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Accommodation of Clean Energy: Challenges and Practices in China Southern Region

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ABSTRACT Clean energy (including hydropower, wind power, solar power, nuclear power, etc.) provides an effective solution to deal with the issue of environmental protection and alleviate the depletion pressure of traditional fossil energy. However, in real practices, there are also many barriers that can challenge the accommodation of clean energy, including geographical condition, economy growth, energy endowment, technology limitation and so on. Due to regional discrepancies, unevenly distribution of power resources and electricity consumption, it is also a challenge for China Southern Power Grid (CSG) to utilize clean energy. To better develop clean energy, CSG has put a series of efforts, include: the long-transmission power network construction, power market support, dispatch optimization, technology innovation, etc. This paper mainly reviews the challenges and practices for the accommodation of clean energy in CSG. The corresponding outcome and future trends are also comprehensively introduced. It is expected through this paper, the case of CSG can inspire the development and accommodation of clean energy, as well as can provide beneficial references to other worldwide regions.

INDEX TERMS China Southern Power Grid, clean energy, HVDC, long distance power transmission, non-fossil, renewable.

I. INTRODUCTION

Electricity is indispensable in our daily life. Considering its production, it can be generated by traditional fossil energy resources such as coal, oil, gas and so on. However, these resources are in limited amount and are key factors leading to environmental changes and pollutions [1], [2]. With the development of modern technology and increasing concern for environmental protection, clean energy is now widely advocated and promoted all over the world [3]. The forms of clean energy for electricity generation include hydropower, wind power, solar power, nuclear power, etc. The widespread application of clean energy has provided a promising way to deal with global environmental pollution and is recognized as an alternative of traditional fossil energy for the realization of low carbonization [4]–[6].

However, there are also some barriers that can challenge the accommodation of clean energy. It is proposed that various aspects, e.g., technology, environment, society, and economy, should be balanced for better accommodation of clean energy [7]. In particular, the combined economic production of interconnecting distant regions poses a challenge to exploit clean energy for future sustainable electricity system [8]. Due to the uneven distribution of energy sources such as hydropower, wind and solar power, etc., power transmission channel is required for delivering clean energy from areas with abundant resources to regions with poor resources [9]. Besides, the economic development of different districts can be unbalanced, meaning that the capability of clean power consumption varies quite diversely in different places. Other challenges for the absorption of clean energy can be geographical condition, government policies, technologies, and so on [10], [11]. All these factors can influence the power consumption of clean energy for power grids.

Ranking as the second largest electricity consumer, the generation capacity and power consumption of China are still increasing at an amazing speed [12]–[14]. However, coal

has still played a dominated role in the power supply of China, accounted for about 75% of its total generation capacity installed [15]. With the ongoing power consumption and concern for fossil energy depletion, China is in an urgent need to develop renewable and clean energy for economic and sustainable development [16], [17]. To promote the nation's clean energy, China has issued several development and action plans, aiming to gradually replace fossil energy with renewable energy, and build a clean, low-carbon, safe and efficient modern energy system [18], [19]. In accordance with China's energy goal and strategy, one of the two national power grids, China Southern Power Grid (CSG), has put a series of efforts into the exploitation and utilization of clean energy. The measures adopted mainly include: the long-transmission power network construction, power market support, dispatch optimization, technology innovation, etc. Consequently, CSG has made prominent achievements in clean energy consumption. This article aims to elaborate the challenges and practices for the development of clean energy in China Southern Region served by CSG. The corresponding outcome and future trends are also comprehensively introduced. It is expected the case of CSG can inspire the development and accommodation of clean energy, as well as can provide beneficial references to other worldwide regions.

The rest parts of this paper are organized as follows: Section II introduces the basic conditions of CSG, including its power consumption, power resources and challenges for the accommodation of clean energy. Section III elaborates the measures, which cover seven different perspectives, adopted in CSG to accommodate clean energy. Section IV presents the outcome of CSG in the utilization of clean energy. Section V points out the outlook and trends of clean energy in CSG. And finally, Section VI gives conclusion of this paper.

II. THE CONDITIONS OF ENERGY RESOURCES IN CSG

The China Southern Power Gird, founded in December 2002, is one of the two state-owned super-large power grid enterprises in China. It is responsible to supply power energy to five provinces/regions in China Southern Region, including Guangdong, Guangxi, Yunnan, Guizhou and Hainan. In total, CSG gives power supply to an area of 1.02 million square kilometers with a service population of 230 million, accounting for 17.8% of the country's total population [20]. However, due to the natural gap in geographical condition, economy growth and energy endowment, the load consumption and power resources vary widely different among the five regions. These differences also lead to the challenges for the accommodation of clean energy in CSG. In the following content, the basic conditions for load and energy resources of CSG will be introduced first, followed by the challenges encountered for the accommodation of clean energy in China Southern Region.

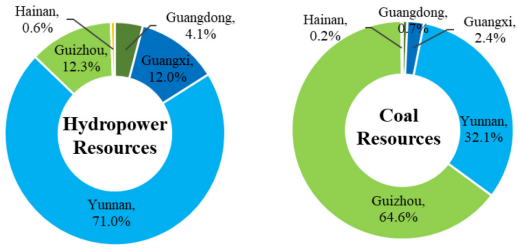

FIGURE 1. The distribution of hydropower and coal resources in CSG.

A. ENERGY RESOURCES IN CSG

Due to the conditions of geographical environment and resource endowment, the power generation resources and installed unit capacity vary greatly different among the 5 regions.

1) Guangdong is short of energy resources, where coal, gas and other energy resources are largely imported from other provinces or countries. The development potential of hydropower in Guangdong is also extremely limited.
2) Guangxi is also short of energy resources and its energy dependence on outside regions is as high as 76.7%. The coal reserve of Guangxi is small, and its coal supply depends mainly on Guizhou and foreign countries. Meanwhile, the development of hydropower in Guangxi has entered a deep stage, with limited potential for further development.
3) Yunnan is a province abundant with energy resources. Specifically, hydropower is the most abundant resource in Yunnan, accounting for 71% of the hydropower in China Southern Region, as shown in Fig. 1. The coal resource in Yunnan is rich with complete categories, meanwhile, the wind and solar energy resources are also abundant in Yunnan.
4) Guizhou is abundant in coal and hydropower. It is the second richest region in primary power energy resources in China Southern Region, which is only lower than Yunnan. The amount of coal resource in Guizhou ranks the first in China Southern Region with a proportion of 64.6%, see in Fig. 1. The hydropower in Guizhou accounts for 12.3% of CSG. However, the construction of large and medium sized hydropower plants in Guizhou has almost reached to its maximum in 2015, with limited development margin left.
5) Hainan is poor in coal resources, and it is an island with long coastline. The coastline is beneficial to develop port constructions to transfer coal from other places through sea transportation. Besides, the sea area under the jurisdiction of Hainan is rich in oil and gas resources, which is conducive for the development of gas power generation resources.

