar Energy Resource Distribution Zones in China.

Type		Radiation (MJ/m² A.)	(%)	Area
Most abundant	I	6300	17.4	Qinghai-Tibet Plateau, northern Gansu, northern Ningxia, southern Xinjiang, northwestern Hebei, northwestern Shanxi, southern Inner Mongolia, southern Ningxia, central Gansu, eastern Qinghai, southeastern Tibet and other places.
Very abundant	II	5040 ~ 6300	42.7	Shandong, Henan, southeastern Hebei, southwestern Shanxi, northern Xinjiang, Jilin, Liaoning, Yunnan, northwestern Shaanxi, southeastern Gansu, southern Guangdong, southern Fujian, north central Jiangsu and northern Anhui.
Rich with an Abundant	III	3780 ~ 5040	36.3	In the middle and lower reaches of the Yangtze River, parts of Fujian, Zhejiang and Guangdong, there are more rainy springs and summers, and solar energy resources are still available in autumn and winter.
General with Normal	IV	< 3780	3.6	It mainly includes Sichuan and Guizhou provinces. This area is the least solar energy area in China.

B. DEVELOPMENT OF CHINA'S PV MARKET

1) PV INSTALLED CAPACITY AND POWER GENERATION

China is very suitable for the development of PV power generation. China's PV development has gone through the initial stage, demonstration and promotion, and large-scale development phase. Now is experiencing new adjustment phase after 531 new policy. The details are as follows.

a: INITIAL STAGE (BEFORE 2009)

Before 2000, due to the limitations of high cost and other factors, the development of PV power generation was slow, and it was only limited to low-power power supply system for a long time, so it was difficult to achieve large-scale development. After 2000, the government launched a series of model projects, such as send the electricity to countryside and Bright Project, to solve the electricity problem in remote areas without electricity. With the maturity of photovoltaic power generation technology, lower cost of power generation, the preliminary clarity of feed-in tariff and the increasing demand of the country to improve the energy structure, large-scale PV projects have been rapidly developed. During the decade from 1994 to 2004, global solar cell production increased 17 times and the average growth rate in the past five years was over 50%.After 2004, the market for solar cells was highly competitive, and the leading pattern in Europe and Japan was broken. Although the sales market was in Europe, the production center was shifted to Asia. In 2007, China produced about one-third of the world's solar cells, making it the world's largest producer of solar cells.

b: DEMONSTRATION AND PROMOTION STAGE (2009-2013)

From 2009 to 2011, domestic photovoltaic power generation projects went to market rapidly, and the installed capacity increased by more than 100% every year. At the same time, the category of photovoltaic projects has also undergone fundamental changes, and grid-connected projects have become the mainstream, accounting for 80% of the total number at the end of 2010, up from 5.1% in 2006, representing changes in the role and status of photovoltaic projects in society.

Since 2009, China has launched the demonstration project of Building-integrated photovoltaic (BIPV), Golden Sun demonstration project and the bidding for the concession of large photovoltaic power station.

By 2012, the development of PV mainly relies on large-scale photovoltaic power station, and the distribution is only under preliminary development. The ''Golden Sun project'' carries out 50% of the initial investment subsidy. The high initial installation subsidy drives the growth of distributed photovoltaic as well as large photovoltaic power stations. In 2011, the new distributed installed capacity is an 245.8% rise from 2010, and in 2012, it is an 79.7% rise from 2011.

However, in 2012, the United States provoked '' antidumping and anti-subsidy''. Later, Europe joined the trade war camp. China's PV industry suffered heavy losses and a large number of enterprises closed down. However, China's PV companies are rapidly turning their bows back to the domestic market. At the same time, the government has increased support for photovoltaic applications, the release of the ''12th Five-Year Plan for Solar Power Development'' and the demonstration of distributed photovoltaic power generation scale demonstration areas, coupled with the continuous decline in investment costs of photovoltaic systems, the photovoltaic application market has picked up.

c: LARGE-SCALE DEVELOPMENT (2013-2018)

In July 2013, the State Council issued the ''Several Opinions on Promoting the Healthy Development of the Photovoltaic Industry'' (''National Eight Articles''), which

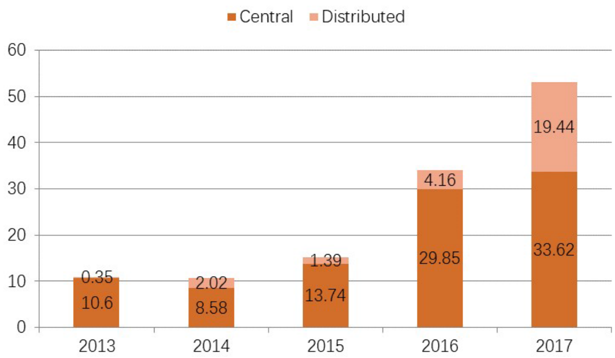

FIGURE 2. **2013-2017 China PV new installed capacity.**

clarified that by 2015 China's total installed capacity will reach 35GW or more, and at the same time, it is the first time that the subside period is confirmed. Core issues such as electricity price settlement and full payment have begun to show rapid growth in China's photovoltaic power generation capacity. In August 2013, the National Development and Reform Commission issued the ''Notice on Playing the Role of Price Leverage to Promote the Healthy Development of the Photovoltaic Industry'', and determined that distributed PV will be subsidized by 0.42 yuan per meter including tax, and the era of photovoltaic power subsidies will be opened. In 2016, the state continued to encourage self-use and distributed, roof distribution, and limited the construction of large-scale power stations due to increasing curtailment of PV power generation in Northwest China, North China and Northeast China. Therefore, distributed PV developed rapidly and distributed PV installed capacity reached 4.24GW, an increase of 205%. Affected by multiple factors such as on-grid tariff adjustment, the scale of photovoltaic power generation market expanded rapidly in 2017, with a new installed capacity of 53.06GW (Figure 2), an increase of 18.52GW over the same period of last year, with a growth rate of 53.62%, once again setting a new record high, far ahead of other renewable energy sources; By the end of December, 2017, the national installed capacity of photovoltaic power generation reached 130 GW. From the perspective of power generation, it also hit a new high. In 2017, China's photovoltaic power generation exceeded 100 billion kWh, reaching more than 118 million kWh, a year-on-year increase of more than 70%. The proportion of photovoltaic power generation to total power generation increased from 1.1% to 1.8% in 2016.

