Institute for Carbon Neutrality, Tsinghua University 清华大学碳中和研究院

School of Environment, Tsinghua University 清华大学环境学院

ENERGY FOUNDATION 能源基金会

中国碳中和目标下的风光技术展望 - 执行摘要

Technology Outlook on Wind and Solar Power toward China's Carbon Neutrality Goal - Summary for policy maker

报告负责人：鲁　玺 清华大学碳中和研究院院长助理、环境学院教授
Principal: LU Xi, Assistant Dean of the Institute for Carbon Neutrality and Professor of the School of Environment, Tsinghua University

章节召集人：
Conveners:

李　丹 中国能源研究会可再生能源专业委员会
LI Dan, Renewable Energy Special Committee, China Energy Research Society
秦海岩 中国可再生能源学会风能专业委员会
QIN Haiyan, Wind Energy Committee, China Renewable Energy Society
于贵勇 中国可再生能源学会风能专业委员会
YU Guiyong, Wind Energy Committee, China Renewable Energy Society
江　华 中国光伏行业协会
JIANG Hua, China Photovoltaic Industry Association
赵晓辉 中国电力工程顾问集团西北电力设计院有限公司
ZHAO Xiaohui, Northwest Electric Power Design Institute Co., Ltd., China Power Engineering Consulting Group
罗　勇 清华大学
LUO Yong, Tsinghua University
何继江 清华大学
HE Jijiang, Tsinghua University

报告作者：
Authors:

于　洋 中国能源研究会可再生能源专业委员会
YU Yang, Renewable Energy Special Committee, China Energy Research Society
张云霞 中国可再生能源学会风能专业委员会
ZHANG Yunxia, Wind Energy Committee, China Renewable Energy Society
王　青 中国光伏行业协会
WANG Qing, China Photovoltaic Industry Association
王海霞 中国电力工程顾问集团西北电力设计院有限公司
WANG Haixia, Northwest Electric Power Design Institute Co., Ltd., China Power Engineering Consulting Group
廖舟怡 清华大学
LIAO Zhouyi, Tsinghua University
郭红艳 清华大学
GUO Hongyan, Tsinghua University
阮梓纹 清华大学
RUAN Ziwen, Tsinghua University
陈　诗 清华大学
CHEN Shi, Tsinghua University
李朝君 清华大学
LI Chaojun, Tsinghua University

王家兴 清华大学
WANG Jiaxing, Tsinghua University
王雨涵 清华大学
WANG Yuhan, Tsinghua University
夏　馨 清华大学
XIA Xin, Tsinghua University
张憧宇 清华大学
ZHANG Chongyu, Tsinghua University
郑隽卿 清华大学
ZHENG Junqing, Tsinghua University
陈　丹 北京大学
CHEN Dan, Peking University
靳双龙 中国电力科学研究院有限公司
JIN Shuanglong, China Electric Power Research Institute Co., Ltd.
沙　恒 中国光伏行业协会
SHA Heng, China Photovoltaic Industry Association
李嘉彤 中国光伏行业协会
LI Jiatong, China Photovoltaic Industry Association
张天宇 中国光伏行业协会
ZHANG Tianyu, China Photovoltaic Industry Association
白桦林 中国光伏行业协会
BAI Hualin, China Photovoltaic Industry Association
廖　杰 中国科学院
LIAO Jie, Chinese Academy of Sciences
马丽芳 中国能源研究会可再生能源专业委员会
MA Lifang, Renewable Energy Special Committee, China Energy Research Society
杨文斌 中国治沙暨沙业学会
YANG Wenbin, China National Sand Control and Desert Industry Society
邹荣松 中国林业科学研究院
ZOU Rongsong, Chinese Academy of Forestry

顾问专家组：
Consultants:

贺克斌 中国工程院院士、清华大学碳中和研究院院长、清华大学环境学院教授
HE Kebin, Academician of Chinese Academy of Engineering, Dean of the Institute for Carbon Neutrality and Professor of the School of Environment, Tsinghua University
李俊峰 国家气候战略中心首任主任、中国能源研究会常务理事
LI Junfeng, First Director of the National Climate Strategy Center and the Executive Director of the China Energy Research Society
邹　骥 能源基金会首席执行官兼中国区总裁
ZHOU Ji, Chief Executive Officer and President of Energy Foundation China

张　强 清华大学地球系统科学系副主任、教授
ZHANG Qiang, Deputy Director, Professor of Department of Earth System Science, Tsinghua University
傅　莎 能源基金会战略规划主任
FU Sha, Director of Strategic Planning, Energy Foundation China
李美成 华北电力大学新能源学院院长、教授
LI Meicheng, Dean, Professor of New Energy Institute, North China Electric Power University
严　刚 生态环境部环境规划院副院长
YAN Gang, Deputy Director of Institute of Strategic Planning, Ministry of Ecology and Environment
张传卫 明阳智慧能源集团股份公司董事长、首席执行官
ZHANG Chuanwei, Chairman and Chief Executive Officer of MingYang Smart Energy Group Limited
刘汉元 通威集团董事局主席
LIU Hanyuan, Chairman of the Board of Directors of Tongwei Group
申彦波 中国气象局风能太阳能中心科学主任、正高级工程师
SHEN Yanbo, Scientific Director and Senior Engineer of Wind Energy and Solar Energy Center, China Meteorological Administration
杜广平 中国可再生能源学会风能专业委员会研究员、北京鉴衡认证中心有限公司总工程师
DU Guangping, Researcher of Wind Energy Committee, China Renewable Energy Society and Chief Engineer of Beijing Jianheng Certification Center Co., LTD
蒋莉萍 国网能源研究院国网三级顾问（原副院长）、正高级工程师
JIANG Liping, Third-level consultant and Senior Engineer of State Grid Energy Research Institute (former Deputy Director)
谢小平 国家电投集团公司专家委员会专家、正高级工程师
XIE Xiaoping, Expert Committee Expert and Senior Engineer of State Power Investment Corporation
汪子阜 隆基绿能科技股份有限公司可持续发展与 ESG 高级经理
WANG Zifu, Senior Manager of Sustainable Development and ESG, LONGi Green Energy Technology Co.,Ltd.
王志峰 中国科学院电工研究所研究员
WANG Zhifeng, Researcher of Institute of Electrical Engineering of the Chinese Academy of Sciences
王卫权 中国能源研究会能源与环境专委会秘书长、高级工程师
WANG Weiquan, Secretary General of Energy and Environment Committee, China Energy Research Society
王　阳 中国气象局国家气候中心正高级工程师
WANG Yang, Senior Engineer of National Climate Center, China Meteorological Administration

免责声明

若无特别声明，报告中陈述的观点仅代表作者个人意见，不代表清华大学碳中和研究院、清华大学环境学院和能源基金会的观点。清华大学碳中和研究院、清华大学环境学院和能源基金会不保证本报告中信息及数据的准确性，不对任何人使用本报告引起的后果承担责任。

凡提及某些公司、产品及服务时，并不意味着它们已为清华大学碳中和研究院、清华大学环境学院和能源基金会所认可或推荐，或优于未提及的其他类似公司、产品及服务。

Disclaimer

Unless explicitly stated otherwise, the views expressed in the report solely represent the personal views of the authors and do not reflect the positions of the Institute for Carbon Neutrality at Tsinghua University, the School of Environment at Tsinghua University, or the Energy Foundation China. The Institute for Carbon Neutrality at Tsinghua University, the School of Environment at Tsinghua University, and Energy Foundation China make no warranties about the accuracy of the information and data contained in this report and will not be held liable for any consequences arising from or related to the use of this report by any third party.

Mentioning specific companies, products and services does not imply endorsement or recommendation by the Institute for Carbon Neutrality at Tsinghua University, the School of Environment at Tsinghua University, and the Energy Foundation China, nor does it suggest that they are preferred over other similar entities, products, or services not mentioned.

引 言

在持续的全球气候变化背景下，中国于 2020 年 9 月在第 75 届联合国大会一般性辩论中宣布了具有重大意义的承诺 “二氧化碳排放力争于 2030 年前达到峰值，努力争取 2060 年前实现碳中和”。这一承诺将推动中国朝着低碳发展的目标迈进，深入进行能源结构转型。在此战略框架下，发展风、光等可再生能源成为实现低碳目标、推动电力系统变革的关键措施，同时也是实现“零碳”电力系统的主力军。风光及配套支持技术的创新成为提高效率和可靠性的关键，为风光发电的可持续发展奠定了坚实基础。以此为背景，清华大学碳中和研究院牵头组织的《中国碳中和目标下的风光技术展望》报告深入剖析风、光等可再生能源产业链所面临的全方位风险和挑战，识别了风、光发电在开发过程中的内在优势，捕捉到新的产业机遇和业态。报告描绘了中国风光发展的路线图和时间表，为未来构建技术先进、成本低廉、安全稳定、生态友好的风光发电技术体系提供了明晰的建议，助力中国可再生能源行业的可持续发展。

Introduction

Amid ongoing global climate change, China announced a landmark pledge at the General Debate of the 75th Session of the United Nations General Assembly on September 22, 2020, aiming for carbon emissions to peak by 2030 and striving for carbon neutrality by 2060. This pledge propels China towards a low-carbon future through a profound energy transformation. Driven by this strategy, advancing renewable energy sources such as wind and solar becomes crucial for meeting carbon reduction goals, transforming the electricity system, and leading the charge towards a "zero-carbon" electricity grid. Innovations in wind and solar technologies and their supporting systems are key to enhance efficiency and reliability, laying a solid foundation for the sustainable growth of wind and solar power (WSP) generation. In this context, the Technology Outlook on Wind and Solar Power towards China's Carbon Neutrality Goal report, led by the Tsinghua University Institute for Carbon Neutrality, provides an in-depth analysis of the comprehensive risks and challenges facing the WSP industry. It identifies the inherent advantages of WSP generation and captures new industrial opportunities and business patterns. The report outlines a roadmap and timeline for China's WSP development and offers clear recommendations for establishing an advanced, cost-effective, secure, stable and eco-friendly WSP generation technology system, supporting the sustainable development of China's renewable energy sector.

1.

中国碳中和目标下的风光电力

WSP under China's goal of achieving carbon neutrality

中国风光资源潜力足以支撑中国全社会的电力需求。中国风、太阳能资源丰富，风能技术可开发10.9至20.1 TW，太阳能技术可开发45.6至58.9 TW。风光的理论装机容量远超碳中和目标需求，风能年发电潜力为2020年全社会用电量的4-6倍，太阳能年发电潜力为2020年全社会用电量的9-13倍。

中国风光资源在中国各地表现出较大的差异，给未来电力系统的发展带来一定的挑战。由于中国地域广阔、地形多变，中国各地风、光资源潜力差异大。陆上风电主要在华北、东北、西北有潜力，海上风电在华东和南方沿海集中，光伏发电在西北、华北潜力大，分布式光伏在华北、华东较为依赖屋顶建筑面积在华北、华东地区潜力较大。风光发展的地区潜力差异可能导致能源开发不均衡、区域电力供应与需求不匹配等问题，一些地区可能更容易实现清洁能源的大规模发展，而其他地区可能因为潜力相对较弱而受到限制。

过去十五年中，中国风光发电的装机量高速发展，为减缓全球气候变化作出巨大贡献。自2000年以来，中国以风电、光伏为主的可再生能源技术不断发展，装备水平逐步提升，风电、太阳能发电的装机规模迅速扩大，占电力结构的比重逐渐增加。截至2022年底，中国风电与光伏总装机容量已达758 GW，占全部电力装机的29.6%，发电量占所有电源的13.8%。

“双碳”背景下，未来中国将以指数式增长的方式发展风光发电。大量的报告及研究显示，中国2030年风光总装机量预计将达到1582至2130 GW，而到2060年将达到5496至7662 GW。这意味着2030年和2060年，风光在电力供应中的占比

China's wind and solar resources possess the immense potential to meet the nation's entire power demand. The country is endowed with rich wind and solar energy resources, enabling the potential development of wind energy technologies up to 10.9 to 20.1 terawatts (TW), and solar energy technologies ranging from 45.6 to 58.9 TW. This vast theoretical capacity of WSP far surpasses the requirements for achieving China's carbon neutrality goals, with the annual generation potential of wind energy estimated to be 4 to 6 times, and solar energy 9 to 13 times, the total power consumed across the country in 2020.