B. POWER CONSUMPTION OF CSG

The development in CSG service regions is very unbalanced, with most of its power consumption located in the east. The

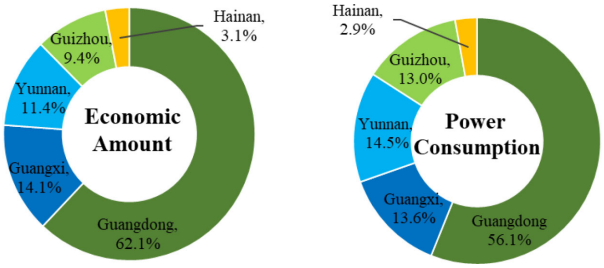

FIGURE 2. Economy and power consumption in CSG.

FIGURE 3. Main supply routine of energy in CSG.

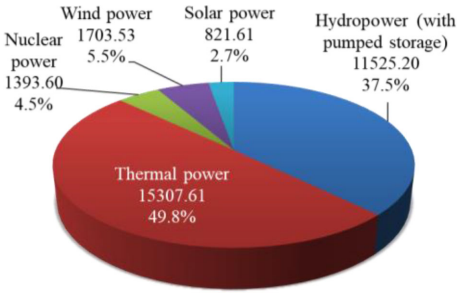

FIGURE 4. Power units installed in China Southern Region, 2017 (Unit: 10^4 kW).

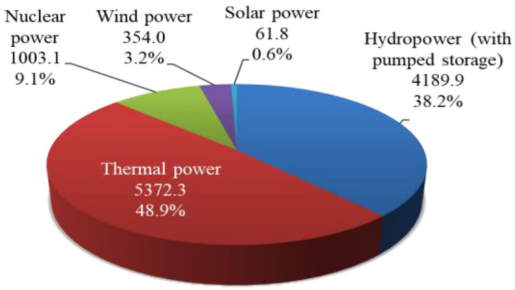

FIGURE 5. Power energy produced in China Southern Region, 2017 (Unit: 10^8 kWh).

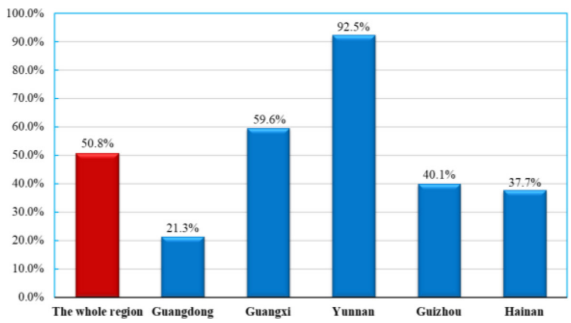

FIGURE 6. Capacity ratios of non-fossil energy generation unit, 2017.

proportions of economy and power consumption in China Southern Region are shown in Fig. 2. According to the statistics, the GDP (Gross regional domestic product) of Guangdong in 2017 reaches approximately 8.99 trillion yuan, accounting for 62.1% of the total amount in China Southern Region. With similar distribution pattern, the total electricity consumption of the China Southern Region in 2017 is 1.09 trillion kWh while Guangdong accounts for a percentage of 56.1%.

From the above analysis, it can be seen the energy resources are abundant in the west regions while poor in the east areas in China Southern Region [21]. However, the economy and load consumption are reversely distributed. The east region especially Guangdong contributes much more economy to China Southern Region than the west region. This determines a main feature of CSG, that is, large scale power supply is delivered from the west to the east region. The main energy routine in CSG is presented in Fig. 3, showing that Guangdong and Guangxi should rely on Yunnan and Guizhou for power provision.

C. CLEAN ENERGY RESOURCES OF CSG

Overall, in CSG, hydropower resource is abundant but distributed unevenly. The hydropower of Yunnan accounts for 71% of China Southern Region, yet leading reservoirs are deficient. Wind and solar energy resources are general, suitable to be consumed in situ and nearby the installed place of generation units.

The power unit capacity and generated electricity in 2017 are presented respectively in Fig. 4 and Fig. 5. By the end of 2017, CSG has an installed generation unit capacity of 308 GW, including 154 GW clean energy resources. The generated power energy of CSG was 1.1 trillion kWh, with 50.8% non-fossil energy production, 20.4% higher than China's average level. Wind and solar power accounted for 3.8% of the total generated electricity and the amount had basically been fully absorbed. The cumulative abandoning rate for wind and solar power were 2.3% and 0.59% respectively, far lower than the national's average level.

The capacity ratios of clean energy to the total generation unit for each region of CSG are given in Fig. 6. As can be seen, the proportion of clean energy in China Southern Region has reached 50.8% in 2017, much higher than the nation's average level. In particular, the non-fossil energy in Yunnan exceeds 90% of its total generation units, revealing its great amount in providing clean energy. Meanwhile, Guangdong is poor in

clean energy, with a capacity ratio of only 21.3% for its non-fossil energy.

D. CHALLENGES OF CLEAN ENERGY IN CSG

Due to natural characteristics and differences of energy resources and economic developments, there are several barriers challenging the accommodation of clean energy in CSG, which can be categorized into the following aspects:

1) The uneven distribution of power resources and load consumption in China Southern Region reveals the essential need of large-scale power transmission from the west to the east, which challenges the construction and operation of CSG.
2) It is still challenging to consume the surplus hydropower of the whole power grid [22], [23]. This issue mainly occurs in Yunnan, where plentiful hydropower is generated in wet season while hydropower is deficient during the drought period. In detail, most of the hydropower resources in Yunnan are of run-of-river hydropower type, mainly regulated weekly and daily; while more than 70% generated hydropower electricity is supplied in flood season. This is caused by the structural contradictions of its power supply and will exist for a long time. The forecasting accuracy for hydropower is also important for its dispatch. It is estimated that if the water inflow of the whole network is 10% lower or higher than the average annual rate, the generation capability of hydropower with 20∼30 billion kWh will be affected.
3) It is difficult to coordinate the interests of all the power market stakeholders to ensure full absorption of clean energy. Under the condition of overall surplus of deployed power generation units, several conflicts still exist in China Southern Region, including: 1) The generation rights between hydropower and thermal power units; 2) The interest conflicts between the eastern and western regions; 3) The power generation contradictions between new energy and conventional energy generations. All the above issues have objectively restricted the consumption of clean energy and limited the proportion of clean energy generated.
4) Due to the differences existing in the planning schemes of clean energy from different level of governments, the coordination of clean energy with conventional power supply and power grid planning is still insufficient. In some areas with abundant energy resources, the construction goals for clean energy are set to be too advanced. In detail, partial planning schemes developing clean energy have not taken into full consideration the constraints of local power load or external transmission capacity of power grids. Besides, in some regions, supporting mechanisms or policies are not ideally matched for clean energy, including the new energy subsidy mechanism, the settlement of electricity charges for residential distributed photovoltaic projects, and the regulations for the registration of new energy. These factors can also restrict the rapid development of clean energy.

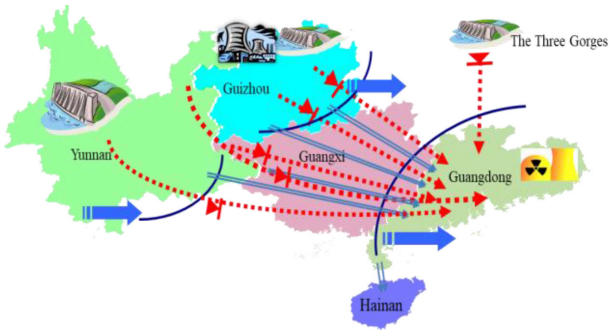

FIGURE 7. Power transmission from the west to the east in China Southern Region.