d: NEW ADJUSTMENT PHASE (2018.6 – NOW)

China's rapid growth in PV is accompanied by some problems. Due to the uneven distribution of installed capacity in the country, the geographical mismatch between the manufacturing end and the application end, the power generation province and the power-consuming province; the growth rate of renewable energy such as PV is much higher than the national electricity consumption growth rate, resulting in a serious shortage of energy funds. The problem of large-scale

TABLE 2. China PV policy milestones.

No.	Milestones
1	The Renewable Energy Law was promulgated in 2005 and entered into force on January 1, 2006
2	According to the "Renewable Energy Law", the "renewable energy price surcharge" will be imposed on August 1, 2006.Increased every 2 years: 0.1fen, 0.2fen, 0.4fen, 0.8fen, 1.5 fen, until 1.9 fen/kWh in 2016 (about 70 billion yuan per year). As of the end of 2016, the accumulated collection and investment funds exceeded 200 billion yuan;
3	In terms of market promotion: In 2008, Licensed tendering rights for photovoltaic power plants was initiated. In 2009, BIPV and "Golden Sun Project" based on initial investment subsidies were launched. In 2011, the "on-grid tariff" policy based on power generation was implemented nationwide. In 2013, "partitioned on-grid tariff" was launched; in 2016, "non-water renewable energy quota system" was issued, and in 2017, "green certificate system" was implemented;
4	In 2015, the National Energy Administration clarified that "roof-distributed PV" and "spontaneous self-use" projects are not subject to quotas, and do not limit the scale of construction, and subsidies are given priority, providing preferential support policies for the development of distributed PV.
5	National PV Model Projects: In 2009, BIPV and "Golden Sun Project" were launched. In 2015, the "Top Runner Program" was launched. In 2016, the "Special Project for Photovoltaic Poverty Alleviation" was launched. In 2017, 23 "Multi-energy Complementary Demonstration Projects" were launched, and then 28 "Micro-Grid Demonstration Projects" were launched, and the Third Top-runners was launched in 2017
6	A number of supporting policies are issued by The Ministry of Finance, the Ministry of Industry and Information Technology, the State Administration of Taxation, the Ministry of Land and Resources, and the State Grid Corporation;
7	More than 20 provinces and autonomous regions across the country have introduced local financial support policies.

curtailment of PV power generation and subsidies not being in place is growing. Moreover, 531 policy caused a great shock to the industry, and enterprises faced greater pressure in the short term. PV industry is under a new adjustment period.

2) ANALYSIS OF PHOTOVOLTAIC POLICIES

The state's policies for supporting the photovoltaic industry mainly include five aspects: 1) government incentives, 2) grid support, 3) operational supervision, 4) technical support and 5) financial support. In the early stage of China's PV industry, the government mainly issued incentive policies and provided technical support to improve innovation capabilities and provide ''soft'' power for industry development. The government continues to provide substantial financial and tax support to the photovoltaic industry, which is an important force for stimulating industrial development [12]–[18]. The milestones of PV policies are summarized as table 2.

TABLE 3. Summary of the three top-runners.

Year	Quantity of Projects	Installed Capacity (GW)	Progress
2015	1	1	Before 2016, all of them were connected to the grid
2016	8	5.5	Most of the projects have been integrated
2017	13	6.5	The bidding was completed at the end of may, 2018, 5GW plans to be grid-connected by the end of 2018, and 1.5GW plans to be grid-connected by June 30, 2019.
Summary	21	13	

After 531 new policies, the policies are: 1) adjusting the industrial structure and energy structure; 2) reducing electricity prices including on-grid tariffs, electricity subsidies and user tariffs; 3) all photovoltaic projects are subject to quota control and 4) the phase-out of subsidies, and forced to grid parity.

3) PV TOP-RUNNER PROJECTS

In 2015, the National Energy Administration proposed the implementation of the ''Top-Runner'' program for photovoltaic power generation and the construction of the Top Runner bases [19]. Through market support and experimental demonstrations, the projects will accelerate the promotion of photovoltaic power generation technology and industrial upgrading, speeding up the application and transformation of technological achievements to the market. The cost of photovoltaic power generation is declining, the price of electricity is reduced, subsidies are reduced, and grid parity is finally achieved. At present, a total of 22 Top runner bases bidding work have been completed, with a scale of 13 GW. Among them, the first Top-runner in 2015 and the second Top-runner in 2016 are basically completed and connected to the grid, as shown in Table 3.

a: TOP-RUNNERS IN 2015

In June 2015, the national advanced technology pioneer base of Datong coal mining subsidence area in Shanxi Province, China was officially approved, becoming the first demonstration project of Top-runner. The total installed capacity of Datong Top-runner base is 3GW, which is implemented in three years. The first-phase construction scale is 1GW, which was started in September 2015, and all connected before June 30, 2016. In 2015, Top-runner advanced technology products should achieve the following indicators: the photoelectric conversion efficiency of polycrystalline silicon cell modules and monocrystalline silicon cell modules reached 16.5% and over 17%, respectively. In the first Top-runner in 2015, the market share of each module enterprise is shown in the Figure.3.