The significant regional disparities of wind and solar resources in China challenge the future equitable expansion of the nation's power systems. The vast territory and diverse topography of China result in notable variations in the potential for WSP resources across different regions. Onshore wind power potential is concentrated mainly in the North, Northeast, and Northwest, while offshore wind power is prevalent in East China and the southern coastal areas. Photovoltaic (PV) power has substantial potential in the Northwest and North, with distributed PV potential, dependent on the availability of rooftop space, being more prevalent in the North and East. These regional variations in WSP potential could lead to uneven energy development and disparities between regional power supply and demand, indicating that some regions might advance more quickly in large-scale renewable energy development, while others may be constrained by relatively lower potential.

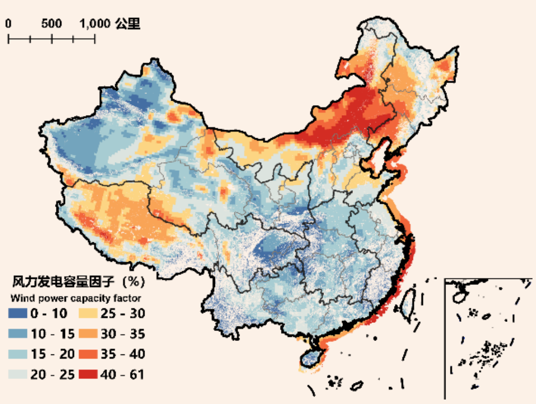
China's installation of WSP capacities has surged over the past fifteen years, making a significant contribution to mitigating global climate change. China's renewable energy technologies, with a focus on wind and PV systems, have advanced steadily since 2000. These advancements have led to a rapid increase in the installation scale of WSP, progressively elevating their share within the overall power generation mix. By the end of 2022, China's combined installed capacity of WSP reached 758 GW, accounting for 29.6% of the country's total power installations and contributing to 13.8% of the total electricity generated.

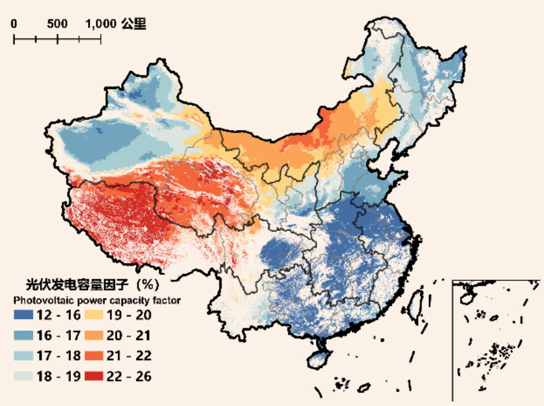
China's WSP deployment is expected to grow exponentially in the context of “dual carbon” goals. Numerous reports and studies forecast that by 2023, the cumulative installed capacity of WSP in China could range from 1,582 to 2,130 GW. By 2060, this capacity is expected to soar to between 5,496

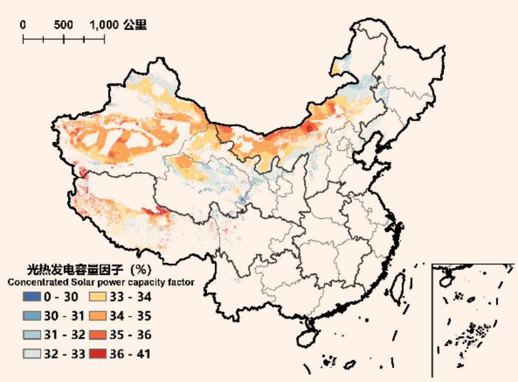
分别将超过 23% 和 65%。此外，在 2023 年 9 月召开的二十国集团（G20）领导人第十八次峰会中，各国领导人就“支持 2030 年全球可再生能源产能增加 2 倍”达成共识。2023 年 11 月，中国国家主席习近平和美国总统约瑟夫·拜登在印尼巴厘岛会晤，中美双方重申致力于合作并与其他国家共同努力应对气候危机，并在发布的声明中强调：“在 21 世纪 20 年代这关键十年，两国支持二十国集团领导人宣言所述努力争取到 2030 年全球可再生能源装机增至三倍，并计划从现在到 2030 年在 2020 年水平上充分加快两国可再生能源部署，以加快煤油气发电替代，从而可预期电力行业排放在达峰后实现有意义的绝对减少。”这意味着中国在未来五至六年要加快风光装机速度，其到 **2030 年有望达到 2200-2400 GW** 左右的总装机规模，为全球气候行动作出贡献。

and 7,662 GW. Accordingly, WSP's share of the electricity supply is anticipated to exceed 23% by 2030 and 65% by 2060. Furthermore, leaders at the 18th G20 Leaders' Summit held in September 2023 reached a consensus to “pursue tripling renewable energy capacity globally by 2030”. In November 2023, Chinese President Xi Jinping met with U.S. President Joseph Robinette Biden in Bali, Indonesia. Both sides reaffirmed their commitment to work jointly and together with other countries to address the climate crisis with other countries. Their joint statement emphasized: “Both countries support the G20 Leaders Declaration to pursue efforts to triple renewable energy capacity globally by 2030 and intend to sufficiently accelerate renewable energy deployment in their respective economies through 2030 from 2020 levels so as to accelerate the substitution for coal, oil and gas generation, and thereby anticipate post-peaking meaningful absolute power sector emission reduction, in this critical decade of the 2020s.” This underscores the imperative for China to hasten the installation pace of WSP, **with an expected total installed capacity of 2,200-2,400 GW by 2030**, contributing significantly to global climate action.

中国风电、光伏、光热发电容量因子分布特征
Distribution characteristics of wind, PV and concentrated solar power capacity factors in China





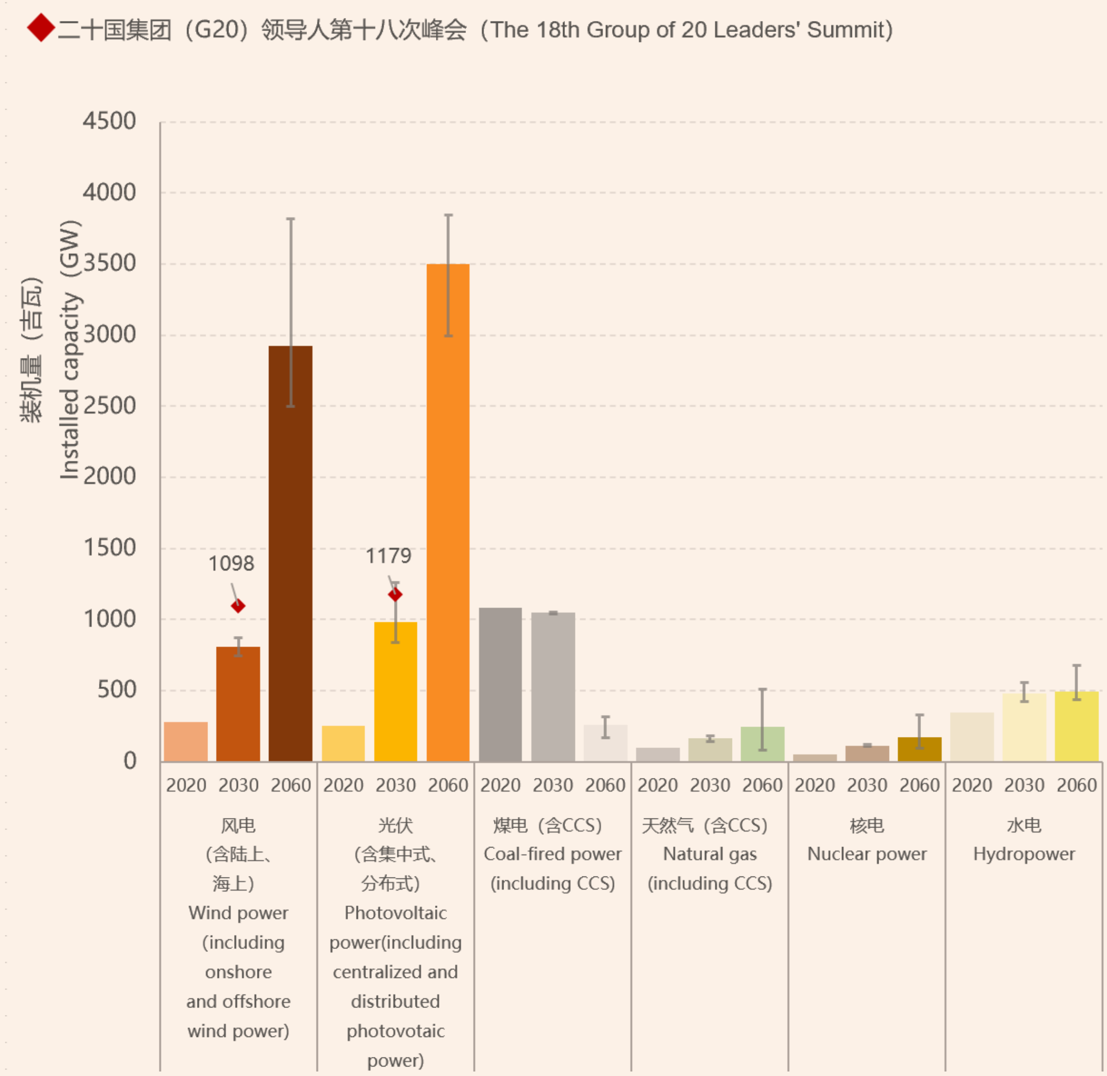


当前主流碳达峰、碳中和情景下 2030 年和 2060 年我国各电源装机变化（其中不同电源 2060 年柱状的垂直误差线代表了不同报告的预测区间）

注：G20 峰会未给出各国明确的风光装机目标，本图中的 G20 数据为 2030 年可再生能源装机量三倍的目标预测的风光装机数据。

The installed capacity for various power sources in 2020, 2030 and 2060 under the prevailing scenarios of carbon peaking and carbon neutrality (The vertical error bars on the columns for different power sources in 2060 represent the forecast ranges from different reports)

Note: The G20 summit did not specify WSP installation targets for each country. The G20 data in this Figure for 2030 represents the predicted WSP installation under a goal three times the renewable energy installed capacity.



2.