III. MEASURES FOR THE ACCOMMODATION OF CLEAN ENERGY IN CSG

In accordance with China's national goal to gradually replace fossil energy with renewable energy and build a clean, low-carbon, safe and efficient modern energy system, CSG has put a series of efforts into the utilization of clean energy. The measures are mainly focused on seven directions, including: power grid construction, power dispatch, electricity trading, political support, smart grid development, scientific innovation, sale expansion and electricity replacement of clean energy.

A. REINFORCEMENT FOR THE CONSTRUCTION OF THE WEST-TO-EAST POWER TRANSMISSION CHANNEL

To support large-scale power transmission from provinces with abundant energy resources (Yunnan and Guizhou) to provinces with poor power sources (Guangdong and Guangxi), long-distance UHVAC (Ultra high voltage alternating current) and UHVDC (Ultra high voltage direct current) power transmission channels have been constructed [24]. Currently, 8 UHVAC and 10 UHVDC transmission lines have been put into service for power delivery from the west to the east in CSG. With these power transmission lines, massive hydropower from Yunnan, Guizhou and the Three Gorges (located in China State Gird) have been successfully delivered to Guangdong, as shown in Fig. 7.

Specifically, the transmission capacity of HVDC lines in CSG for delivering power from the west to the east has been dramatically increased, with a 140-fold increase from 1800MW in 2001 to 27.2 GW by the end of 2015, shown in Fig. 8. The capacity of HVDC line is expected to reach 47.5 GW by the end of the national 13th five-year plan (year 2016 to year 2020).

The long-distance high voltage transmission channels have played a significant role in delivering clean energy from the west to the east. The transprovincial trade of energy electricity

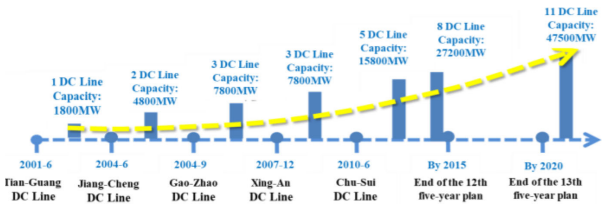

FIGURE 8. **The scale of HVDC transmission lines of CSG in recent 2 decades.**

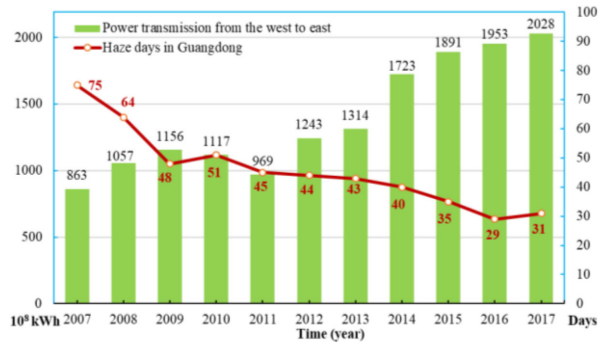

FIGURE 9. **Power transmission from the west to the east and haze days in Guangdong (Metered at the sending side, and the haze data source is from Guangdong meteorological bureau).**

from the west to the east reached 194.8 billion kWh in 2017, with 85.5% non-fossil power (166.5 billion kWh) in total. It is equivalent to reduce the standard coal consumption by 47.97 million tons and the carbon emission by 227.6 million tons.

For Guangdong, the received amount of electricity from the west is 176.8 billion kWh with 84.2% non-fossil power in 2017. The western electricity consumed in Guangdong accounts for about 30% of its total social electricity consumption. This amount is equivalent to reduce the coal consumption of 50 million tons in the pearl river delta region and nearly 140 million tons' carbon dioxide emissions per year. It has made outstanding contributions to reduce the haze weather of the pearl river delta region, as shown in Fig. 9. It has also driven the economic and social development in the western region and achieved win-win cooperation for different regions in CSG.

B. OPTIMIZATION FOR POWER DISPATCH

To maximize the accommodation of clean energy, several measures have been adopted to facilitate the dispatch of clean energy, including mainly four points.

1) OPTIMIZE THE HYDROPOWER DISPATCH [25], [26]

Dynamic adjustments and refined schemes of power generation for thermal plants before flood season are made to ensure the power generation space of hydropower units. Besides, during the flood season, the optimal plan for water management and cascaded hydroelectric dispatch are scheduled, ensuring

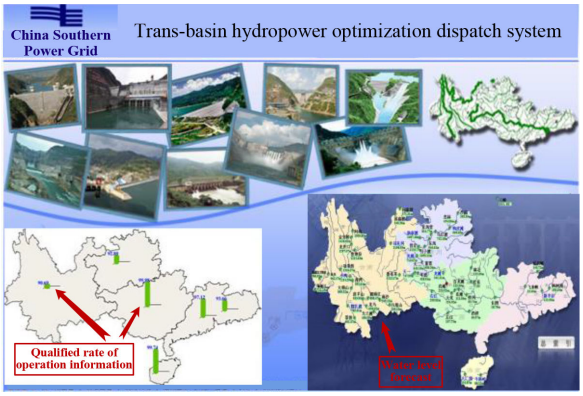

FIGURE 10. **The demonstration of trans-basin hydropower dispatch automation system in CSG.**

the water target level of main reservoirs before the flood season.

In addition, to deal with the situation of massive distributed small hydropower stations with weak dispatch management, water-situation tracking and warning mechanism as well as long-term coordination mechanism of integrated water use for river basins fitted CSG have been designed and implemented [27]. Meanwhile, to monitor and dispatch trans-basin and trans-provincial hydropower consumption, the largest power grid water dispatch automation system in China has been constructed in CSG, as demonstrated in Fig. 10. At present, the water information for 198 hydropower stations and a total of 7,536 information points for water situation telemetry and water calculation have been connected to the system, covering all the basins of the entire CSG. With the above measures, the level of hydropower dispatch has been improved.

2) STRICTLY CONTROL THE OUTPUT OF THERMAL POWER

For some areas with partial wind or solar power abandonment such as Chuxiong and Dali in Yunnan, and Weining in Guizhou, the power output of thermal power is strictly controlled. Firstly, CSG subsidiary companies try to cooperate with the government to complete the verification of the minimum technical output for thermal power units, then the operation of the thermal power units is arranged according to the verification results. Secondly, during the flood season, the power generated from the thermal power units is controlled to ensure the consumption of clean energy. What's more, long-term standby compensation mechanism for thermal power units is also investigated and implemented, thus greatly shutdown the power generation of thermal power units while ensuring the basic living space of thermal power enterprises. All these measures aim to ensure clean energy can be consumed to its maximum extent.

3) OPTIMIZE THE ARRANGEMENT FOR PEAK-SHAVING

To maximize the power transmission potential of the West-to-east power transmission channel, the power dispatch of the

load center in China Southern Region (i.e., Guangdong) is optimized. In detail, on the premise of power grid safety, the peak-valley arrangement of Guangdong is refined to minimize the peak-valley difference of its power grid.