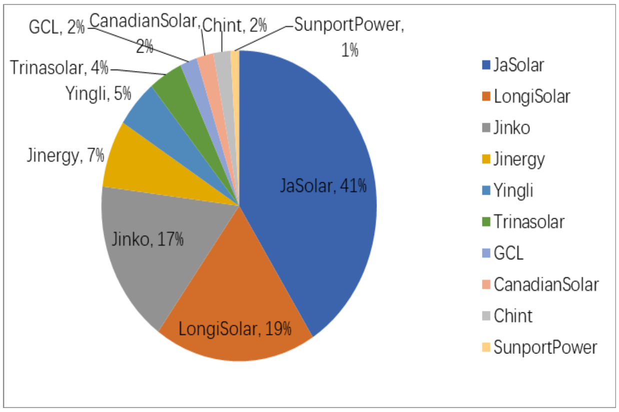

FIGURE 3. Module supplier percentage for Top-runner projects in Datong, Shanxi Province.

TABLE 4. Top-runner project overview in 2016.

Top-runner base	Total capacity (million kW)	Platform project (10,000 kW)
Shanxi Yangquan	100	5
Shanxi RuiCheng	50	5
Anhui Huaibei	100	X
Shandong Jining	50	5
Shandong Xintai	50	5
Inner Mongolia Baotou	100	10
Wuhai, Inner Mongolia	50	X
Zhangjiakou, Hebei	50	X

According to statistics, in the 1GW Datong Top-runner base, monocrystalline silicon modules are used for about 60% and polycrystalline modules for about 40%.

2015 Datong front-runner base adopted new modules including PERC, black silicon, n-type bifacial module and other technical routes, as shown in Figure 3.According to the statistics of the CEPRI, the monocrystalline silicon PERC module accounts for 21%, which is far ahead in the proportion of new modules.

b: THE SECOND TOP-RUNNERS IN 2016

The second "Top-runner" projects have completed all the base tenders by the end of October 2016, and not all of them have been connected to grid. Table 4 shows the Top-runner bases.

Compared with the leading technical indicators in 2015, the threshold of the leading technical indicators in 2016 was not increased, and the photoelectric conversion efficiency of polymodules and monomodules reached 16.5% and 17%, respectively. However, in 2016, the pace-setter base adopts competitive comparison, such as bidding and selection, to allocate projects. According to the investment subject preferred scoring standard of the leading base issued by the national energy administration, among the indicators of technological advancement, if the modules efficiency exceeds 0.5% and 1% above the leading indicator, higher scores will be given correspondingly to guide enterprises to adopt more advanced technology products.

TABLE 5. Key performance for top runners in 2017.

Top-runner base	Module Type	Minimum efficiency	Minimum Module Power (60 pieces)	Maximum efficiency	Maximum Module Power (60 pieces)
Application Top-runner	Poly-module	17%	280 w.	17.90%	295 w.
	Mono-module	17.80%	295 w.	18.70%	310 w.
Technology Top-runner	Poly-module	18%	295 w.	19.40%	320 w.
	Mono-module	18.90%	310 w.	20.40%	335 w.

According to incomplete statistics, the proportion of PERC components accounts for 30%, and the proportion of monocrystalline PERC modules is about 80%. Compared with the 21% PERC ratio of Top-runners in 2015, the application ratio and scale of PERC products in 2016 have been greatly improved.

c: THE THIRD TOP-RUNNERS IN 2017

In November 2017, the state energy administration issued the notice on the announcement of the list of leading bases for photovoltaic power generation and the implementation of related requirements, and confirmed the list of leading bases and technologies for the application of photovoltaic power generation in 2017, with a total of 10 Top-runner bases. The threshold of technical indicators for Top-runners base has been raised in 2017. The photoelectric conversion efficiency of the polycrystalline silicon cell module and monocrystalline silicon cell module used in the application top-runner must reach 17% and 17.8% respectively. The photoelectric conversion efficiency of the poly module and mono module used in the technology Top-runner base should reach 18% and 18.9% respectively.

In addition to threshold efficiency indicators, the energy administration also specified module full scale efficiency indicators. In the competitive optimization standard of the leading base of photovoltaic power generation, it is pointed out that the conversion efficiency of poly-module and mono-module adopted by the leading base in 2017 reached 17.9% and 18.7%, which can reach the full score standard of the technology. The full scale conversion efficiency of poly-module and mono-module used in the technology leading base is 19.4% and 20.4%, respectively as seen in the table 5.

It can be seen from the bidding of the application Top-runner of 5GW and the technical Top-runner of 1.5GW:

- PERC modules have become the first choice for Top-runner projects, and the application ratio of monocrystalline module is much higher than that of polysilicon, which is close to 90%.
- Over the past three years, Top runner projects have greatly promoted technological progress and promoted grid parity.
- The advantages of state-owned investment enterprises are becoming more and more obvious, and the participation of private enterprises is gradually decreasing.

- Bifacial module plus Tracker system will be the typical configuration and be used widely.

III. DEVELOPMENT OF PV TECHNOLOGY IN CHINA

PV technology includes high efficient module technology inverter technology and system design technology.

A. HIGH EFFICIENT MODULE TECHNOLOGY

After China's new photovoltaic 531 policy, the national quotas were reduced and subsidies were lowered, and the consequent price drop of the whole industrial chain products push that installation cost has been rapidly reduced to less than 4 yuan /W, and the originally expected goal of achieving grid parity in some parts of China in 2020 without national subsidies has been realized two years ahead [20], [21].