风光技术发展展望

Development outlook of WSP technology

2.1 风电技术

回顾中国风电技术发展历程，先后经历了风电技术应用探索、风电技术示范推广、规模化开发准备、风电规模化开发这四个阶段。目前，中国风电已具备成熟产业链和技术研发能力，中国风电机组呈现了不断的大型化发展特征，2022 年新增的陆上风电与海上风电平均装机容量达到 4.3 MW 和 7.4 MW。同时中国也已成为全球最大的风电装备制造基地，中国风电机组的产量占到全球的 2/3 以上，发电机、轮毂、机架、叶片、齿轮箱、轴承等关键大部件的产量占全球 60%-70%。截至 2022 年底，中国自主研发的风电机组已经遍布全球 40 多个国家和地区。

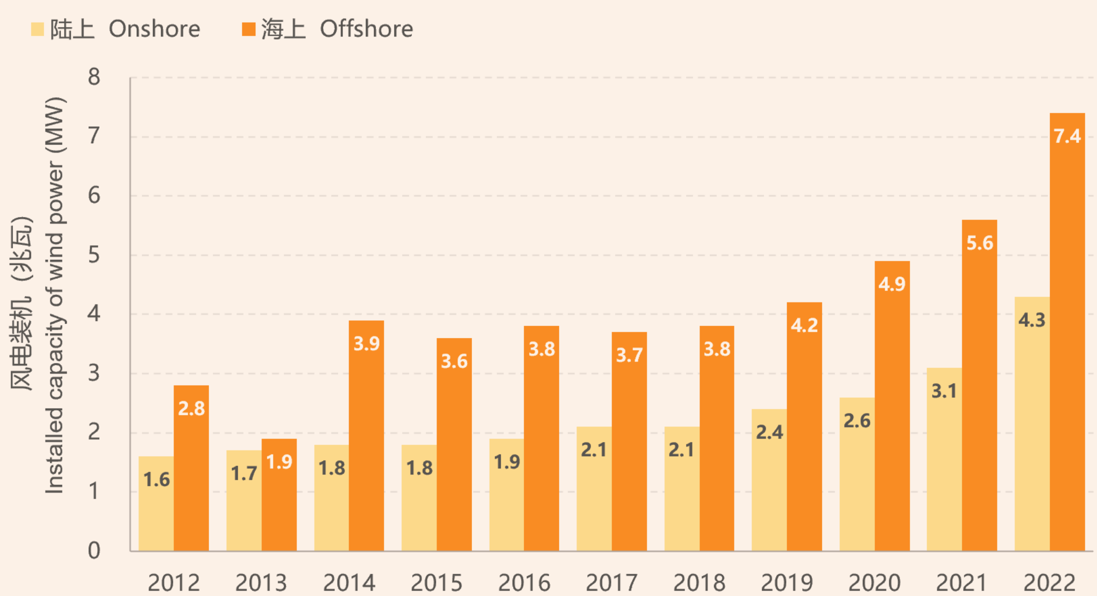
在过去的三十多年来，中国已经形成了一套涵盖风电开发建设、设备制造、技术研发、检测认证、

2.1 Wind power technology

The evolution of wind power technology in China has traversed four distinct stages: initial application exploration, demonstration and broader promotion, subsequent preparation for large-scale development, and ultimately, the large-scale deployment. Today, China's wind power sector boasts a mature industry chain and robust capabilities in technological research and development, epitomized by a trend towards increasingly large wind turbine models. In 2022, the average installed capacity of newly commissioned onshore and offshore wind power projects was 4.3 MW and 7.4 MW, respectively. Simultaneously, China has solidified its position as the world's largest manufacturing base for wind power equipment. Chinese wind turbine output contributes to over two-thirds of the global total, with key components such as generators, hubs, racks, blades, gearboxes, and bearings accounting for 60%-70% of the global output. By the end of 2022, wind turbines developed independently in China have been deployed in over 40 countries and regions around the world.

Over the past 30 years, China has meticulously crafted an all-encompassing industrial ecosystem for wind power,

中国新增陆上和海上风电机组平均单机容量
Average capacity of newly commissioned onshore and offshore wind turbines in China



我国风电机组关键环节全球市场占有率

Global market share of key components of wind turbines in China

零部件 Components	我国制造全球占比 China's share of global manufacturing	技术门槛 Technical threshold	集中度 Concentration ratio
发电机 Generator	65%	高 High	较高 Relatively high
叶片 Blade	60%	较高 Relatively high	较高 Relatively high
齿轮箱 Gearbox	64%	中高 Medium-high	较高 Relatively high
变流器 Converter	68%	较高 Relatively high	较低 Relatively low
主控系统 Master control system	59%	较高 Relatively high	较高 Relatively high
变桨系统 Pitch system	59%	较高 Relatively high	较高 Relatively high
铸件 Casting	77%	较高 Relatively high	较高 Relatively high
塔筒 Tower	86%	较低 Relatively low	偏低 Relatively low
主轴 Main shaft	78%	高 High	低 Low
轴承 Bearing	77%	高 High	偏低 Relatively low

金融保险等全方位的产业链体系。除主轴轴承外，中国风电产业链已基本实现 95% 国产化进程，但是在部分零部件仍依赖进口：5 MW 级以上大兆瓦风电机组主轴轴承 60% 来自进口，国内风电机组变流器 70% 的 IGBT 模块由德国英飞凌、日本富士、瑞士 ABB 等国外企业提供，控制器的 PLC 模块 100% 由国外企业供应。

在成本方面，自 2006 年以来中国陆上风电项目的平均平准化度电成本（LCOE）下降了 70%，海上风电自 2010 至 2021 年下降了 56%，风电 LCOE 下降最主要的贡献来自技术进步带来的发电效率的提升。未来随着风电机组的大型化发展趋势，风电成本预计还有很大的下降空间，其中风电产品成本下降是驱动风电项目造价变化的主要因素。未来，预

which includes development, construction, equipment manufacturing, technological innovation, testing and certification, and financial and insurance services. The country has essentially achieved a 95% rate of domestic manufacturing, except for mainshaft bearings, indicating a still present dependency on imported components for some parts. Notably, for large-scale wind turbines exceeding 5 MW, around 60% of their mainshaft bearings are imported. Additionally, 70% of the IGBT modules used in domestic wind turbine converters are sourced from international companies such as Infineon (Germany), Fuji (Japan), and ABB (Switzerland). Furthermore, 100% of the PLC modules for controllers are procured from overseas companies.

In terms of costs, the average levelized cost of electricity (LCOE) for onshore wind power projects in China has witnessed a remarkable 70% reduction since 2006. Similarly, the LCOE for offshore wind power projects has experienced significant cost reductions, with a 56% decrease from 2010 to 2021. This decrease is largely due to efficiency gains in power generation achieved through technological advancements. As the trend towards large wind turbines models continues, there is significant potential for further cost reductions in wind power

计 2025-2030 年陆上风电项目 LCOE 约达 0.17-0.22 元 /kWh（2020 年不变值，下同），海上风电项目约达 0.34-0.38 元 /kWh；到 2035 年，陆上风电项目 LCOE 达到 0.14-0.19 元 /kWh，海上风电项目约达到 0.21-0.23 元 /kWh；到 2060 年，陆上风电项目 LCOE 约达到 0.1-0.15 元 /kWh，海上风电项目约达到 0.19-0.20 元 /kWh。

展望未来的十年，大型化和轻量化依然是风电发展的主要趋势，根据全球风能理事会最新分析，预计到 2025 年海上风电机组单机容量约达到 15 MW，到 2030 年达到 20 MW，海上风电将逐步向深远海发展，这将对风电机组的研发、制造、安装运维、相关装备制造等环节提出更高的要求。基于现有的风电技术及中国风电产业链发展情况，我们提出如下风电技术和产业链发展的建议：

1. 提升基础制造业工艺水平和材料制造水平。重点集中在大型化轻量化的叶片、模块化智能化的齿轮箱、集成化和子系统模块化的变流器控制系统；

2. 提升风电电子芯片的基础设计与制造工艺，进一步推进风电智能化发展。电子芯片在数据采集、处理和传输中发挥了关键作用，高性能、低功耗的芯片使得风电场能够更加高效地处理海量数据，支持先进的数据分析和人工智能应用，为风电运营和维护提供更精准的决策支持；

3. 支持、推动风电行业公共验证平台建设。公共验证平台有助于建立共同的标准和规范，提高整个行业的水平，确保风电项目达到一定的质量和性能标准，同时能够促进风电技术创新、提高产业水平、推动可持续发展；

4. 开发新工艺、研发新材料促使产业走向零碳时代。提升碳纤维等原材料及大叶片产品的性能、质

projects, primarily driven by decreases in the cost of wind power products. Projected figures suggest that the LCOE for onshore wind power projects will range from CNY 0.17 to 0.22 per kWh for the period between 2025 and 2030, with offshore wind power projects estimated to achieve an LCOE of CNY 0.34 to 0.38 per kWh. By 2035, the LCOE for onshore wind power projects is expected to decline to between CNY 0.14 and 0.19 per kWh, and for offshore wind power projects, to between CNY 0.21 and 0.23 per kWh. Looking further ahead to 2060, the LCOE for onshore wind power projects is anticipated to be the range of CNY 0.1 to 0.15 per kWh, while offshore wind power projects are expected to achieve an LCOE of between CNY 0.19 and 0.20 per kWh.

Looking ahead to the next decade, the wind power sector is poised to continue its focus on scaling up and lightening the design of turbines. The Global Wind Energy Council's recent analysis forecasts that the capacity of individual offshore wind turbines is expected to hit approximately 15 MW by 2025, and rise to 20 MW by 2030. As offshore wind ventures further into deeper and more distant waters, this evolution will necessitate elevated standards for turbine research and development, manufacturing, installation, operation, and maintenance, as well as for the production of associated equipment. Given the current trajectory of wind power technology and the development of China's wind power industry chain, we recommend the following strategies for advancing wind power technology and its industry ecosystem:

1.Enhance the caliber of foundational manufacturing processes and material production. Prioritize the development of large-scale and lightweight blades, modular and intelligent gearboxes, and the integrated and subsystem modular inverter control systems.

2.Elevate the foundational design and manufacturing techniques of electronic chips for wind power, pushing the sector towards smarter solutions. Electronic chips are critical for efficient data collection, processing, and transmission. Chips that are high-performing and energy efficient can enable wind farms to process vast amounts of data more effectively, and support sophisticated data analytics and AI applications, thereby offering more precise support for operational and maintenance decisions.

3.Advocate for and facilitate the establishment of a public verification platform within the wind power industry. Such platform would develop common standards and norms, raising the industry's overall quality, and ensuring wind power projects meet specific quality and performance standards. Simultaneously, it would also encourage technological innovation, elevate industry standards, and promote sustainable development.

4.Pioneer new processes and materials to propel the industry towards a zero-carbon future. Enhance the

量和良品率，形成批量化生产能力，不断降本增效。在新型工艺方案，实现低成本分解叶片用环氧树脂。开发新型的具备易分解或易溶解特性的树脂材料，增加材料重复利用和再循环的可能性；

5. 鼓励推动“风电＋多种产业”的融合发展模式。扩大风电在各个领域的应用场景，如风电制氢、海上风电＋海洋牧场，能源岛等创新技术融合发展，以及深远海技术，助力实现了“双碳”目标。

2.2 光伏技术

中国光伏技术与产业的发展历程包括小规模应用的起步、海外市场拉动的成长、国内外市场共同拉动的规模化发展，以及如今的提质增效阶段。目前，中国光伏各组件产量逐年上升，电池实验室效率不断刷新技术纪录。中国光伏发电技术在全球范围内全面领先，从光伏的技术、装机到产业链均成为中国可再生能源发展的关键推动力。

performance, quality, and yield rate of raw materials like carbon fiber and large blade products to achieve scalable production, continually reducing costs and increasing efficiency. Employ epoxy resin in the new process scheme for the cost-effective decomposition of blades. Develop novel resin materials that are easily decomposable or soluble, enhancing the potential for material reuse and recycling.

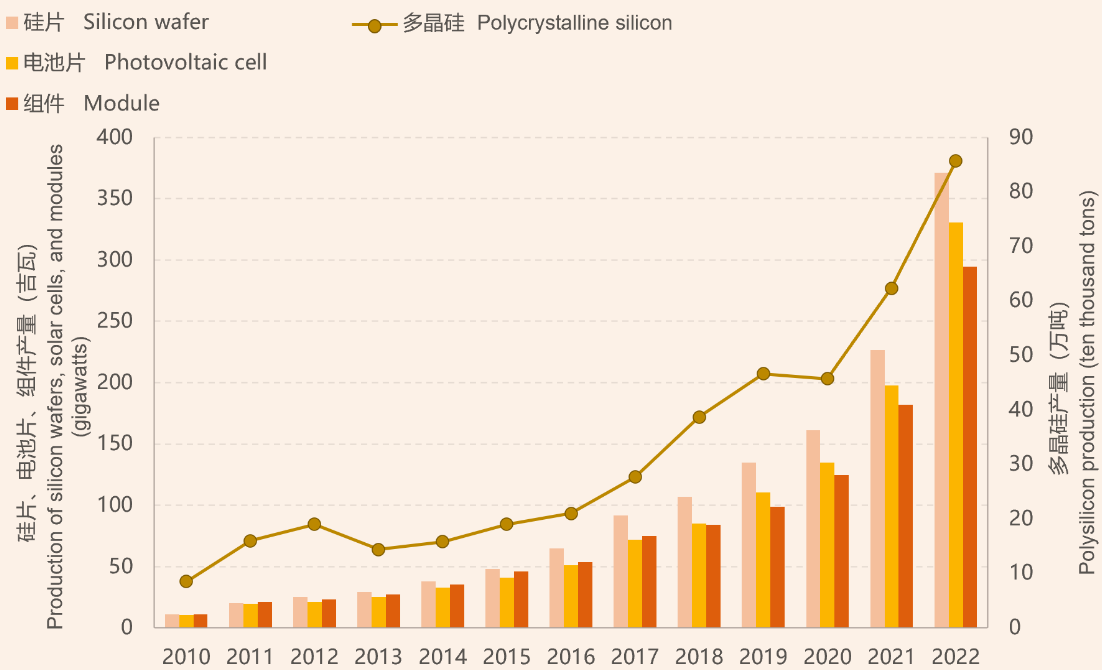
5.Encourage and facilitate the integrated development model of "wind power + diverse industries." Expand the application of wind power across various domains, such as wind-to-hydrogen production, the integration of offshore wind power with marine farming, energy islands, and other innovative technological integrations, including advancements in deep-sea technology. This multifaceted approach is key to achieving the ambitious "carbon peaking and carbon neutrality" targets.