4) OPTIMIZE POWER OPERATION AND MAINTENANCE

To ensure long-term stable operation of power delivery channels to deliver clean power of Yunnan to the west regions, the operation and maintenance of the West-to-east power transmission channel are strengthened. The power outage schedules of the west-to-east power transmission channels are coordinated and optimized, thus promote the clean energy delivery from Yunnan power gird. The optimization of maintenance arrangement can also reduce the potential risk of power operation.

C. IMPLEMENTATION OF "PLAN + MARKET" TRANS-PROVINCIAL AND CROSS-DISTRICT POWER TRADING MODEL

To facilitate the consumption of clean energy, mechanisms for promoting clean energy trading in power market have been applied, including:

1) The accommodation of Yunnan hydropower is listed as a priority work of CSG. The surplus capacity of power transmission channels linking the west and east and the allocation of power generation in the power market are utilized [28]. In detail, the electricity replacements of Yunnan hydropower for Guizhou and Guangxi thermal power are promoted. The above measures are implemented to fully promote the consumption of Yunnan hydropower.
2) The trading mechanism of the power market is also innovated [29]–[31]. A trans-provincial and cross-district power trading mode in CSG is established, featuring with mainly medium-and-long term electricity agreements, and supplementary temporal transactions. Market mechanisms such as preferential trading of clean energy, water and thermal power replacement, and long-term standby compensation of thermal power are also implemented. Meanwhile, CSG is now orderly building a unified electricity spot market in China Southern Region. As clean energy is cheaper than traditional power energy, the construction of a competitive spot market will certainly promote the consumption of clean energy.
3) In addition, the electricity pricing mechanism for long-distance power transmission is refined to facilitate clean energy consumption. Under the premise of ensuring the investment recovery of power transmission channel, the price of DC transmission in northwest Yunnan is audited. To maximize the absorption of clean energy, transmission and distribution power prices are dynamically adjusted with seasonal and temporary measures studied and formulated. With the above mechanisms, trans-provincial and cross-district power market transactions in CSG have been promoted.

FIGURE 11. Distributed photovoltaic power generation project in Xinlong village, Waxi town, Zijin county.

The above measures have resulted in outstanding outcome. In 2017, the west power from Yunnan sent to the east regions reached 124.2 billion kWh, with about 27.66 billion kWh more than planned. Specifically, a breakthrough of hydropower replacement with 0.62 billion kWh for thermal power generation was achieved. In 2017, the actual amount of abandoned hydropower in Yunnan was 28.87 billion kWh with a decrease of about 2.5 billion kWh as compared with 2016. Besides, the water energy utilization rate of Yunnan province in 2017 had reached 88%.

D. SUPPORT FOR RAPID GROWTH OF NEW ENERGY AND DISTRIBUTED ENERGY SOURCES

To promote the utilization of clean energy, distributed renewable energy resources are widely supported. In 2017, the cumulative installed capacity of wind power and solar power in China Southern Region has reached 25.25 GW, with a year-on-year growth of 34%. The generated amount of wind and solar electricity in CSG was 41.6 billion kWh in 2017, with a year-on-year growth of 35%.

To support the national policies on photovoltaic poverty alleviation, related projects are also depolyed, such as the construction of "distributed photovoltaic power generation project in Xinlong village, Waxi town, Zijin county" in Heyuan city of Guangdong, as shown in Fig. 11. The installed capacity of this project is 1.1MW and was connected to the power grid on June 28, 2018. It is expected to generate 1.15 million kWh of electricity and generate more than 0.9 million Yuan of electricity income annually.

E. CONSTRUCTION OF SMART GRID

The construction of smart grid is promoted which can facilitate the consumption of clean energy [32]–[34]. The smart grid architecture of CSG covers nine areas including five links and four support systems, as shown in Fig. 12:

1) Five links, including: clean and friendly power generation, safe and efficient power transmission and transformation, flexible and reliable power distribution, diversified and interactive electricity consumption, smart energy and energy Internet.
2) Four supporting systems, including: comprehensive and interconnected communication network, efficient and

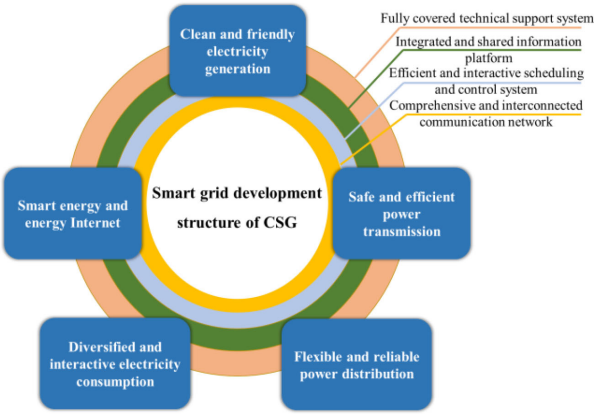

FIGURE 12. Architecture of smart grid in CSG.

interactive scheduling and control system, integrated and shared information platform, and fully covered technical support system.

With the construction of smart power grids, the provision of clean and friendly electricity will be steadily facilitated. By 2020, CSG is expected to have the capability to accept and absorb 129 GW hydropower, 28 GW wind power, 13 GW photovoltaic and 4 GW biomass power generation in a timely manner.

F. PROMOTION ON SCIENTIFIC AND TECHNOLOGICAL INNOVATION

Scientific and technological innovation is also advocated to promote the absorption of clean energy, including "Internet +" smart energy demonstration, in-depth research on key large-scale energy storage, technologies for offshore wind power, and measures on new energy power prediction technologies [35].

1) "Internet +" smart energy demonstration projects are facilitated in China Southern Region, as displayed in Table I, including two projects in Guangzhou and Zhuhai that listed in the first batch of "Internet +" smart energy demonstration projects initiated by the national energy administration of China [36]. The demonstrations, covering applications of demand response, energy storage, smart building, etc., aim to promote the complementation and efficient coordination of multi-energy, and to build an open and shared energy internet ecosystem. By means of "Internet +" and based on intellectualization techniques, the public participation level into power grids can be improved, and flexible transformation and coordination in-between multi-energy can be also promoted [37], [38]. The measures are aimed at creating an open and inclusive innovation environment to support the construction of power market system and innovate power trading business model. The achievements, at the same time, can facilitate the comprehensive utilization of clean energy.