The sharp decline in installation costs in the short term has largely reduced the profit margin of all links in the industry chain. However, with the popularization and application of various cost-down technologies, the industry chain profit level will gradually return to a reasonable level, among which, high-efficiency module technology, which is mature and easy to expand, has low capital expenditures, and has a significant effect on reducing electricity costs, is expected to usher in rapid popularization.

The so-called high-efficiency module technology [18], [19], we define it as: under the premise of the existing cell efficiency, in the module packaging, use different processes to increase the component output power or increase the single-watt power generation in its whole life cycle. The technical routines mainly include: bifacial, Halfcut-cell, MBB, Shingled-cell, N-type TOPcon etc. (partially requires the process of cell bonding). The power/power generation gain is significant, and can be superimposed on multiple technologies, contributing up to 20% reduction in power cost.

Bifacial module technology achieves 5%∼30% power generation gain by back-end power generation; halfcut-cell module reduces 75% internal resistance loss to achieve power gain of 5∼10W; MBB cell electrode resistance and electrode occlusion decrease synchronously, reducing silver consumption At the same time, the power is increased by 5∼10W; the design of the stacked tile without the main grid and no soldering strip increases the number of cells that can be placed by 13%, and the power is increased by 15∼20W. In addition to the stacked tiles, the above-mentioned high-efficiency component processes can also be superimposed on each other, and can simultaneously amplify the effect of high-efficiency processes such as PERC, HJT, and black silicon in the cell section, so that the monocrystalline component with higher basic power, The power gain is also greater with the use of efficient component technology. The bifacial + halfcut-cell(or N-type TOPcon) + MBB technology superimposes the power gain of 10∼25W, and the power generation gain is 5%∼30%. Under the same installation conditions, the maximum cost can be reduced by more than 20% as shown Table 6.

TABLE 6. Power comparison of 60 pieces of modules in different technical routes.

Technical routes	Increased power	power generation gain per watt	Increased Cost	Lower LOCE
	W.		Yuan/W	
Bifacial	NA	5% ~ 30%	0	3.8 ~ 18.5%
Halfcut-cell	5 ~ 10 w.	NA	0	0.5 ~ 1.0%
MBB	5 ~ 10 w.	NA	0.05	1.3% ~ 1.8%
Bifacial+Halfcut	5 ~ 10 w.	5% ~ 30%	0	4.3% ~ 19.3%
Bifacial + MBB	5 ~ 10 w.	5% ~ 30%	0.05	5.0% ~ 19.9%
Bifacial + halfcut +MBB	10 ~ 20 w	5% ~ 30%	0.05	5.5% ~ 20.6%

Remark:
Let's say with Assuming the initial investment is 4.5 yuan /W, and the power generation hours are 1200h

TABLE 7. Future inverter main characteristics.

Efficiency	Above 99.5%
System voltage level	1500V will be used widely. 1500V/3.125MW central inverter. 1500V string inverter will be 100kw above
System integration	• Integrating inverter and Step-up Transformer Tracker Energy storage
Intelligent	• Support IV curve scanning， • With SVG* and VSG* functions • Can integrate into weak grid
Inverter Topology& Driver Technology	• Topology：Multi-level MMC • Power Unit: SiC, GaN • Controller: double DSP 200M,main frequency • Magnetic core: amorphous and ultra - crystalline technology

SVG: Static Var Generation; VSG:Virtual Synchronous Generation

B. SOLAR INVERTER TECHNOLOGY

According to practical application, PV inverters are divided into centralized inverters, string inverters and central-distributed inverters. The three types of inverters have their own characteristics. The main advantage of centralized inverter is large-scale application. The advantage of string inverter is multi-channel MPPT controller. The central distributed inverter takes into account the advantages of centralization and cluster, decentralized control, centralized grid-connection, and is widely used [22]–[29]. Table 7 describes the main functions of the next generation inverter.

C. PV SYSTEM TECHNOLOGY

The guiding ideology of PV system design: based on minimizing LCOE minimum, using advanced tracking technology, and reasonable DC/AC ratio, better module layout design technology [30].

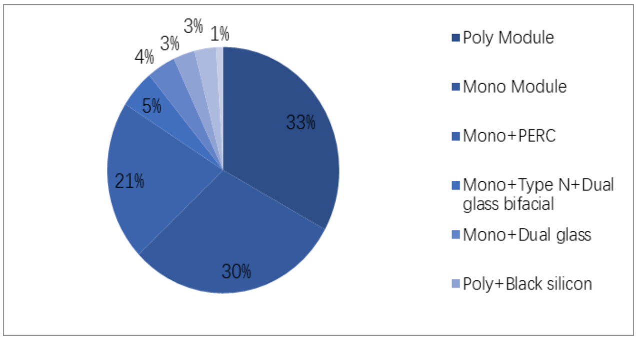

FIGURE 4. Different module applications in 2015 in Datong Top Runner.

Tracker technology can improve system power generation performance by about 10%-20% compared with fixed structure. The specific power generation performance is improved depending on local meteorological conditions, direct ratio, latitude and longitude. Among them, the tracking technology is divided into flat single axis, oblique single axis and double axis tracking. Due to its simplicity, reliability and economy, the flat single shaft has a high degree of recognition in the market.

The DC/AC ratio refers to the ratio of the DC and AC side capacity of the PV system. The ratio of DC/AC is different in all regions of the world [12]. Such as Europe: 1.2-1.4 times; the United States and India: > 1.4 times; Japan: 2 times. Appropriate ratio of DC/AC can increase the economical cost of the entire PV power station and reduce LCOE [31]–[33].