2.2 PV technology

The evolution of China's PV technology and its industry encapsulates a journey from humble beginnings with small-scale applications to a period of growth propelled by overseas markets, followed by a phase of expansive development driven by a synergistic demand from both global and domestic markets, leading to the current focus on quality and efficiency enhancement. Presently, the output of PV modules in China is on a continual rise, with cell laboratory efficiencies continuously setting new benchmarks. Positioned at the global

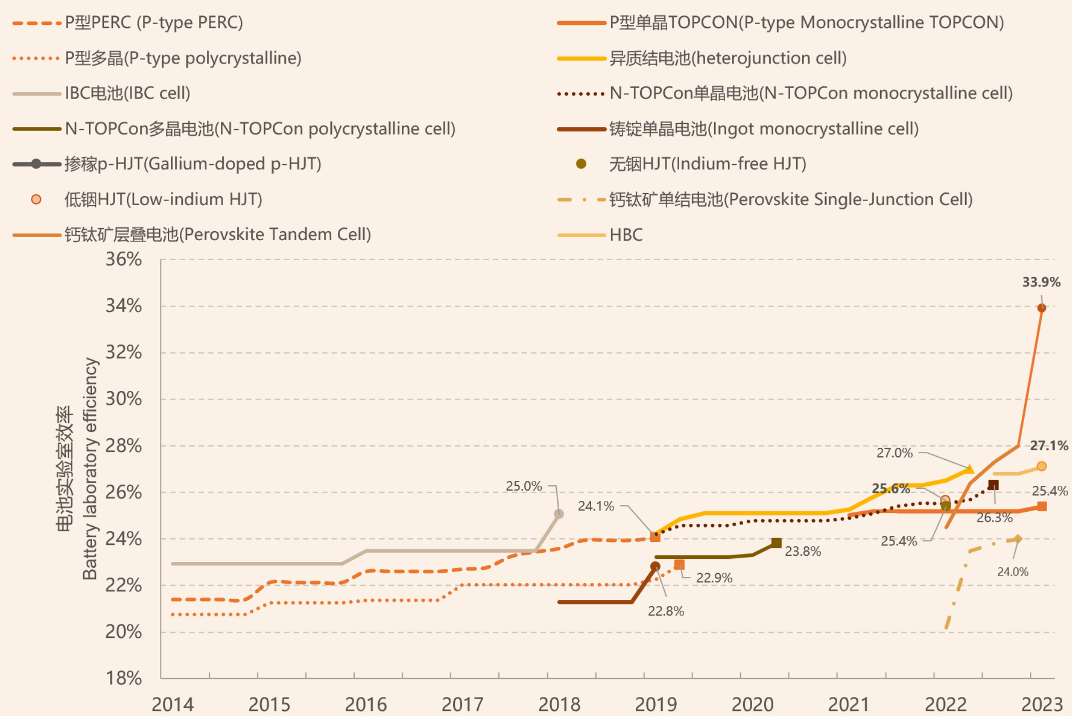
2010-2022 年中国光伏产品关键技术产量

Output of key technologies of PV products in China (2010-2022)



中国光伏晶硅电池实验室效率刷新纪录情况

Record-setting efficiency of photovoltaic crystalline silicon cell laboratory in China



从制造业布局来看，中国大陆如今成为全球光伏组件生产制造的重心。2021 年中国大陆多晶硅产量约 50.6 万吨，约占全球总产量的 78.8%；硅片产量约 226.6 GW，占全球硅片产量的 97.3%；电池片产量约 197.9 GW，占全球总产量的 88.4%；光伏组件产量达到 181.8 GW，约占全球总产量的 82.3%。2021 年中国光伏组件出口额为 246.1 亿美元，占光伏产品（硅片、电池片、组件）出口总额的 86.6%，光伏组件出口量约为 98.5 GW，约占中国光伏组件产量的 54.2%。

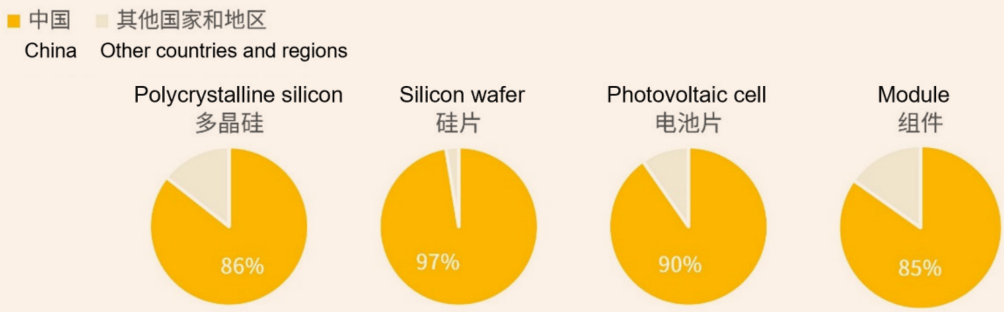
虽然中国是目前全球最大的光伏产品制造国，但在产品制造中，使用的部分零部件或原材料仍主要来自海外进口：光伏电池浆料用银粉依赖日本的制造企业进口；光伏胶膜的原材料——胶膜粒子主要产能集中于海外；多晶硅、单晶硅光伏生产用的扩散管、承载器及坩埚等设备的原材料——高纯石英砂主要从美国进口等。

forefront of PV generation technology, China's prowess in PV technology, installation, and its industry chain have become instrumental in propelling the nation's renewable energy sector forward.

For global PV module manufacturing, Chinese mainland has emerged as the core hub for the production of PV components. In 2021, the output of polycrystalline silicon in the Chinese mainland reached approximately 506,000 tons, constituting 78.8% of the global output. The silicon wafer production was around 226.6 GW, representing a dominant 97.3% of the worldwide market. Moreover, the cell output in China amounted to nearly 197.9 GW, capturing 88.4% of the global share. PV module production stood at 181.8 GW, accounting for 82.3% of the global output. That year, China's export value of PV modules amounted to US $24.61 billion, encompassing 86.6% of the total export value of PV products, which includes silicon wafers, cells, and modules. Notably, the export volume of PV modules stood at about 98.5 GW, constituting 54.2% of China's total PV module output.

While China stands as the world's largest manufacturer of PV products, the country still predominantly relies on international sources for specific components and raw materials. Notably, the silver powder used in PV cells is sourced from manufacturers in Japan. Furthermore, the critical raw material for PV encapsulant films, the encapsulant particles, sees its

2022 年中国光伏产品关键组件全球市场占有率
Global market share of key modules of PV products in China in 2022



随着光伏技术的不断进步和规模效应，加速了光伏发电的成本下降趋势。中国集中式光伏发电的 LCOE 从 2012 年的 1 元 /kWh，下降至 2021 年的 0.30 元 /kWh。预计到 2030 年，中国集中式光伏发电的 LCOE 将下降到约 0.13 元 /kWh，分布式光伏发电下降至约 0.18 元 /kWh。到 2060 年，集中式光伏发电的 LCOE 将下降到约 0.05 元 /kWh，分布式光伏发电下降至约 0.13 元 /kWh。

在过去的十年里，世界光伏技术着重于硅片的大尺寸化发展，未来十年内光伏硅片的大型化轻薄化发展、多种电池技术并存发展已经成为必然趋势。基于现有的光伏技术及中国光伏产业链发展情况，我们提出如下光伏技术和产业链的发展建议：

1. 加快产业技术创新，实现全链条绿色发展。加快高效率大尺寸超薄单晶硅片开发，提升直拉单晶生产效率技术，降低多线切割硅片成本及机加工成本，提升单位重量硅棒的出片数。支持高效电池及组件封装技术的研发及产业化，促进新型光伏电池结构与多维技术路线的研发推广；

2. 优化和完善技术标准体系。建立更为完备和先进的光伏技术标准体系，覆盖光伏组件、发电系统及相关设备，以推动技术创新和产业升级和适应迅猛

primary production capacity situated abroad. Additionally, the production of polysilicon and monocrystalline silicon PV products requires high-purity quartz sand for diffusers, load receptors, and crucibles, which is predominantly imported from the United States.

The continuous refinement in PV technology combined with the economies of scale has markedly accelerated the downward trend in the cost of PV generation. In China, the Levelized Cost of Electricity (LCOE) for centralized PV generation has reduced from CNY 1 per kWh in 2012 to CNY 0.30 per kWh in 2021. Projections indicate that by 2030, the LCOE for centralized PV generation in China will further decrease to approximately CNY 0.13 per kWh, while that of distributed PV generation will see costs reduce to around CNY 0.18 per kWh. Looking ahead to 2060, it is anticipated that the LCOE for centralized PV generation will decrease to roughly CNY 0.05 per kWh, with distributed PV generation expected to reach about CNY 0.13 per kWh.

Over the past decade, the global photovoltaic industry has prioritized the advancement of large-scale silicon wafers. As we look to the next ten years, the trend towards not only larger but also lighter PV silicon wafers, alongside the diversification of cell technologies, is poised to become a defining movement. Drawing insights from the existing technology landscape and the evolution of China's industry chain, we recommend the following directions for the development of PV technology and its industry framework:

1.Accelerate industrial technological innovation for a green supply chain. Expedite the development of high-efficiency, large-size, ultra-thin monocrystalline silicon wafers. Enhance the efficiency of czochralski silicon production and reduce the costs linked to silicon wafers multi-wire cutting and machining to maximize the output from each silicon rod. Foster the research, development, and industrialization of high-efficiency cell and module encapsulation technologies and advocate

发展的行业需求；

3. 推动光伏行业数字化、智能化转型。联合开发自动化、数字化、智能化装备技术，促进智能化生产装备及工艺的研发与应用，提升企业信息化管理系统和数字化辅助工具应用率，提高光伏生产全周期数字化管理水平，实现智能化生产作业和精细化生产管控，推动生产制造向数字化、智能化转型；

4. 加强检测评价能力建设，建立行业信息共享平台。支持国产替代技术的检测验证体系，促进研发优化，建立市场信心，确保新品商业化条件。加强光伏检测机构，鼓励企业提升能力，推动第三方机构发展。强化标准，确保质量和服务可靠性，建立检测信息共享平台，促进技术创新与发展；

5. 鼓励“光伏 + 多种产业”的融合发展模式。为解决光伏发电占用土地面积较大的问题及促进消纳，探索光伏与工业、建筑、交通等多领域融合的开发体系，助力相关项目的开发、落地和实施，助力其他行业“双碳”目标的实现。

2.3 光热技术

光伏技术是可再生能源中的关键组成部分，在电力生产、储能和供热方面发挥着重要作用。国际上在十九世纪七十年代已开始重点开展光热发电技术及示范项目，但中国在这一领域的起步相对较晚，目前仍处于大规模推广的初期阶段。尽管中国光热仍在发展的起步阶段，中国新建的光热发电示范项目中自主化设备部件和材料比例已高达 95%，并且在成本方面相较于其他国家具有优势。

中国太阳能热发电产业链通过易于获得、安全且丰富的原材料为起点，带动了自主知识产权的产业

for the exploration and widespread adoption of innovative PV cell structures alongside multidimensional technological strategies.