TABLE I "Internet +" Energy Demonstration Projects in CSG

Areas	Projects	Key demonstrations
Guangzhou	Demonstration project of energy Internet for megalopolis power grid	Electric vehicles, "Internet +" intelligent energy interconnection service platform, intelligent buildings, comprehensive energy infrastructure, cloud/cascade utilization demonstration projects of energy storage, etc.
Zhuhai	City-district dual-level "Internet +" smart energy demonstration supporting the revolution of energy consumption	Demonstration of highly reliable power distribution network, flexible multi-terminal AC/DC power distribution network of MW level, wide access and cloud control to new energy and energy storage.
Shenzhen	Demand response based demonstration project of smart energy system in urban center	Flexible energy integration system based on demand response, including smart energy efficiency buildings, smart charging stations for electric vehicles and smart power consumption communities.
Guangxi	Innovation project of distribution network infrastructure support and service model for energy Internet	By using big data and existing system platforms of Hechi power network in Guangxi, realize lean management of distribution network through big data analysis and application based on grid GIS platform. Develop user-side smart energy utility cloud service platform and mobile terminal APP to provide value-added services.
Yunnan	Dulong river energy Internet demonstration project	Based on the micro-grid of Dulong river and the "Internet+" smart energy technology, put forward new ideas for solving power supply problems in remote areas.
Guizhou	Energy Internet demonstration project in Guian new area of Guizhou	Develop and build operating system applicable to different application scenarios of energy Internet, and provide exclusive solutions for typical and important loads such as data center in new areas, electronic information industrial parks, high-end equipment manufacturing industrial factories, etc.
Hainan	Smart energy network demonstration project in Yongxing island, Sansha	Plan and build a multi-energy complementary intelligent micro-grid system with island characteristics, and realize the sustainable development of power supply, cooling and energy supply of the micro grid by integrating multiple energy technologies.
Foshan	"Internet +" smart energy demonstration project in financial high-tech service area of Guangdong	Build a smart energy Internet based on smart grid and informatization to enhance user interaction and service level.

2) Carry out in-depth researches on key technologies for large-scale energy storage systems. Access technologies of new energy into distribution networks and associated pilot projects are promoted. The participation of large-scale energy storage devices in system peak-shaving is studied to solve the problem of local consumption for clean energy in partial time periods and sectional power grids. Specifically, the pilot projects of the national 863 program "Research and integration demonstration for key technologies of user-side smart micro-grid based on distributed energy" and "Research and demonstration of key technologies for active distribution network integrated renewable energy" were constructed and completed. The projects have verified that good performance can be achieved in supporting the development of new energy with energy storage.
3) Research on technologies for offshore wind power and new energy absorption is being implemented [39]–[41]. In CSG, the offshore wind power industry is planned, and the installed capacity of offshore wind power (within 50 meters of water depth) is planned to reach 71 GW. The key involved techniques for offshore wind power are demonstrated in Fig. 13, where technologies for key equipment, market consumption, transmission channels, dispatch, testing and detection are needed. At present, pilot projects of large-scale integration of remote coastal wind power have already been deployed, such as Guishan off-shore wind power farm interconnection project [42]. In addition, to promote the wind power consumption through the load forecasting level, a large-scale offshore wind power data platform and an intelligent real-time simulation platform for large-scale offshore clustered wind farms will be respectively built. By 2025, it is expected that large-scale offshore wind

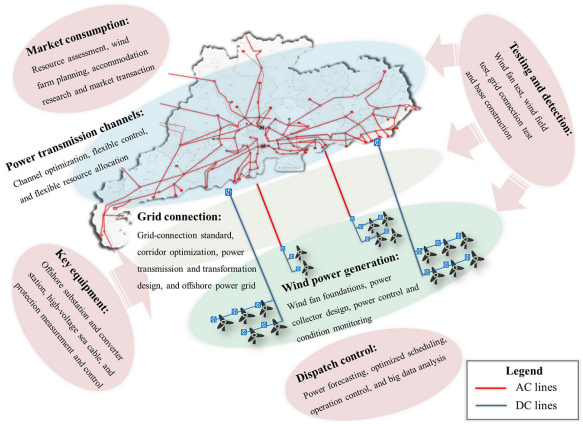

FIGURE 13. Blueprint for offshore wind power technologies in Guangdong.

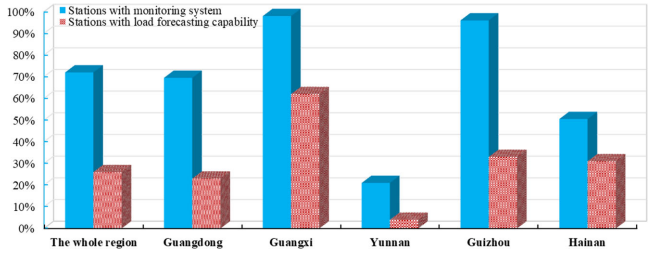

FIGURE 14. Monitoring and control levels of new energy stations in China Southern Region, 2017.

power can be fully absorbed without obstacles in China Southern Region.

4) Measures on new energy power prediction technologies for wind power, solar power, etc., are adopted. The meteorological factors in China Southern Region are integrated to constantly improve the accuracy of new energy forecast, and finally promote the development and utilization of clean energy.

The development and application of new energy monitoring platform have been implemented, and the proportion of construction for station side monitoring system of new energy in CSG has been increased year by year. By 2017, there are 900 new energy stations (including small hydropower) equipped with station side monitoring system in China Southern Region, with the deployed proportion as high as 72.3%, as shown in Fig. 14. Many of the new energy stations are also enabled with load forecasting capability (see in Fig. 14). This can effectively improve the management level of clean energy.

G. BOOST FOR SUPPLY INCREASE, SALES EXPANSION AND ELECTRICITY REPLACEMENT OF CLEAN ENERGY

To expand the market for clean energy, multiple consumption channels are also developed. It is estimated that, when the share of electricity in the terminal energy consumption is increased by 1%, the energy consumption per unit of GDP can be reduced by about 4% [43], [44]. In 2017, CSG continued to focus on electric power replacement in nine areas, including

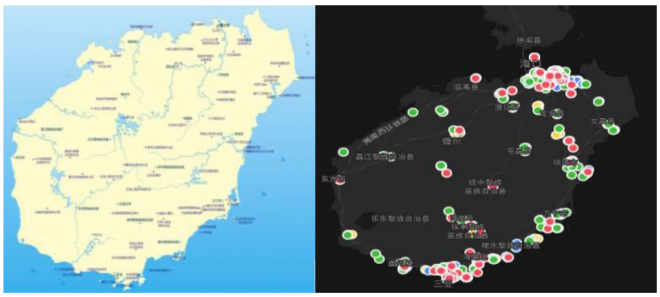

FIGURE 15. Distribution map for Hainan EV charging stations (Left: overview of Hainan; right: distribution of EV stations).

electric boilers, marine shore power, electromagnetic kitchen, and electric vehicles, etc. A total of 4,232 power replacement projects were carried out throughout the year, increasing over 11.4 billion kWh of electricity.

Specially, the development of EV (electric vehicle) is being supported all over the world and CSG also takes measures to promote the popularization of EVs. In 2017, CSG has built 225 EV charging stations, with a year-on-year increase of 285%; in total, CSG has built 4,992 new charging piles in this year, with a year-on-year increase of 115%. This gives more convenience for green power transportation in China Southern Region. Specifically, Hainan power grid has constructed a total of 11 quick charging stations (including 2 urban demonstration stations) and 40 charging piles at Hainan trans-island expressway and middle route expressway, with one charging station for every 65 kilometers along the way, as shown in Fig. 15. Hainan is now entering into the era of electric vehicles around the island.

IV. OUTCOME FOR THE ACCOMMODATION OF CLEAN ENERGY IN CSG

With the above efforts, CSG has made prominent achievements in the development and utilization of clean energy, as introduced below.