IV. DEVELOPMENT OF PV INDUSTRY CHAIN

A. PV MODULE INDUSTRY CHAIN

The solar photovoltaic industry chain includes silicon materials, ingots (pull rods), slicing, solar cell, modules, application systems, etc. The upstream is the silicon material and the silicon wafer; the middle is the cell and modules; the downstream is the application system. From a global perspective, the number of enterprises involved in the six links of the industrial chain has increased substantially, and the industrial chain of the photovoltaic market has a pyramid structure [7], [34]–[36]. In 2017, China's photovoltaic manufacturing industry experienced rapid growth. Domestic polysilicon production reached 242,000 tons, up 24.7% year-on-year; domestic wafer production reached 87GW, up 39% year-on-year; domestic solar cell production reached 68GW, up 33.3% year-on-year; domestic module production reached 78GW, an increase of 43.3% as shown in Figure 5(a) and (b).

1) PRICE TREND OF PV INDUSTRIAL CHAIN

In terms of price of silicon wafers, in June 2018, monocrystalline wafer manufacturers such as Longji and Zhonghua lowered the price of silicon wafers to 3.35 and 3.32 yuan/pian (Figure.6), and the price difference between monocrystalline silicon wafers and polycrystalline silicon wafers returned to 1 yuan. There is still a market for monocrystalline silicon, but

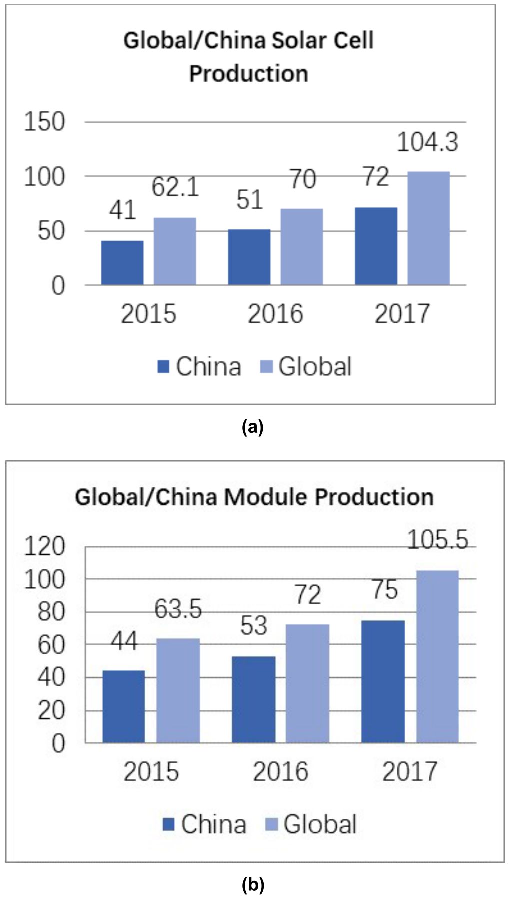

FIGURE 5. Global/China production (a) Solar cell production ;(b) Module production.

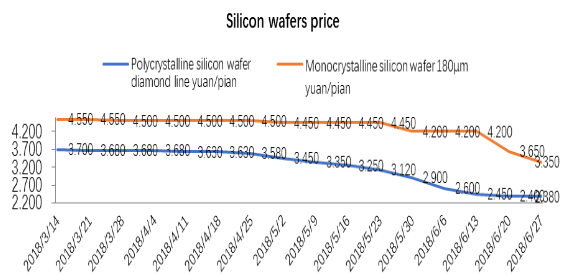

FIGURE 6. Silicon wafers price trend.

passive price cuts will follow due to the impact of polycrystalline prices.

In terms of solar cell price, with the end of PV 630, the purchase of conventional mono/poly PREC is reduced, and the price of monocrystalline cell is greatly dived. The conventional mono/poly solar cell market will be further compressed, which will stimulate the price drop to seek follow-up orders as Figure 7 shown; overseas polycrystalline orders began to recover due to its good performance and low cost, and some manufacturers began to increase the operating rate of polycrystalline cells or some conventional mono/poly solar cell. The production line turned to polycrystalline.

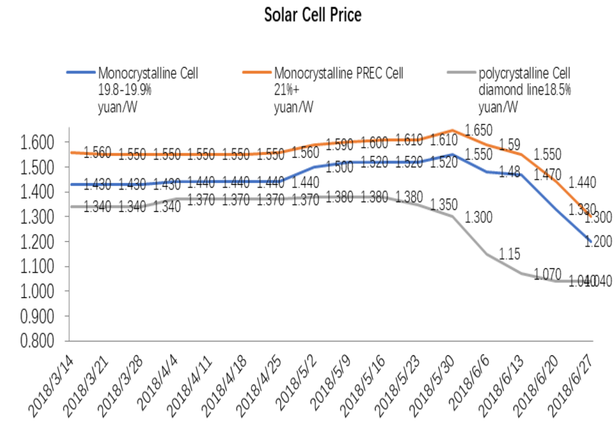

FIGURE 7. Solar cell price trend.

TABLE 8. Global/Domestic ranking of module manufactures.