2.Optimize and enhance the technical standards system. Establish a comprehensive and advanced technical standards system for PV technologies, covering modules, generation systems, and associated equipment. This initiative aims to catalyze technological innovation, facilitate industry elevation, and adapt to the fast-evolving needs of the sector.

3.Promote digital and intelligent industry transformation. Collaborate on advancing automation, digitization, and smart technology solutions. Foster the R&D and application of intelligent production tools and processes, boost the integration of enterprise information management systems and digital tools, and improve digital management practices throughout the PV production cycle. Aim to achieve intelligent production operations and precise manufacturing control, steering the industry towards a digital and intelligent manufacturing transition.

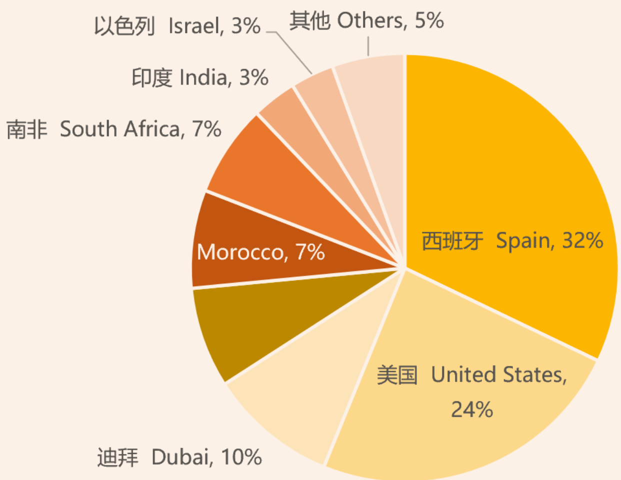
4.Strengthen testing and evaluation capabilities with an information sharing platform. Bolster the testing and verification system for domestic alternative technologies to streamline R&D, build market confidence, and ensure the commercialization readiness of new products. Empower PV testing institutions, motivate enterprises to fortify their capabilities, and promote the development of third-party agencies. Implement rigorous standards to ensure the reliability of quality and services, and establish an information sharing platform for testing data to foster technological innovation and progress.

5.Encourage "PV + various industries" integrated development models. Address the challenge of large land occupation by PV power generation and promote absorption by exploring integrated development models that combine PV with industries such as manufacturing, construction, and transportation. This approach supports the development, deployment, and implementation of related projects, aiding other industries in achieving their "dual carbon" goals.

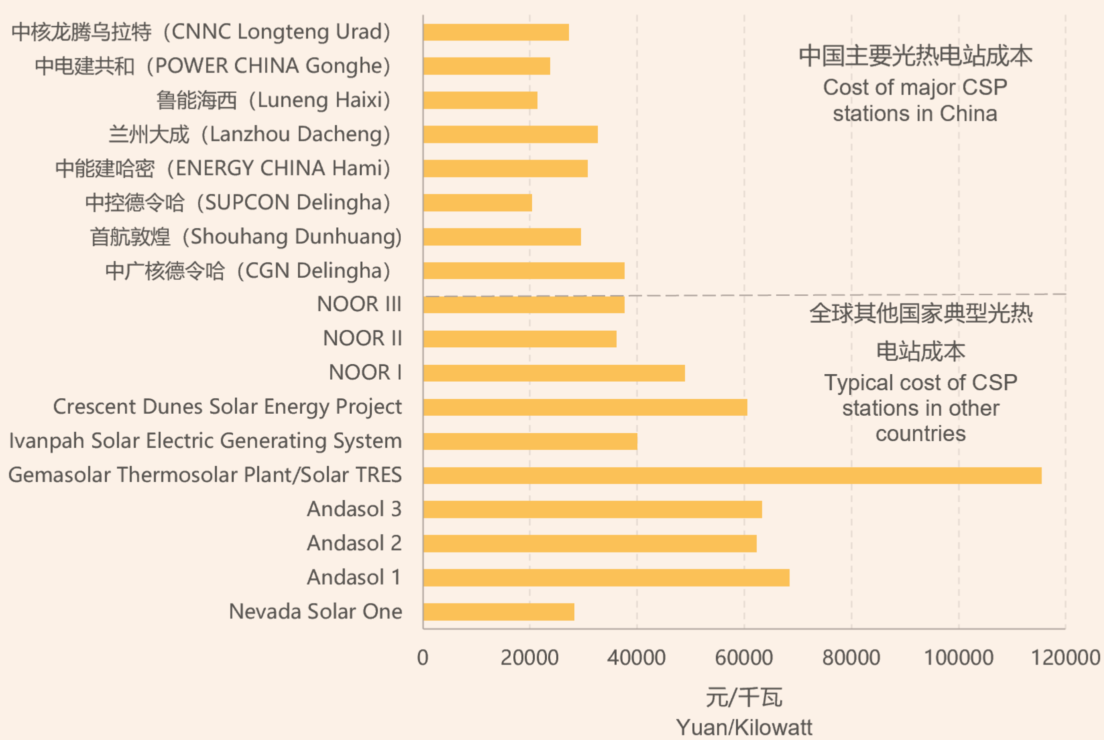
2.3 Concentrated solar power technology

Concentrated solar power (CSP) technology stands as a pivotal element within renewable energy, playing a crucial role in power generation, energy storage, and heating. While the global focus on CSP generation technology and its demonstration projects began in the 1870s, China's engagement in this field started relatively later and is currently in the early stages of broad-scale deployment. Despite its early stage of development, China's new CSP generation demonstration projects boast a high degree of domestic sourcing, with up to 95% of autonomous equipment and materials being locally produced, offering

截至 2023 年底全球在运行的光热电站地区分布（总容量 6494 MW）
Global distribution of operating CSP stations by the end of 2023 (total capacity of 6,494 MW)



中国与世界典型光热电站成本对比
Cost comparison of typical CSP stations between China and the rest of the world



链核心装备的发展。但中国太阳能热发电产业同样存在对国外技术的依赖，如熔盐阀、熔盐泵、高温熔盐流量计、槽式电站柔性连接件仍主要依赖国外进口。

如今，中国新建光热发电LCOE约0.7-1.0元 /kWh，

China a notable cost advantage over other nations.

Leveraging readily accessible, safe, and abundant raw materials, China's CSP industry chain has propelled the development of core equipment underpinned by independent intellectual property rights. However, there remains a dependency on foreign technologies for certain components, such as molten salt valves, molten salt pumps, high-temperature molten salt flow meters, and flexible connectors

远高于风电和光伏发电成本，初始投资成本高是光热发电成本偏高的主要原因。以当前主流的 100 MW 装机、8 小时储热塔式光热电站为例，单位千瓦造价在 1.2-1.7 万元。聚光、吸热、储换热系统占据初始投资的主要部分，约占整个电站成本的 77% 左右，是决定光热发电站造价高低最重要的因素。受制于国内光热发电项目装机规模小和政策不稳定造成的市场不稳定和延续性问题，关键设备和材料的生产成本居高不下。通过系统性地分析中国太阳能光热发电站成本构成，明确了影响成本电价的三个主要动因：产能规模化效应，运营维护成本和技术工艺进步及管理优化。预计到 2030 年，中国光热发电的 LCOE 下降至 0.70 元 /kWh 以下，随着新技术的全面突破，2040-2050 年期间 LCOE 可达 0.35-0.45 元 /kWh。

随着对碳排放问题更高程度的关注以及对清洁能源的持续需求，光热技术有望在完善和扩大应用领域方面取得进一步的突破。为推动光热发电技术在中国的商业化应用，基于现有的光热技术及中国光热产业链发展情况，我们提出如下光热技术和产业链的发展建议：

1. 给予光热发电稳定的价格政策，推动光热发电装机量进一步发展。稳定的电价政策对可再生能源发展至关重要，建议借鉴 2019-2020 年支持光伏发电、2020-2022 年支持生物质发电的做法，在“十四五”期间每年安排一定数量的资金支持新增光热发电项目建设。通过加大电价支持、鼓励参与市场等支持政策，推动降低建设成本、提高项目收益；

2. 扩大光热发电的专项资金支持，推进光热发电新技术研发和新技术示范工程建设。建议通过可再生能源发展专项资金安排相关资金，鼓励发展技术先进、成本降低较快的技术路线，支持光热发电先进技术研发和示范应用。同时，在国家科技创新

for trough power stations.

Currently, the Levelized Cost of Electricity (LCOE) for new CSP generation projects in China stands notably higher, ranging from approximately CNY 0.7 to CNY 1.0 per kWh, significantly surpassing the costs associated with wind and PV power generation. The discrepancy primarily stems from the hefty upfront investment required for CSP technology. For instance, a standard100 MW CSP station equipped with 8 hours of thermal storage is priced between CNY 12,000 and CNY 17,000 per kW. A considerable portion of this initial cost, approximately 77%, is dedicated to the concentrators, heat absorption, storage, and exchange systems, highlighting them as the pivotal factors influencing CSP station costs. The elevated costs of key equipment and materials are further exacerbated by the relatively small scale of domestic CSP projects and market volatility due to policy fluctuations. Through an analytical breakdown of the cost structure for CSP stations in China, three primary dynamics have been pinpointed as influencing the cost of electricity: the economy of scale, operational and maintenance expenses, and the contributions of technological advancements and management efficiencies. Looking forward, projections suggest a downward trend for CSP LCOE in China, with expectations to fall below CNY 0.70 per kWh by 2030. As new technologies break through comprehensively, it is anticipated that between 2040 and 2050, the LCOE could decrease to between CNY 0.35 and CNY 0.45 per kWh.

As the focus on carbon emissions intensifies and the quest for clean energy persists, CSP technology is poised for further advancements and broader application. To spur the commercial use of CSP technology in China, considering the present CSP technological landscape and the evolution of China's CSP industry chain, the following recommendations are put forward for the development of CSP technology and its industry ecosystem:

1.Implement a stable pricing policy for CSP generation to foster capacity expansion. A consistent electricity pricing policy is essential for the sustainable development of renewable energy. Echoing the supportive measures for PV generation (2019-2020) and biomass power generation (2020-2022), it is recommended to allocate dedicated annual funds during the "14th Five-Year Plan" period to support the construction of new CSP projects. Enhancing electricity pricing support and encouraging market participation are crucial steps towards reducing construction costs and enhancing project returns.

2.Enhance special fund support for CSP generation to drive research and development. Expand support through targeted funds dedicated to the development of renewable energy to encourage research and development of new CSP generation technologies and the execution of demonstration projects. This funding should support the advancement of cost-efficient, technologically progressive paths, underpinning the research,

项目中，安排资金支持光热发电关键性或原创性技术的研究；

3. 拓展国际合作渠道，吸引更多国际投资和技术合作。通过深化国际合作，不仅可以加速光热发电领域的全球交流，还能够共同推动该技术的全球发展，展示其在实际应用中的可行性和经济性，推动光热发电技术的市场化应用；

4. 鼓励“光热 + 多种电源”的融合发展模式。广泛开展风电、光伏和光热一体化项目的建设，实现产业的可持续发展。在资源较好地区，在沙漠、戈壁、荒漠大型风光基地中持续安排一定容量的光热发电装机，通过低价的风电、光伏发电项目平衡消化光热发电的成本，实现风电、光伏、光热（及水电）等多种可再生能源互补的平价上网就地消纳或平价远距离外送消纳。

development, and demonstration of state-of-the-art CSP technologies. Furthermore, funds should be designated within national science and innovation projects to explore core or innovative CSP technologies.

3.Broaden international cooperation channels for increased investment and technical collaboration. Deepen international cooperation to attract additional international investment and technical collaborations, fostering a more rapid exchange within the CSP field and collectively advancing global technology development. Demonstrating its feasibility and cost-effectiveness will pave the way for CSP technology's market acceptance.