A. CAPACITY PROPORTION OF CLEAN ENERGY RESOURCES

The trend of capacity proportion for clean energy resources in the overall generation units from year 2015 to year 2017 has been given in Fig. 16. As displayed, the capacity proportions of energy resources including hydropower, nuclear power, wind power and solar power have increased year by year in CSG. The total unit capacity of non-fossil energy has increased from 134.1 GW in 2015 to 154.4 GW in 2017, and the capacity proportion of non-fossil energy in the overall generation units has increased from 49.8% to 50.2% in these years.

B. POWER ENERGY PROPORTION OF CLEAN ENERGY RESOURCES

The proportions of electricity generated from clean energy resources including nuclear power, wind power and solar power

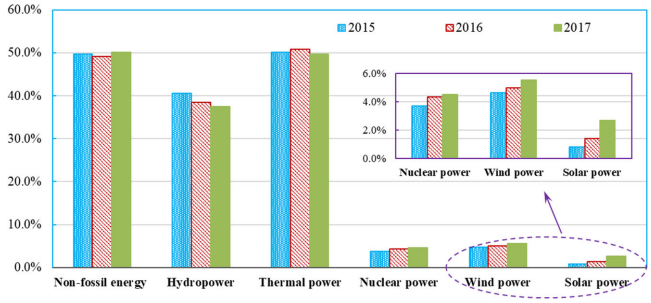

FIGURE 16. **The trend of capacity for clean energy resources in China Southern Region from year 2015 to year 2017 (Hydropower contains pumped energy).**

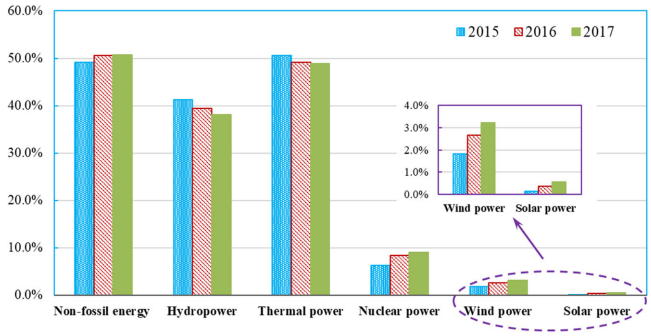

FIGURE 17. **The trend of generated electricity from clean energy resources in China Southern Region from year 2015 to year 2017 (Hydropower contains pumped energy).**

have also steadily increased from year 2015 to year 2017 in China Southern Region, as presented in Fig. 17. The electricity generated from non-fossil resources has increased year by year, from 484.9 billion kWh in 2015 to 557.6 billion kWh in 2017. Consequently, the electricity proportion of non-fossil energy has increased from 49.2% in 2015 to 50.8% in 2017.

C. TRANSPROVINCIAL TRADE OF CLEAN ENERGY

The transprovincial trades of energy electricity from the west to the east within year 2015 to year 2017 have been presented in Fig. 18. The total West-to-east electricity has increased from 180.2 billion kWh in 2015 to 194.8 billion kWh in 2017. The proportion of electricity generated from clean energy to the total electricity delivered has also gradually improved, from 79.1% in 2015 to 85.5% in 2017. In short, the West-to-east power transmission channels have made significant contributions for delivering the western abundant clean energy to the eastern regions including Guangdong and Guangxi.

D. DEVELOPMENT GOALS OF CLEAN ENERGY IN CSG

During the national 13th five-year plan period of China, CSG will vigorously support the development of clean energy, driving the company to be a "clean and low carbon, energy saving, environment friendly and utilization efficient" modern green power grid enterprise.

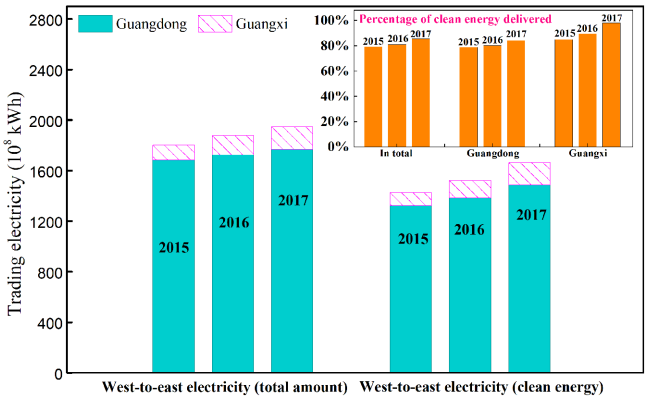

FIGURE 18. **Transprovincial trade of West-to-east electricity from year 2015 to year 2017 (Metered at the receiving side; Data presented includes: Total electricity amount, electricity from clean energy and its percentage).**

TABLE II **The Development Goals of Clean Energy in CSG**

Item	2015 (GW)	2020 (GW)	Annual growth rate
Total installed capacity	269	363	6.2%
Hydropower	109	129	3.4%
Thermal power	135	167	4.3%
Nuclear power	10.03	21.96	17.0%
Wind power	12.55	28.00	17.4%
Solar power	2.20	13.00	42.7%
Biomass power	0.80	4.00	38.0%
Clean power	134.58	195.96	7.8%

It is expected by 2020, the installed unit capacity of clean energy in CSG will reach 196 GW, and the details for each kind of power resources are presented in Table II. The annual growth rate of clean energy during the 13th five-year plan period is approximately 8.0%.

V. OUTLOOK FOR ACCOMMODATION OF CLEAN ENERGY IN CSG

With the development of technologies in power grid, it is predicted clean energy will go through great changes, and the main trends include: 1) fossil energy is expected to be gradually replaced by clean energy; 2) the energy would be gradually decentralized; 3) traditional fossil energy will be much more efficiently utilized; 4) multiple energy networks are to be developed.

A. FOSSIL ENERGY GRADUALLY REPLACED BY CLEAN ENERGY

The structure of energy supply will be shifted from fossil energy to non-fossil energy, from energy sources mainly depending on hydropower and thermal power to the coordination of traditional energy sources and new energy sources. Then the goal of substitution of fossil energy by clean energy can be gradually realized.

For CSG, the main energy sources providing power from the west to the east are mainly large hydropower stations located in the southwest and surrounding areas of China. In addition, the hydropower potential in southeast Tibet and east

FIGURE 19. Blueprint of power delivery in the future from southeast Tibet and east overseas.

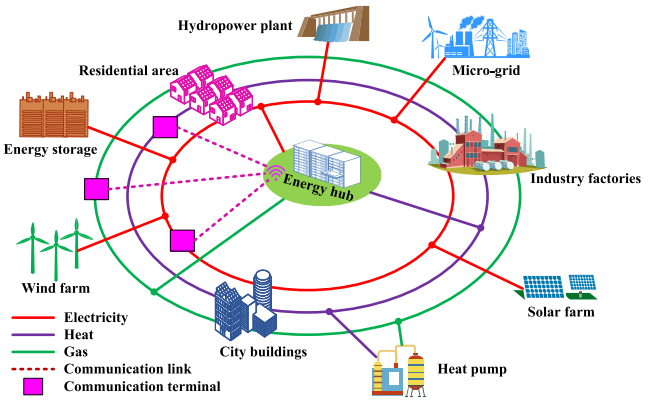

FIGURE 20. Demonstration for in-depth connection of multi-energy.

overseas is also huge [45], and hydropower stations in these places will be considered to deliver power to the east regions in CSG, as shown in Fig. 19.