2018 Global Module Shipment Ranking		2018 China Module Shipment Ranking	
1	JinkoSolar	1	LongiSolar
2	JaSolar TrinaSolar	2	TrinaSolar
3	Q Cell	3	JinkoSolar
4	TrinaSolar	4	GCL
5	LongiSolar	5	JaSolar
6	Canadian Solar	6	Suntech
7	Risenergy	7	Risenergy
8	GCL	8	Canadian Solar
9	Suntech	9	Yingli
10	Talesun	10	Talesun

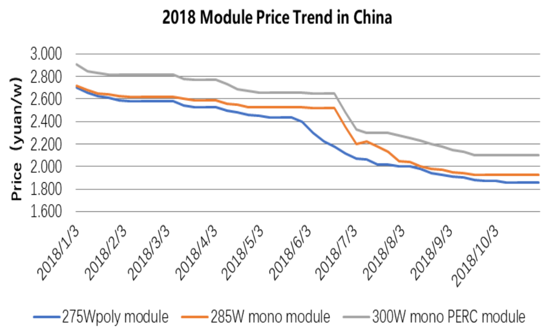

FIGURE 8. Module price trend.

Module price is about 50% of PV system cost, module price represents the cost development trend of the system in a certain sense. According to PVInfoLink quoted on October 31, Figure 8 presents that the current 275W polycrystalline module is 1.86 yuan / W, 285 monocrystalline module is 1.93 yuan / W, 300W monocrystalline module is 2.1 yuan / W; on the market monocrystalline bifacial PERC module 2.4 yuan / W. It is predicted the module price will drop 10% every year in the future two years, and the module price will be 1.6∼2yuan/w [37]–[39].

2) HIGH-EFFICIENCY SOLAR CELL AND MODULE PRODUCTION

Through investigation on solar cell and module manufacturers, the basic situation in China is:

1) In terms of silicon wafer technology, mortar cutting is still the mainstream in 2017. According to preliminary statistics, in 2018, diamond line cutting will become the mainstream process of polysilicon chips;

2) About polycrystalline black silicon cells and polycrystalline black silicon + PERC cell, in 2017, the total capacity of polycrystalline black silicon is 7.3GW, the output is 4.2. GW, the average conversion efficiency is 19%. In 2018, the planned production capacity reached 17.2GW. Polycrystalline black silicon + PERC cell capacity of 1.6GW, output of 976MW, average conversion efficiency of 19.9%, planned capacity of 6 GW in 2018;

3) Monocrystalline crystal PERC cell production is 10.3GW in 2017, the output is 6.1GW. The average conversion efficiency is 21.3%. The planned production capacity in 2018 is 37.9 GW. Tongwei and Longji have a planned production capacity of 10GW and 8.8GW respectively.

4) For N-type cell, in 2017, the domestic HIT cell has a production capacity of 1GW, a production output of 60MW, and an average conversion efficiency of 22.7%. The planned production capacity in 2018 is 3.5GW. The medium-sized N-type bifacial cell currently has a capacity of 900 MW, which proves an average conversion efficiency of 21.6%. Its N-type IBC cell conversion efficiency exceeded 23%. The main production company of N-PERT is Yingli, with a capacity of 750MW in 2017, and no expansion plan, the output is about 100MW, and the average conversion efficiency is 21%.

5) In terms of high-efficiency modules, in 2017, the total capacity of components was 76.4GW, and the output was 64.5GW; the production capacity of Halfcut-cell module was 1.1GW, and the output was 367MW. In 2018, the planned production capacity will reach 9.6GW. The main production enterprises include Trina, CanadianSolar, Jinke, etc.; due to patent protection restrictions, the shingle modules are only produced by Huansheng and Selafu, with a total capacity of 900MW, but the output in 2017 Only 91MW. The planned production capacity is 1.2GW in 2018; the output of dual-wave modules in 2017 is 2.6GW, which is expected to increase to 13.4GW in 2018.

Table 8 shows the global rankings and domestic rankings of component manufacturers. Chinese domestic module manufacturers also attach great importance to the international layout.

B. SOLAR INVERTER PRODUCTION

In 2017, the domestic inverter production reached 62GW, a year-on-year increase of 55%. The inverter enterprise shipments increased significantly. In 2017, domestic shipments

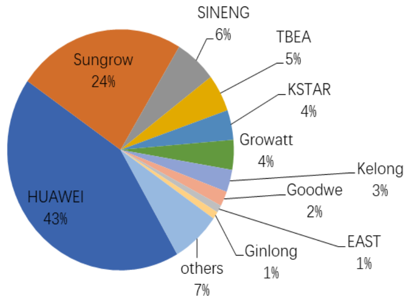

FIGURE 9. **Chinese inverter manufactures markets share in 2017.**

were about 55GW, and the market concentration was further improved. The top ten companies accounted for 95% of the market. The technical level is continuously improved, the international competitiveness is enhanced, and there are 9 companies that have shipped more than 2GW. In 2017, there were 6 companies in the top ten global inverter shipments. In 2017, the export volume reached 1.5 billion US dollars. It is about 12GW, a year-on-year increase of 140%. Major countries: India, Japan, the Netherlands, Mexico, Australia. As figure 9 shown, domestic inverter product prices continue to decline, and competition in the string market is intensifying. Among the many inverter manufacturers in China, Huawei and Sunshine account for 67% of the domestic market.

It is predicted that modules costs will fall by 10% annually in the next two years, entering the price range of 1.6-2 yuan / W. EPC price will be in the range of 4-4.5 yuan / W, and the EPC winning price of the Golmud leader project of the Three Gorges + Sunshine Power Supply has been as low as 3.699 yuan / W, and the inverter is likely to drop to 0.1 yuan / W.

Chinese Inverter Manufactures Market Share in 2017.