4.Promote the integrated development model of "CSP + multiple power sources". Encourage the construction of integrated projects that blend CSP with wind and PV power to achieve industry sustainability. In resource-rich areas, such as deserts, gobi, and desert steppe, continue to allocate CSP capacity within extensive wind and solar bases. By offsetting CSP generation costs with more affordable wind and solar projects, it is possible to achieve economically viable, complementary consumption of diverse renewable energies, including wind, solar, CSP, and hydroelectric power, either on-site or through long-distance distribution.

3.

风光可持续发展的应对措施

Measures for the sustainable development of WSP

3.1 风光发电量预报技术

由于风光发电固有的波动性带来的上网不确定性，风光发电量预报技术可为电力系统提供可靠的规划、优化能源调度和储存、降低能源成本以及提高收益。未来风光预报技术的突破主要看功率预测技术方面发展和数值天气预报技术的发展方面，长期和短期预报技术的不断创新，有助于电力系统的管理且参与电力市场的决策，从而为稳定供电提供更为可靠的基础。

基于当前风光预报技术现状及未来需求，我们

3.1 WSP generation forecasting technology

The inherent variability of WSP introduces significant uncertainties in grid integration. To mitigate these challenges, WSP generation forecasting technology plays a pivotal role, enabling precise planning and reliable operations within the power system. This technology is key to optimizing energy deployment and storage, reducing energy costs, and enhancing revenue. The future advancements in WSP forecasting hinge on progress in power forecasting and numerical weather prediction technologies. Continual innovation in both long-term and short-term forecasting methods will greatly enhance power system management and support strategic decision-making in the power market, thereby providing a more robust foundation for consistent electricity supply.

Considering the current landscape and future demands of WSP

不同尺度的预报类型常见的预报方法和应用场景
Common forecasting methods and application scenarios of forecasting types at different scales

预报类型 Forecasting type	预报尺度 Forecasting scale	预报方法 Forecasting method	应用场景 Application scenario
超短期预报 Ultra-short-term forecasting	1 小时以内 Within 1hour	天空图像、统计外推和机器学习 Weather map, statistical extrapolation and machine learning	实时调配、发电管理 Real-time deployment, power generation management
短期预报 Short-term forecasting	1 天以内 Within 1 day	卫星数据、数值预报系统、和机器学习订正 Satellite data, numerical weather prediction system, and machine learning correction	经济调度、系统备用安排、日前电力市场 Economic dispatch, system standby arrangement, day-ahead power market
中期预报 Medium-term forecasting	1 天 -15 天 1-15 days	数值预报系统、统计和机器学习 Numerical weather prediction system, statistics and machine learning	机组安排、检修计划、电力市场交易、拥塞管理 Turbine arrangement, maintenance plan, electricity market transaction, congestion management
长期预报 Long-term forecasting	以月、年为单位 On a monthly/ yearly basis	气象模型和统计算法 Weather model and statistical algorithm	电站规划、电网规划、意外事件分析 Power station planning, power network planning, accident analysis

提出以下两点建议：

1. 优化与创新模型，促进功率预测技术的发展。建立气象要素到功率的转化模型是关键，应优化传统方法，同时引用人工智能算法应用于发电量预测。未来可考虑利用更先进的方法模拟风光中长期出力特征，并将运行、维护、气候和储能纳入转化模型，以适应新型电力系统；

2. 提升数值天气预报的准确性与应用范围。当前数值预报面临的挑战包括模型准确性、多模型支持、数据同化和高性能计算需求等问题。未来应加强地球系统建模、促进国际协作与沟通，提高数值天气预报的精准度和应用范围，满足未来风光能源系统的需求，并更有效地融入电力系统。

3.2 风光发电系统对极端天气的应对

全球气候变化带来的极端天气对风光发电的影响是不容忽视的，区域极端天气事件呈现“多发、频发、强发、并发”的态势。一方面，极端天气可能导致风光发电设备的损坏，影响发电设施的正常运行。另一方面，极端天气也可能影响风光发电的电能质量。提高电力系统对极端天气事件的应对能力，对降低风光发电能源安全风险、提高风光资源利用效率和优化区域风光发电产业结构具有重要意义，为此我们提出以下六点应对措施：

1. 从硬件角度对风光发电设施进行改造和优化。对于已经建成电站，合理加固基础设施，定期开展隐患排查工作，及时进行设备维修和更换。对于规划中的设施，提高配电网和发电站的建设标准，优化设计，加强线路元件强度和架空线路电缆化，提高防雷、防风、防雨、防冻、抗高温能力，降低多重故障的发生概率，缩小故障规模，提高配电网韧性；

forecasting technology, we present the following two focused suggestions:

1.Optimize and innovate models to propel power forecasting technology. Central to advancing power forecasting technology is the development of models that accurately convert meteorological data into power output predictions. This initiative should extend beyond refining traditional methodologies to embracing artificial intelligence algorithms for enhanced accuracy in power generation forecasting. Future strategies should also explore advanced methods to model the medium- and long-term output traits of wind and PV powers. Additionally, integrating operational, maintenance, climatic, and energy storage considerations into these models will make more responsive to the needs of an evolving power system.

2.Enhance accuracy and applicability of numerical weather prediction. Currently, numerical weather prediction faces challenges related to model accuracy, multi-model support, data assimilation, and high-performance computing requirements. Going forward, it is imperative to strengthen earth system modeling and foster international cooperation and dialogue. This concerted effort aims to boost the accuracy and extend the utility of numerical weather prediction, ensuring they meet the nuanced needs of wind and PV energy systems and their effective incorporation into the broader power infrastructure.

3.2 Response of WSP generation system to extreme weather

The impacts of extreme weather, intensified by global climate change, significantly challenge WSP generation. These events, increasingly frequent, intense, and simultaneous, can damage WSP infrastructure and disrupt operations, while also affecting power quality. Enhancing resilience against such extremes is pivotal for reducing energy security risks associated with WSP, boosting the efficiency of wind and solar resource use, and optimizing the regional WSP industry's structure. Consequently, we propose the following six countermeasures:

1.Transform WSP generation facilities from a hardware perspective. For existing power stations, it is critical to reinforce infrastructure robustly, conduct regular hazard assessments, and ensure promptly equipment maintenance or replacement. For upcoming projects, priorities are given to raising construction standards for distribution networks and power stations, along with designing for resilience against extreme weather conditions like lightning, wind, rain, freezing, and high temperatures. These steps aim to mitigate the likelihood of multiple faults, limit the extent of potential outages, and enhance distribution network resilience.

2. 加强极端天气的监测预报与预警。在新能源电站集中地区安装气象测量设备，大力开展极端天气下新能源预测技术研究，制定大规模停电应急预案和预警系统，及时投入备用设备、接入备用能源或调整潮流以限制故障扩展。对部分微网采用离网运行方式，保证其中关键负荷的供电，配合储能装置提高整个孤岛内的可控性；

3. 做好极端天气下风光电站的事故预案和应急处置。建议编制事故预案时考虑极端天气的影响，做好风光电站在极端情况下出现事故的应急处置预案。完善应急响应机制，提升调度运行人员的应急

2.Enhance monitoring, forecasting, and early warning of extreme weather. Install meteorological measurement equipment in areas dense with renewable energy installations. Conduct advanced research in forecasting technologies specifically under extreme weather conditions, and establish emergency plans and early warning systems for significant outages. Promptly deploy standby equipment, leverage alternative energy sources, or adjust power flow to prevent fault escalation. For specific microgrids, consider off-grid operations to ensure continuity of critical loads and collaborate with energy storage devices to enhance the controllability of the entire isolated island.

3.Develop plans and emergency responses for WSP station accidents during extreme weather. Developing emergency plans should thoroughly account for the extreme weather impacts, preparing for swift and effective responses to incidents at WSP stations under severe conditions. Enhancing

常见极端天气类型以及对风光发电的影响
Common extreme weather types and their impacts on WSP generation

极端天气类型 Extreme weather types	主要影响 Main impact	影响机理 Detailed causes
极端低温 Extreme low temperature	风机 Wind turbine	1. 风机低温停机；2. 叶片覆冰 1. The wind turbine stops at low temperatures; 2. The blades are icing
极端高温 Extreme high temperature	风机、光伏 Wind turbine, PV	1. 高温影响设备散热，加速老化；2. 风速极小，风机处于无风待机状态；3. 高温下光伏光电转换效率低 1. High temperature affects equipment cooling, accelerating aging; 2. As the wind speed is extremely small, the wind turbine is in a windless idling condition; 3. Low PV conversion efficiency at high temperatures
大风 Gale	风机 Wind turbine	风机大风停机 Wind turbine stops due to gale
降雪 Snowfall	风机、光伏 Wind turbine, PV	1. 影响风机大部件可靠性；2. 光伏板积雪 1. Affect the reliability of large components of wind turbine; 2. Snow on PV panels
雾霾 Smog	光伏 PV	辐照度减弱，发电出力减小或无法发电 Reduced irradiance leads to decreased power output or inability to generate electricity
日食 Solar eclipse	光伏 PV	辐照度减弱，发电出力减小或无法发电 Reduced irradiance leads to decreased power output or inability to generate electricity
沙尘 Sand and dust	光伏 PV	辐照度减弱，发电出力波动 Reduced irradiance results in fluctuating power output
雷暴 Thunderstorm	风机 Wind turbine	雷击造成风机受损甚至爆裂、通信元件烧毁 Lightning strikes cause the wind turbine to be damaged or even burst, and the communication components burned
强降冰 Severe icing	光伏 PV	辐照度长时间处于较低水平，发电出力减小或无法发电 Extended periods of low irradiance lead to decreased power output or inability to generate electricity

处置能力。优化故障后的恢复策略，提高故障修复水平，缩短故障修复时间；

3.3 生态环境友好的风光技术措施

在过去二十年中，欧美等国家深入研究了风光发电对生态环境的综合影响。关注焦点包括风电和光伏在生态系统中的作用，尤其侧重于分析其对土壤、植被和水资源等方面的长期影响。风光发电在制造阶段使用大量资源和能源，可能对原材料开采地的生态系统造成损害。建设阶段需要广泛利用土地，涉及多项土方工程，导致环境影响如施工扬尘、废水排放、垃圾产生、噪声扰民、植被和地表水土流失，造成局地生态系统的损害。运维阶段产生噪声、气象扰动，影响局地气象条件、动植物和水资源。退役阶段的设备废弃物处理和土地修复成为关键问题。全面考虑各阶段的环境影响，采取科学措施最小化负面效应，促进可持续的风光发电发展是实现清洁能源目标的关键。

优化风光发电项目空间布局，合理安排风光项目新增用地规模、布局和开发建设时序，布设先进的生态修复技术措施显得尤为重要。为此，我们提出以下政策建议，从政策层面支撑风电场、光伏电站工程的低生态环境影响技术的实施：

1. 风光用地的规划与科学供给。排查适宜发展风光发电且具有生态修复需求的潜在土地资源，建立数据库，厘清土地确权问题，进行土地资源统计和分级管理，开展基于碳中和、能源安全、生态安全、粮食安全等约束条件下的土地资源规划；

2. 建立生态友好选址平台。依托国土空间规划数据，并整合关键生态元素，制作新能源环境友好地图，合理规划风光项目选址，降低对生态的不良影响及选址成本；

emergency response mechanisms and strengthening dispatch operators' ability to manage emergencies are essential. It is also critical to optimize post-fault recovery strategies, elevate fault repair efficiency, and reduce downtime.

3.3 Eco-friendly technical measures for WSP generation

In the past two decades, European and American countries have extensively investigated the overarching impacts of WSP generation on the ecological environment. These investigations have zoomed in WSP's interactions within ecosystems, with a special focus on their long-term effects on soil, vegetation, and water resources. It is crucial to acknowledge that the manufacturing phase of WSP generation involves significant resource and energy consumption, potentially causing harm to the ecosystems of raw material extraction sites. The construction stage demands widespread land utilization, involving numerous earthmoving activities. These activities can lead to environmental impacts such as construction dust emissions, wastewater discharge, waste generation, noise pollution, and the erosion of vegetation and surface soil, all contributing to local ecosystem degradation. Moreover, during the operation and maintenance stage, WSP facilities can cause noise and meteorological disturbances, adversely impacting local meteorological conditions, as well as affecting animals, plants, and water resources. The decommissioning stage poses crucial environmental challenges, particularly concerning the disposal of waste materials and land restoration. Embracing a holistic view of environmental impacts across all these stages and implementing targeted, scientific interventions to minimize negative outcomes are crucial for promoting the sustainable development of WSP generation and moving closer to achieving clean energy goals.