B. CENTRALIZED ENERGY GRADUALLY REPLACED BY DISTRIBUTED ENERGY

With the development of energy storage, distributed energy resources, micro-grid and other technologies, the pattern of energy supply will be changed. It is expected that centralized-and-integrated energy supply will be developed towards energy provision with the coordination of centralized and distributed power resources [46]. In addition, bidirectional interaction between the supply and demand will be widely supported [47].

Meanwhile, since renewable energy resources are decentralized, their development and utilization will be mostly depended on distributed consumption near the user side. The rapid development of self-occupied distributed energy resources may have a disruptive impact on the operation mode of power enterprises.

C. EFFICIENT AND CLEAN USE OF TRADITIONAL FOSSIL ENERGY

The basic characteristics with rich coal, poor oil and low gas of energy resources in China result in that coal will remain the main energy source of the country for a long time.

To promote the transformation and upgrading of China's energy, the development and utilization of non-fossil energy combined with efficient and clean utilization of fossil energy should be put into force [48], [49]. Besides, the utilization efficiency of traditional fossil energy will be constantly improved via technology and mechanism innovation.

D. INTEGRATION AND INTERACTION OF MULTIPLE ENERGY NETWORKS

With the in-depth integration of sensor, information, communication, control technology and energy system, the traditional single power network is being developed towards intelligent direction with multi-energy (including water, hot, gas, etc.) complementation [50]–[52]. Energy demands in various fields such as electricity, heat (cold) and gas are to be coordinated to realize coordinated supply with multi-energy and cascade utilization, as demonstrated in Fig. 20.

VI. CONCLUSION

The challenges and practices for the development of clean energy in China Southern Region are introduced. With a series of efforts involving power grid construction, power dispatch, electricity trading, political support, smart grid construction, scientific innovation, sale expansion and electricity replacement, CSG has made prominent achievements in both unit capacity and generated power energy of clean energy resources. It is expected the experiences of CSG can give inspirations for other worldwide regions in both academic or industrial studies for the consumption of clean energy.

With the development and application of advanced power grid technologies, it is also predicted clean energy will go through great changes. It is anticipated that fossil energy will be gradually replaced by clean energy while traditional fossil energy will be much more efficiently utilized. Besides, the utilization of power energy would be gradually decentralized, and multiple energy networks will be coordinated and co-optimized.

REFERENCES

[1] R. Dominguez, A. J. Conejo, and M. Carrion, "Toward fully renewable electric energy systems," *IEEE Trans. Power Syst.*, vol. 30, no. 1, pp. 316–326, Jan. 2015.

[2] A. Mahone *et al.*, "On the path to decarbonization: Electrification and renewables in California and the Northeast United States," *IEEE Power Energy Mag.*, vol. 16, no. 4, pp. 58–68, Jul./Aug. 2018.

[3] Accelerating Clean Energy Innovation, European commission, Brussels, Belgium, 30 Nov. 2016.

[4] D. C. Momete, "Analysis of the potential of clean energy deployment in the european union," *IEEE Access*, vol. 6, pp. 54811–54822, Oct. 2018.

[5] X. Yang, Y. Song, G. Wang, and W. Wang, ''A comprehensive review on the development of sustainable energy strategy and implementation in China," *IEEE Trans. Sustain. Energy*, vol. 1, no. 2, pp. 57–65, Jul. 2010.

[6] W. You *et al.*, "Technical and economic assessment of RES penetration by modelling China's existing energy system," *Energy*, vol. 165, pp. 900–910, Dec. 2018.

[7] L. Zhang, P. Zhou, S. Newton, J. X. Fang, D. Q. Zhou, and L. P. Zhang, "Evaluating clean energy alternatives for Jiangsu, China: An improved multi-criteria decision making method," *Energy*, vol. 90, pp. 953–964, Oct. 2015.

[8] H. Liu, G. B. Andresen, and M. Greiner, "Cost-optimal design of a simplified highly renewable Chinese electricity network," *Energy*, vol. 147, pp. 534–546, Mar. 2018.

[9] J. Sun *et al.*, "Renewable energy transmission by HVDC across the continent: System challenges and opportunities," *CSEE J. Power Energy Syst.*, vol. 3, no. 4, pp. 353–364, Dec. 2017.

[10] F. Amri, "Renewable and non-renewable categories of energy consumption and trade: Do the development degree and the industrialization degree matter?" *Energy*, vol. 173, pp. 374–383, Apr. 2019.

[11] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, and N. Duić, "Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447–455, Oct. 2018.

[12] REN21 Secretariat. Renewables 2017: Global status report. Jun. 2017, [Online]. Available: http://www.indiaenvironmentportal.org.in/content/443683/renewables-2017-global-status-report/

[13] Y. Li and A. Oberheitmann, "Challenges of rapid economic growth in China: Reconciling sustainable energy use, environmental stewardship and social development," *Energy Policy*, vol. 37, no. 4, pp. 1412–1422, Apr. 2009.

[14] Chinese Central Government. "China's national climate change programme," Beijing: National Development and Reform Commission, 2007. [Online]. Available: https://www.adaptation-undp.org/sites/default/files/downloads/chinas_national_climate_change_program.pdf

[15] H. Liu, C. Wang, M. Tian, and F. Wen, "Analysis of regional difference decomposition of changes in energy consumption in China during 1995-2015," *Energy*, vol. 171, pp. 1139–1149, Mar. 2019.

[16] C. Zhang, K. Zhou, S. Yang, and Z. Shao, "On electricity consumption and economic growth in China," *Renewable Sustain. Energy Rev.*, vol. 76, pp. 353–368, Sep. 2017.

[17] Z. Ming, X. Song, M. Mingjuan, and Z. Xiaoli, "New energy bases and sustainable development in China: A review," *Renew. Sustain. Energy Rev.*, vol. 20, pp. 169–185, Apr. 2013.

[18] Beijing. "Action plan for clean energy consumption (2018-2020)," National Development and Reform Commission, and National Energy Administration, Oct. 2018, [Online]. Available: http://www.ndrc.gov.cn/gzdt/201812/W020181204585956678476.pdf

[19] Beijing. "Medium and long term development plan for renewable energy," National Development and Reform Commission, Aug. 2017, [Online]. Available: http://www.ndrc.gov.cn/zcfb/zcfbghwb/200709/W020140220601800225116.pdf

[20] H. Zhou, Y. Su, Y. Chen, Q. Ma, and W. Mo, "The China southern power grid: Solutions to operation risks and planning challenges," *IEEE Power Energy Mag.*, vol. 14, no. 4, pp. 72–78, Jun. 2016.

[21] B. Zhou *et al.*, "Principle and application of asynchronous operation of China southern power grid," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 6, no. 3, pp. 1032–1040, Sep. 2018.

[22] C. Cheng, J. Shen, X. Wu, and K. Chau, "Operation challenges for fast-growing China's hydropower systems and respondence to energy saving and emission reduction," *Renew. Sustain. Energy Rev.*, vol. 16, no. 5, pp. 2386–2393, Mar. 2012.

[23] Z. Ming, Z. Kun, and L. Daoxin, "Overall review of pumped-hydro energy storage in China: Status quo, operation mechanism and policy barriers," *Renew. Sustain. Energy Rev.*, vol. 17, pp. 35–43, Jan. 2013.