V. CONCLUSION

The development of China's photovoltaic industry is influenced by the international environment and domestic policies. After China experienced 531 new policies, it entered a new adjustment cycle. In order to better understand the law of China's PV development, the article combs the history of China's PV development, introduces the application of PV system technology and the production capacity of the PV industry chain, and focuses on the application of the Top runner projects. Through sharing, it can be concluded that

- The regulation of photovoltaic scale and subsidies will be the main idea of national policy. The 531 new policy is a signal that has a certain impact on the scale of PV installation. According to preliminary analysis, by 2022, China's domestic installed capacity will be about 40GW per year.
- PV development needs innovative solutions to meet market demand, of which distributed market transactions and incremental distribution network reform are two breakthroughs. Therefore, opening the door of distributed market transactions and incremental distribution networks will be the most important measures to solve the problem of PV grid parity from macro policies.
- Driven by the Top-runner project, the range of domestic high-efficiency modules has been further expanded, especially for mono-crystal bifacial modules, in which the bifacial module + tracking system will become the standard for the Top-runner project. At the same time, with the decline of system cost, PV + energy storage is also deployed widely.
- In the new adjustment cycle, overseas markets shall be paid more attentions, the products and these products' certification for overseas markets need to make planning in advanced.

REFERENCES

[1] C. Zheng and D. M. Kammen, "An innovation-focused roadmap for a sustainable global photovoltaic industry," *Energy Policy*, vol. 67, pp. 159–169, Apr. 2014.

[2] *International Energy Agency Photovoltaic Power Systems Programme*. Accessed: May 25, 2018. [Online]. Available: http://www.iea-pvps.org/index.php?id=6

[3] W. Bohua, *China PV Industry Development Status and Outlook*. Beijing, China: PV Industry Associate, 2017.

[4] H. Sun, Q. Zhi, Y. Wang, Q. Yao, and J. Su, "China's solar photovoltaic industry development: The status quo, problems and approaches," *Appl. Energy*, vol. 118, pp. 221–230, Apr. 2014.

[5] Z. Ming, O. Shaojie, S. Hui, and G. Yujian, "Is the 'Sun' still hot in China? The study of the present situation, problems and trends of the photovoltaic industry in China," *Renew. Sustain. Energy Rev.*, vol. 43, pp. 1224–1237, Mar. 2015.

[6] X.-G. Zhao, G. Wan, and Y. Yang "The turning point of solar photovoltaic industry in China: Will it come?" *Renew. Sustain. Energy Rev.*, vol. 41, pp. 178–188, Jan. 2015.

[7] Z. Ming, L. Ximei, L. Yulong, and P. Lilin, "Review of renewable energy investment and financing in China: Status, mode, issues and countermeasures," *Renew. Sustain. Energy Rev.*, vol. 31, pp. 23–37, Mar. 2014.

[8] M. Ding, Z. Xu, W. Wang, X. Wang, Y. Song, and D. Chenb, "The profitability of onshore wind and solar PV power projects in China—A comparative study," *Renew. Sustain. Energy Rev.*, vol. 53, pp. 639–652, Jan. 2016.

[9] Q. Tu, R. Betz, J. Mo, and Y. Fand, "The profitability of onshore wind and solar PV power projects in China—A comparative study," *Energy Policy*, vol. 132, pp. 404–417, Sep. 2019.

[10] *China's Renewable Energy Development and Market Trends*, document 20180606, Taoye, 2018.

[11] *China PV Market Analysis After 531 New Policy*, Sicheng, Wang, 2018.

[12] *China Photovoltaic Industry Association*, China PV Industry Development Roadmap, Beijing, China, 2018.

[13] C. Yuan, S. Liu, Y. Yang, D. Chen, Z. Fang, and L. Shui, "An analysis on investment policy effect of China's photovoltaic industry based on feedback model," *Appl. Energy*, vol. 135, pp. 423–428, Dec. 2014.

[14] Q. Zhi, H. Sun, Y. Li, Y. Xu, and J. Su, "China's solar photovoltaic policy: An analysis based on policy instruments," *Appl. Energy*, vol. 129, pp. 308–319, Sep. 2014.

[15] S. Li, J. Wang, Q. Liu, L. Li, Y. Hua, and W. Liu, "Analysis of status of photovoltaic and wind power abandoned in China," *J. Power Energy Eng.*, vol. 5, no. 1, pp. 91–100, 2017.

[16] J. S. Peng, W. X. Sun, and W. G. Zhong, "The evolution of Chinese technological and innovational policies and the empirical research on the performance (1978-2006)," *Sci. Res. Manag.*, vol. 29, pp. 134–150, Apr. 2008.

[17] X. Z. Wang, Z. G. Peng, W. Gao, and S. B. Ji, "The policy evolution and effect evaluation of wind power industry in China," *Stud. Sci. Sci.*, vol. 34, pp. 1817–1829, Dec. 2016.

[18] G. Xinneng, "Reply to the agreement to build a national advanced technology photovoltaic demonstration base in the Datong coal mining subsidence area in Shanxi," (in Chinese), no. 222, 2015.