It is crucial to optimize the spatial layout of WSP generation projects, especially when considering new land allocations' scale, layout, and development timeline. Implementing advanced ecological restoration measures becomes paramount. To support the integration of ecologically low-impact technologies into WSP projects, we propose the following policy recommendations:

1.Plan and scientifically supply land for WSP generation projects. Identify potential lands suitable for WSP development that also have ecological restoration needs. Establish a comprehensive database to resolve land ownership issues, conduct land resources assessments, and manage resources categorically. Planning should be driven by considerations such as carbon neutrality, energy security, ecological stability, and food security.

2.Establish an eco-friendly site selection platform. Utilize land spatial planning data and integrate key ecological

3. 科学评估风光项目与生态修复协同增效的可行性。政策设计需考虑太阳能资源、电网接入、生态修复紧迫性、生态红线、环境底线、资源上限、社会经济能力等多方面条件，统筹规划风光发电和生态修复政策，制定县级风光发展与生态保护宏观治理方案；

4. 推动风光电站园区化管理模式。设计园区化生态管理模式，通过园区化生态管理模式可实现各相关方（电力企业、林业部门）的协同互补；

5. 降低风光项目的非技术成本。引入风光电站生态成本市场化交易机制，有效促进风光电站增加生态投入的积极性，开发风光 + 生态修复项目的生态标签，鼓励市场优先购买具有生态标签属性的绿色电力。

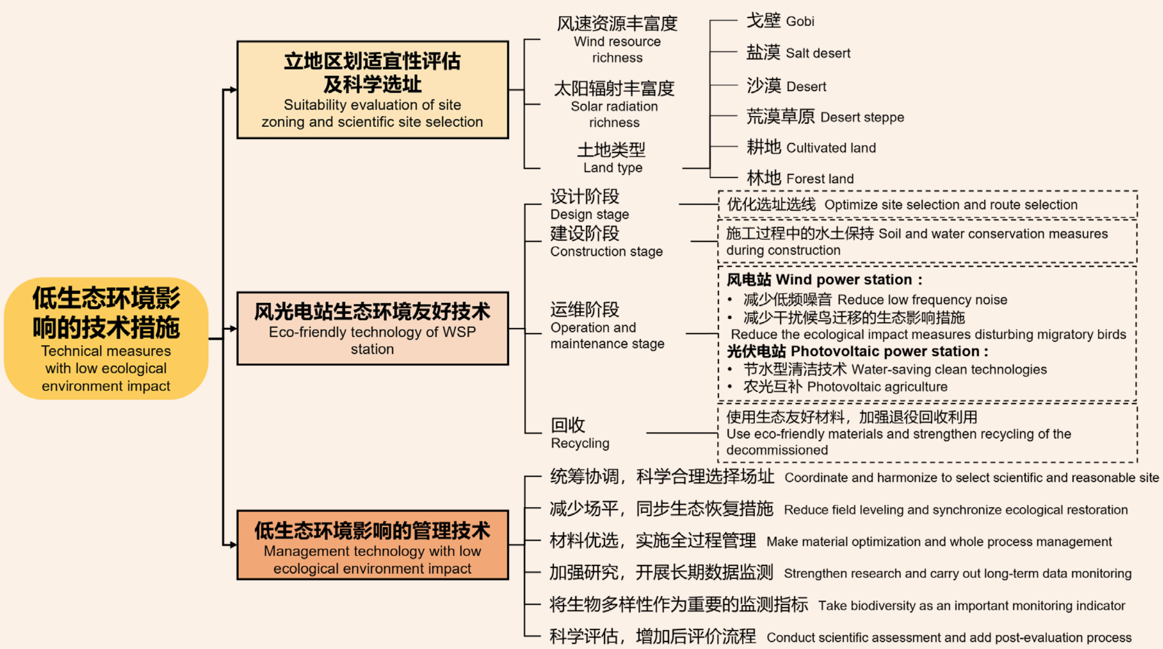
elements to create an eco-conscious map for WSP project siting. This strategy aims to minimize adverse ecological impacts and reduce site selection costs.

3.Scientifically evaluate feasibility of synergistic interaction. In policy design, consider factors such as solar energy resources, power grid accessibility, urgency for ecological restoration, ecological red line, environmental bottom line, resource upper limit, and social and economic capacity. Aim to cohesively plan WSP development and ecological restoration, formulating comprehensive county-level macro-governance plans that align energy generation with environmental conservation.

4.Promote park-oriented management mode of WSP stations. Design a park-style ecological management approach to encourage synergy and mutual support among stakeholders, including energy companies and forestry departments.

5.Reduce non-technical costs of WSP projects. Introduce a market-oriented trading mechanism for the ecological costs associated with WSP stations to boost ecological investments. Develop eco-labels for projects that merge WSP generation with ecological restoration, encouraging the market to prioritize green power with such eco-label attributes.

风光发展的低生态环境影响技术措施
Technical measures with minimal ecological environmental impacts for WSP development



4.

中国风光发展技术路线展望与政策建议

The technical route outlook and policy suggestions for the development of WSP in China

为实现碳中和目标下的风光发电装机目标，我们基于上述内容制定了包括风光发展潜力、技术路线和生态环境影响在内的发展计划，并提出以下政策建议：

（一）2024 至 2030 年期间：该期间为中国实现碳达峰的关键阶段，也是电力结构改革的关键时期。《联合国气候变化框架公约》第 28 次缔约方大会上也为该阶段的风光发展提出了更高的要求，预计 2030 年中国风光装机规模将达到 2200 至 2400 GW。

加速风光技术研发，推进光热商业化，提高效率并快速降低成本。全面推动风光制造业及电子芯片研发，实现关键零部件技术上的突破，平衡陆上风电、集中式光伏与海上风电、分布式光伏的发展。

着力发展“风光 +”储能、制氢、短期预报等配套技术及平台，并展开风电、光伏与光热等多能源协同发展示范。推进跨区域电力传输和电网建设。制定智能短期风光发电预报技术和平台，通过增强地球系统建模、数据共享与资源投入，智能化处理风光发电波动性。

在生态环境方面，广泛开展风光发展对生态影响的研究，建立生态友好型风光利用技术。加强管理细则以降低集中式风光电站对生态环境的影响。提升风光材料回收技术，形成复合标准和规范的回收产业链。

完善风光发电的政策法规体系，推动化石燃料工业向可再生能源的过渡。制定更具激励性的补贴政策、强化环境标准以及建立碳交易制度等，促进风光

To attain the installed capacity targets for WSP generation within the framework of carbon neutrality, a comprehensive development roadmap based on the preceding sections encompassing development potential, technical routes, and the ecological environmental impact of WSP is designed. Meanwhile, the following policy suggestions are proposed:

(I) 2024 ~ 2030: As China strides towards carbon peaking and reshaping its power landscape, the 28th Conference of the Parties to the United Nations Framework Convention on Climate Change has set forth more ambitious expectations for WSP development. By 2030, the WSP installed capacity in China is anticipated to hit between 2,200 and 2,400 GW.

Accelerate WSP R&D, promote CSP commercialization, enhance efficiency, and rapidly reduce costs. Commit to broadening the WSP base and advancing semiconductor research to break new ground in essential component technologies. Strive for harmonious development among onshore wind power, concentrated PV, offshore wind power, and distributed PV.

Prioritize the "wind +" initiative by incorporating supporting technologies and platforms like energy storage, hydrogen production, and short-term forecasting. Launch pilot projects that demonstrate the collaborative potential of wind power, PV, and CSP. Promote the expansion of cross-regional power transmission and the enhancement of grid construction. Formulate intelligent short-term wind and PV power generation forecasting technologies and platforms that utilize advanced earth system modeling and data sharing to intelligently address WSP generation variability.

Conduct extensive research on the ecological impacts of WSP development, and establish eco-friendly WSP utilization technologies. Tighten regulatory oversight to mitigate the ecological footprint of centralized WSP installations. Improve recycling processes for WSP materials, establishing a standardized, regulated industry framework for material recovery.

Enhance the legislative and policy landscape governing WSP generation to facilitate the shift away from fossil fuel towards renewables. Develop incentivizing subsidy schemes, strengthen environmental guidelines, and establish a carbon

行业的可持续和健康发展。建立更加灵活和市场化的机制，鼓励创新和竞争，以提高整个可再生能源行业的竞争力。

（二）2030 至 2050 年期间：该阶段是中国电力系统深度转型，旨在实现碳中和目标的关键时期。风光发电将迎来高速发展，预计 **2050 年风光装机规模将达到 4700-6731 GW，是 2030 年的 2-4 倍。**

全面推动风电、海上风电、集中式光伏、分布式光伏和分散式风电的综合发展。实现 95% 以上的全产业链国产化，并完善行业公共测试验证平台。同步高速发展风光配套储能和制氢技术，推动光热电站为核心的多能互补一体化基地建设。

注重风光电站建设过程中的局地生态修复，协同风光与生态环境的发展，减少对土地资源的浪费。确保风光项目在选址、设计和建设中充分考虑生态敏感性，加强土地使用监管，提倡集约化布局和多功能共享用地，确保风光电站占地与生态环境协调。

加强对风光电站设施的保障措施。通过硬件和软件改造电网和发电设施，完善短期预报技术，应对极端天气事件，促进各种能源协同发展，建立能源系统的区域互联，构建安全稳定的电力系统。

实现风光与其他行业协同绿色发展，促进不同产业之间的良性互动。比如风光 + 农业、风光 + 交通等行业协同，优化资源利用，提升系统灵活性，并促使不同行业共同致力于减少碳排放和环境影响。

逐步完善风光发电的回收技术和产业链，开发新工艺、新材料，推动全产业链朝零碳时代发展。大规模风光发展加强对稀土材料的依赖，未来伴随设备的退役，强化回收效率，实现风光设备的高效循环利用，促进风光发电的可持续发展。

market to promote sustainable and healthy development within the WSP sector. Establish dynamic, market-driven mechanisms to encourage innovation and competitiveness, thus enhancing the renewable energy industry's market presence.

(II) 2030 ~ 2050: The critical period for the profound transformation of China's power system, focusing on achieving carbon neutrality. WSP generation is poised to surge, with projections suggesting **the installed capacity could swell to between 4,700 and 6,731 GW by 2050, a two to fourfold increase from 2030.**

Vigorously promote the expansion of onshore and offshore wind power, centralized and distributed PV power, and decentralized wind power. Aim to achieve more than 95% localization of the entire industry chain and enhance public testing and verification platforms. Accelerate and synchronize the development of complementary energy storage and hydrogen production technologies. Focus on establishing integrated bases around CSP stations for a synergistic multi-energy ecosystem.

Prioritize local ecological restoration during the construction of WSP stations. Harmonize the development of WSP with the ecological environment to minimize land resource waste. Ensure ecological considerations are paramount in the site selection, design, and construction phases, promoting rigorous land management and advocating for space-efficient, multi-functional, and shared land use that aligns with ecological objectives.

Strengthen the safeguard measures for WSP stations facilities. Transform the power grid and power generation facilities through hardware and software upgrades. Enhance short-term forecasting to anticipate and manage the impacts of extreme weather, creating a cohesive and resilient energy network that enhances the power system's stability and reliability.

Achieve coordinated green development of WSP with other industries. Foster synergies that integrate WSP with other sectors such as agriculture and transportation, optimizing the overall resource efficiency and system flexibility. Aim for a collaborative effort to reduce carbon emissions and environmental impacts across industries.