[24] J. Shen, C. Cheng, X. Cheng, and J. R. Lund, "Coordinated operations of large-scale UHVDC hydropower and conventional hydro energies about regional power grid," *Energy*, vol. 95, pp. 433–446, Jan. 2016.

[25] C. Cheng, B. Liu, K. W. Chau, G. Li, and S. Liao, "China's small hydropower and its dispatching management," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 43–55, Feb. 2015.

[26] J. Shen, C. Cheng, J. Zhang, and J. Lu, "Peak operation of cascaded hydropower plants serving multiple provinces," *Energies*, vol. 8, no. 10, pp. 11295–11314, Oct. 2015.

[27] L. C. T. Hongbin and L. Shushan, "Generation dispatching management of small hydropower plants in CSG," in *Proc. China Int. Conf. Elect. Distribution*, Xi'an, China, Sep. 2016, pp. 1–4.

[28] M. Zeng, Y. Yang, Q. Fan, Y. Liu, and Z. Zou, "Coordination between clean energy generation and thermal power generation under the policy of "direct power-purchase for large users," in China," *Utilities Policy*, vol. 33, pp. 10–22, Apr. 2015.

[29] M. Meng, S. Mander, X. Zhao, and D. Niu, "Have market-oriented reforms improved the electricity generation efficiency of China's thermal power industry? An empirical analysis," *Energy*, vol. 114, pp. 734–741, Nov. 2016.

[30] C. Cheng *et al.*, "Reform and renewables in China: The architecture of Yunnan's hydropower dominated electricity market," *Renew. Sustain. Energy Rev.*, vol. 94, pp. 682–693, Oct. 2018.

[31] X. Zhang, W. Liu, Y. Chen, Y. Bai, J. Li, and J. Zhong, "Electricity market design and operation in guangdong power," in *Proc. 15th Int. Conf. Eur. Energy Market*, Lodz, Poland, Jun. 2018, pp. 1–5.

[32] H. Chen, P. Xuan, Y. Wang, K. Tan, and X. Jin, ''Key technologies for integration of multitype renewable energy sources–Research on multi-timeframe robust scheduling/dispatch," *IEEE Trans. Smart Grid*, vol. 7, no. 1, pp. 471–480, Jan. 2016.

[33] J. Yuan, J. Shen, L. Pan, C. Zhao, and J. Kang, "Smart grids in China," *Renew. Sustain. Energy Rev.*, vol. 37, pp. 896–906. Sep. 2014.

[34] D. N. Y. Mah, Y. Y. Wu, and P. R. Hills, "Explaining the role of incumbent utilities in sustainable energy transitions: A case study of the smart grid development in China," *Energy Policy*, vol. 109, pp. 794–806, Oct. 2017.

[35] J. Zhu, P. Xie, P. Xuan, J. Zou, and P. Yu, "Renewable energy consumption technology under energy internet environment," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integration (EI2)*, Beijing, China, Nov. 2017, pp. 1–5.

[36] Beijing. "List of the first "Internet +" smart energy (energy Internet) demonstration projects," National Energy Administration, Jun. 2017, [Online]. Available: http://zfxxgk.nea.gov.cn/auto83/201707/t20170706_2825.htm

[37] J. Zhu, P. Xie, P. Xuan, J. Zou, and P. Yu, "Renewable energy consumption technology under energy internet environment," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integration (EI2)*, Beijing, China, Nov. 2017, pp. 1–5.

[38] G. Bedi, G. K. Venayagamoorthy, R. Singh, R. R. Brooks, and K. Wang, "Review of Internet of Things (IoT) in electric power and energy systems," *IEEE Internet Things J.*, vol. 5, no. 2, pp. 847–870, Apr. 2018.

[39] B. K. Sahu, "Wind energy developments and policies in China: A short review," *Renew. Sustain. Energy Rev.*, vol. 81, pp. 1393–1405, Jan. 2018.

[40] S. Sun, F. Liu, S. Xue, M. Zeng, and F. Zeng, "Review on wind power development in China: Current situation and improvement strategies to realize future development," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 589–599, May 2015.

[41] X. G. Zhao and L. Z. Ren, "Focus on the development of offshore wind power in China: Has the golden period come?" *Renewable Energy*, vol. 81, pp. 644–657, Sep. 2015.

[42] F. Li, P. D. Chen, J. W. Yang and L. Guan, "Guishan off-shore wind power farm interconnection: A real project study," in *Proc. IEEE PES Asia-Pacific Power Energy Eng. Conf.*, Kowloon, Hong Kong, Dec. 2013, pp. 1–5.

[43] H. Geller, P. Harrington, A. H. Rosenfeld, S. Tanishima, and F. Unander, "Polices for increasing energy efficiency: Thirty years of experience in OECD countries," *Energy Policy*, vol. 34, no. 5, pp. 556–573, Mar. 2006.

[44] A. Shiu and P. L. Lam, "Electricity consumption and economic growth in China," *Energy Policy*, vol. 32, no. 1, pp. 47–54, Jan. 2004.

[45] L. Han, "Viewing the sustainable development of the Qinghai-Tibet plateau from water resources system," in *Proc. IOP Conf. Ser.: Earth Environmental Sci.*, vol. 170, no. 3, pp. 1–4, Jul. 2018.

[46] L. Pingkuo and T. Zhongfu, "How to develop distributed generation in China: In the context of the reformation of electric power system," *Renew. Sustain. Energy Rev.*, vol. 66, pp. 10–26, Dec. 2016.

[47] L. Steg, R. Shwom, and T. Dietz, "What drives energy consumers?: Engaging people in a sustainable energy transition," *IEEE Power Energy Mag.*, vol. 16, no. 1, pp. 20–28, Jan. 2018.

[48] A. S. Brouwer, M. van den Broek, A. Seebregts, and A. Faaij, "Operational flexibility and economics of power plants in future low-carbon power systems," *Appl. Energy*, vol. 156, pp. 107–128, Oct. 2015.

[49] C. Song, M. Li, F. Zhang, Y. L. He, and W. Q. Tao, "A data envelopment analysis for energy efficiency of coal-fired power units in China," *Energy Convers. Manage.*, vol. 102, pp. 121–130, Sep. 2015.
[50] H. Zhang, Y. Li, D. W. Gao, and J. Zhou, "Distributed optimal energy management for energy internet," *IEEE Trans Ind. Informat.*, vol. 13, no. 6, pp. 3081–3097, Dec. 2017.
[51] X. Xing, J. Lin, Y. Song, Y. Zhou, S. Mu, and Q. Hu, "Modeling and operation of the power-to-gas system for renewables integration: a review," *CSEE J. Power Energy Syst.*, vol. 4, no. 2, pp. 168–178, Jun. 2018.
[52] M. A. Hannan *et al.*, "A review of internet of energy based building energy management systems: Issues and recommendations," *IEEE Access*, vol. 6, pp. 38997–39014, Jul. 2018.

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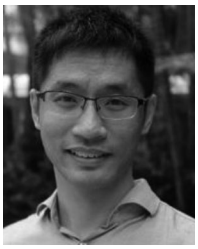

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