[19] R. Fu, T. L. James, and M. Woodhouse, "Economic measurements of polysilicon for the photovoltaic industry: Market competition and manufacturing competitiveness," *IEEE J. Photovolt.*, vol. 5, no. 2, pp. 515–524, Mar. 2015.
[20] V. V. Tyagi, N. A. A. Rahim, N. A. Rahim, and J. A. L. Selvaraj, "Progress in solar PV technology: Research and achievement," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 443–461, Apr. 2013.
[21] G. R. Walker and P. C. Sernia, "Cascaded DC-DC converter connection of photovoltaic modules," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1130–1139, Jul. 2004.
[22] M. Yao and X. Cai, "Preliminary study on voltage level standardization of DC grid based on VSC-HVDC technology in China," in *Proc. IEEE Eindhoven PowerTech*, Jun./Jul. 2015, pp. 1–4.
[23] M. De Prada-Gil, J. L. Domínguez-García, L. Trilla, and O. Gomis-Bellmunt, "Technical and economic comparison of various electrical collection grid configurations for large photovoltaic power plants," *IET Power Gener.*, vol. 11, no. 3, pp. 226–236, 2016.
[24] J. Echeverría, S. Kouro, M. Pérez, and H. Abu-Rub, "Multi-modular cascaded DC-DC converter for HVDC grid connection of large-scale photovoltaic power systems," in *Proc. 39th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2013, pp. 6999–7005.
[25] J. Lyu, X. Zhang, X. Cai, and M. Molinas, "Harmonic state-space based small-signal impedance modeling of a modular multilevel converter with consideration of internal harmonic dynamics," *IEEE Trans. Power Electron.*, vol. 34, no. 3, pp. 2134–2148, Mar. 2019.
[26] G. Chen and X. Cai, "Reconfigurable control for fault-tolerant of parallel converters in PMSG wind energy conversion system," *IEEE Trans. Sustain. Energy*, vol. 10, no. 2, pp. 604–614, Apr. 2019.
[27] C. Zhang, X. Cai, M. Molinas, and A. Rygg, "On the impedance modeling and equivalence of AC/DC-side stability analysis of a grid-tied type-iv wind turbine system," *IEEE Trans. Energy Convers.*, vol. 34, no. 2, pp. 1000–1009, Jun. 2019.
[28] Y. Chang and X. Cai, "Hybrid topology of a diode-rectifier-based HVDC system for offshore wind farms," *IEEE Trans. Emerg. Sel. Topics Power Electron.*, vol. 7, no. 3, pp. 2116–2128, Aug. 2019.
[29] N. Hua, Z. Wei, and Y. Yanfei, "Key issues in scientific design of photovoltaic power plants," *Renew. Energy*, vol. 33, no. 7, pp. 1005–1012, 2015.
[30] T. Harighi, R. Bayindir, and S. Padmanaban, "An overview of energy scenarios, storage systems and the infrastructure for vehicle-to-grid technology," *Energies*, vol. 11, no. 8, p. 2174, 2018.
[31] S. Kouro, J. I. Leon, and D. Vinnikov, "Grid-connected photovoltaic systems: An overview of recent research and emerging PV converter technology," *IEEE Ind. Electron. Mag.*, vol. 9, no. 1, pp. 47–61, Mar. 2015.
[32] H. Xu, J. Su, and N. Liu, "A grid-supporting photovoltaic system implemented by a VSG with energy Storage," *Energies*, vol. 11, no. 11, p. 3152, 2018.
[33] H. Shin, E. Han, and N. Park, "Thermal residual stress analysis of soldering and lamination processes for fabrication of crystalline silicon photovoltaic modules," *Energies*, vol. 11, no. 12, p. 3256, 2018.
[34] A. Murtaza, U. Munir, M. Chiaberge, "Variable parameters for a single exponential model of photovoltaic modules in crystalline-silicon," *Energies*, vol. 11, no. 8, p. 2138, 2018.
[35] L. Y. Chang, Y. N. Chung, and K. H. Chao, "Smart global maximum power point tracking controller of photovoltaic module arrays," *Energies*, vol. 11, no. 3, p. 567, 2018.
[36] H. L. Cha, B. G. Bhang, S. Y. Park, J. H. Choi, and H. K. Ahn, "Power prediction of bifacial Si PV module with different reflection conditions on rooftop," *Appl. Sci.*, vol. 8, no. 10, p. 1752, 2018.
[37] Y.-H. Wang, G.-L. Luo, and Y.-W. Guo, "Why is there overcapacity in China's PV industry in its early growth stage?" *Renew Energy*, vol. 72, pp. 188–194, Dec. 2014.
[38] F. Urban, S. Geall, and Y. Wang, "Solar PV and solar water heaters in China: Different pathways to low carbon energy," *Renew. Sustain. Energy Rev.*, vol. 64, pp. 531–542, Oct. 2016.
[39] U. Pillai, "Drivers of cost reduction in solar photovoltaics," *Energy Econ*, vol. 50, pp. 286–293, Jul. 2015.

MEIQI YAO received the master's degree in electrical power system engineering from Northeast Dianli University, Jilin, China, in 2005. He is currently pursuing the Ph.D. degree in electrical engineering with Shanghai Jiao Tong University, Shanghai, China.

He was a Senior Engineer of Alstom Grid, from 2008 to 2014, a Vice Chief Engineer of TrinaSolar, from 2014 to 2017. He has been the Engineering Director of CanadianSolar, since 2019. His research interests include PV and energy storage integration, grid code, and power system analysis.

XU CAI received the B.Eng. degree from Southeast University, Nanjing, China, in 1983, and the M.Eng. and Ph.D. degrees from the China University of Mining and Technology, Jiangsu, China, in 1988 and 2000, respectively, all in electrical engineering. He was with the Department of Electrical Engineering, China University of Mining and Technology, as an Associate Professor, from 1989 to 2001. He was the Vice Director of the State Energy Smart Grid R&D Center, Shanghai, China, from 2010 to 2013. He has been with Shanghai Jiao Tong University, Shanghai, as a Professor, since 2002, where he has also been the Director of the Wind Power Research Center, since 2008. His current research interests include power electronics and renewable energy exploitation and utilization, including wind power converters, wind turbine control systems, large power battery storage systems, clustering of wind farms and its control systems, and grid integration.