Gradually enhance recovery technology and the industry chain for WSP generation. Develop new processes and materials to steer the entire industry chain towards the zero-carbon era. Address the growing dependence on rare earth materials. With the decommissioning of WSP equipment in the future, increase recycling efficiency to achieve the effective recycling of WSP equipment, thereby promoting the

（三）2050 至 2060 年期间：该阶段为实现碳中和目标的决定性阶段，该十年风光装机将缓慢增长，仍持续助力电力系统深度脱碳。

智能化风光技术推动电力系统演进。数字化风光技术在这一时期将迎来成熟，为电力系统智能化建设提供系统性支持。通过结合大数据控制技术，实现风光资源的日前优化调度，全面实现电力系统的智能化。这涵盖了源、网、荷、储一体化的结构性建设，以及虚拟电厂等新兴供需侧资源的深度融合，与灵活性资源如储能、制氢等进行合理配置，从而提高系统运行效率和可靠性。

全面实现零碳的风光发展。在碳中和的大背景下，全面实现零碳风光发展成为必然趋势。这包括全面实现生态友好型风光电站建设，实现风光与生态协调发展。同时全面推动风光产业链的绿色发展，确保资源可持续性的利用，全面推动中国电力系统的绿色与可持续发展。

sustainable evolution of WSP generation.

(III) 2050 ~ 2060: The decisive stage for achieving the goal of carbon neutrality. During this decade, WSP installations are expected to grow steadily, furthering the deep decarbonization of the power system.

Propel the evolution of the power system through intelligent WSP technologies. In this decade, digital WSP technologies will reach full maturity, offering systematic support for the smart evolution of the power system. Leveraging big data for day-ahead optimized scheduling of WSP resources will catalyze the full-scale intelligence of the power system. This includes seamless blend of sources, the grid, loads, and storage, along with deep integration of emerging resources such as virtual power plants with flexible assets like energy storage and hydrogen production, thereby enhancing the system's operational efficiency and reliability.

Fulfill zero-carbon WSP ambitions. In the context of carbon neutrality, fully embracing zero-carbon WSP stations that align with their ecological environments but also champion the green transformation of the entire WSP sector is inevitable. Ensuring the sustainable use of resources is key to propelling the green and sustainable forward momentum of China's power system.

清华大学碳中和研究院 Institute for Carbon Neutrality, Tsinghua University | ENERGY FOUNDATION 能源基金会

	风光高速多元发展阶段（2024-2030） Stage of high-speed diversified development of wind and solar power (2024-2030)	风光高效协同发展阶段（2031-2050） Stage of efficient and collaborative development of wind and solar power (2031-2050)	风光成熟稳定发展阶段（2051-2060） Stage of mature and stable development of wind and solar power (2051-2060)
装机与发电目标 Installed capacity and power generation targets	**中国风能与太阳能资源潜力远高于碳中和目标下风光装机规模** The potential of wind and solar resources in China far exceeds the scale needed for carbon neutrality goals. **风光发电总装机容量“倍增”式增长：2030年风光总装机量增长两倍，达到所有电源总装机规模的45%，在总发电量中的比重达到27%的水平** The installed capacity of wind and solar power generation will experience "exponential" growth: by 2030, the total installed capacity of wind and solar power will double, reaching 45% of the total installed capacity of all power sources, and accounting for 27% of the total electricity generation.	**风光发电总装机容量快速增长：2035、2040、2050年风光总装机量分别达到所有电源总装机规模的55%、65%、75%，风光合计发电量在2035、2040、2050年的总发电量中的比重分别达到35%、45%、55%的水平** The total installed capacity of wind and solar power is poised for rapid growth: by 2035, 2040, and 2050, the cumulative installed capacity of wind and solar power is expected to represent 55%, 65%, and 75% of the total capacity of all power sources. Wind and solar generation will contribute 35%, 45%, and 55% to the total power generation in 2035, 2040, and 2050, respectively.	**风电和太阳能发电总装机容量增长趋势放缓：到2060年风光总装机量达到所有电源总装机规模的83%，总发电量中的比重将超过65%的水平** The growth trend of installed capacity for wind and solar power generation is slowing down: by 2060, the total installed capacity of wind and solar power will reach 83% of the total installed capacity of all power sources, with their share of total electricity generation exceeding 65%.
技术发展重点 Key points of technology development	☆ 风电技术（Wind power technology） **风电大型化、轻量化发展，环境友好的新材料加速研发** Enhance the technological advancement of large-scale and lightweight wind turbines, along with the accelerated development of environmentally friendly new materials. ☆ 光伏技术（Photovoltaic technology） **光伏组件大型化、轻薄化发展，电池技术快速发展** Promote the development of large-scale and lightweight photovoltaic modules, with rapid advancements in solar cell technologies. ☆ 光热技术（CSP technology） **光热产业链成熟度进一步提升，第四代光热技术快速发展** Advance the maturity of the CSP industry chain and the fourth generation of CSP technology. ☆ 配套技术（Supporting technologies） **风光配套储能、制氢技术快速发展，初步建成新型电力系统** Develop energy storage and hydrogen production technologies rapidly and lay the foundation for the initial establishment of a new power system.	☆ 风电技术（Wind power technology） **风电新材料新技术成熟应用，智能化、数字化风电实现商业应用** Enhance mature application of new materials and technologies in wind power, coupled with the commercialization of intelligent and digitalized wind power generation. ☆ 光伏技术（Photovoltaic technology） **资源节约型光伏技术快速发展，智能化、数字化光伏发电实现商业应用** Develop resource-saving photovoltaic technology, and promote commercial application of intelligent and digital photovoltaic power. ☆ 光热技术（CSP technology） **新型光热技术不断发展，大规模光热发电实现产业化、商业化应用，“光热+”多能互补基地协调发展** Develop new types of CSP and achieve industrialization and commercialization of large-scale CSP generation. Realize coordinated development of “CSP+” multi-energy complementary bases. ☆ 配套技术（Supporting technologies） **构网型储能技术高速发展并实现商业化应用，风光制氢技术实现商业应用，新型电力系统实现技术创新突破且成熟化发展** Advance grid-forming energy storage technology commercially. Enable commercial adoption of “WSP + hydrogen” production technology, and advance innovation and maturity in new power systems.	☆ 风电技术（Wind power technology） **风电智能化、数字化技术实现系统性应用** Enhance the systematic application of intelligent and digital technologies in wind power. ☆ 光伏技术（Photovoltaic technology） **光伏智能化、数字化技术实现系统性应用** Promote the systematic application of intelligent and digital technologies in photovoltaic power. ☆ 光热技术（CSP technology） **“光热+”多能互补基地实现高效、系统化应用** Advance the efficient and systematic application of “CSP+” multi-energy complementary bases. ☆ 配套技术（Supporting technologies） **风光配套储能、制氢技术成熟高效应用，新型电力系统全面建成** Accomplish mature and efficient application of wind and solar energy storage, hydrogen production technologies, and the comprehensive establishment of a new power system.
生态环境影响预判与应对 Prediction and measures of ecological environment impact	• **大规模风光电站的开发可能造成局地土壤与植被的破坏，导致地表裸露、植被破坏、土壤肥力受损和水土流失** • The development of large-scale wind and solar power stations may lead to the destruction of local soil and vegetation, resulting in exposed ground, vegetation damage, soil fertility loss, and soil erosion. • **风光发电站运行时带来的地表风速下降、温度变化，可能影响局地降水、土壤湿度及植被覆盖率** • During the operation of wind and solar power stations, the decrease in surface wind speed and temperature changes may affect local precipitation, soil moisture, and vegetation coverage. • **开展风光电站生态修复示范工作，建立风光电站生态指标** • Conduct demonstrations of ecological restoration for wind and solar power stations and establish ecological assessment standards.	• **大规模风光材料退役与处理可能造成固体废物与污染物排放问题** • The large-scale retirement and disposal of wind and solar materials may result in issues related to solid waste and pollutant emissions. • **大规模风光发电的开发可能造成土地资源的浪费** • Large-scale wind and solar power generation development may lead to inefficient use of land. • **广泛开展风光电站生态修复工作，降低大规模风光发展的负面影响** • Widespread initiatives in ecological restoration at wind and solar power stations aim to mitigate the adverse effects of large-scale wind and solar development. • **完善风光电站建设的生态标准，开展生态友好型风光电站建设** • Improve the ecological standards for the construction of wind and solar power stations and promote the construction of eco-friendly wind and solar power stations.	• **健全全生命周期管理机制，对风光发电的生态影响进行实时监测，并及时响应新出现的生态问题** • Implement a life-cycle management system for real-time monitoring of the ecological impact of wind and solar stations and promptly address emerging ecological issues. • **实现风光电站和国土空间的统筹协调，减少土地资源浪费** • Achieve coordination between wind and solar stations and land use to minimize land resource wastage. • **风光发展的生态标准体系成熟化应用，全面推进生态友好型风光电站建设** • The mature application of ecological standards in wind and solar development advances the comprehensive construction of eco-friendly wind and solar power stations.

风光高速多元发展阶段（2024-2030）
Stage of high-speed diversified development of wind and solar power (2024-2030)

- ✓ **陆海风电均衡发展，推动分布式风电发展和远海风电示范**
- ✓ Promote the balanced development of onshore and offshore wind power, driving the development of distributed wind power and demonstrating offshore wind power.
- ✓ **集中式和分布式光伏综合发展**
- ✓ Develop centralized photovoltaic and distributed photovoltaic comprehensively .
- ✓ **风电、光伏、光热新技术加速发展，进一步提高发电效率**
- ✓ Accelerate the technological development of WSP and CSP, further enhance power generation efficiency.
- ✓ **风光退役材料回收技术快速发展，逐步建立起回收产业链**
- ✓ Accelerate the development of recycling technologies for retired wind and solar materials and gradually establish a recycling industry chain.
- ✓ **风光与生态协同发展示范项目开展，初步构建生态规范标准**
- ✓ Initiate projects considering synergistic development of WSP with ecology, laying the groundwork for ecological standards.
- ✓ **潜力预报技术时空分辨率快速提升**
- ✓ Develop high-resolution hourly potential forecasting technology.

风光高效协同发展阶段（2031-2050）
Stage of efficient and collaborative development of wind and solar power (2031-2050)

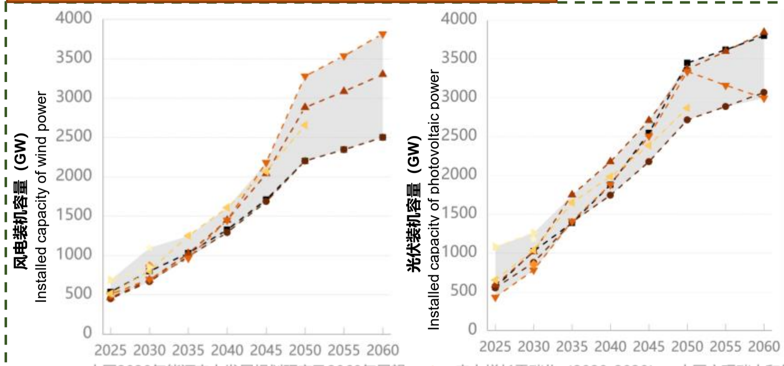
- ✓ **东中西部陆上风电、近远海上风电和分布式风电的综合发展**
- ✓ Develop onshore wind power in the Eastern, Central, and Western regions, as well as nearshore and deep offshore wind power, along with distributed wind power comprehensively.
- ✓ **集中式、分布式光伏的综合发展**
- ✓ Achieve the integrated development of centralized and distributed photovoltaic.
- ✓ **风光热同场项目广泛开展，制氢、储能和新型电力系统深度融合**
- ✓ Carry out WSP and CSP co-located projects, with mature solutions for hydrogen production, energy storage, and new power systems.
- ✓ **针对风光退役材料构建成熟的回收体系与产业链**
- ✓ Develop a mature recycling system and industry chain for retired wind and solar materials.
- ✓ **风光配套的分秒级预报技术成熟应用，加强对极端气候事件的应对**
- ✓ Apply supporting sub-second forecasting technology maturely, and strengthen response to extreme weather events.
- ✓ **生态友好型风光电站广泛建立，风光发展与生态规范标准建立**
- ✓ Establish eco-friendly wind and solar power stations widely, and improve standards for the ecological norms.

风光成熟稳定发展阶段（2051-2060）
Stage of mature and stable development of wind and solar power (2051-2060)

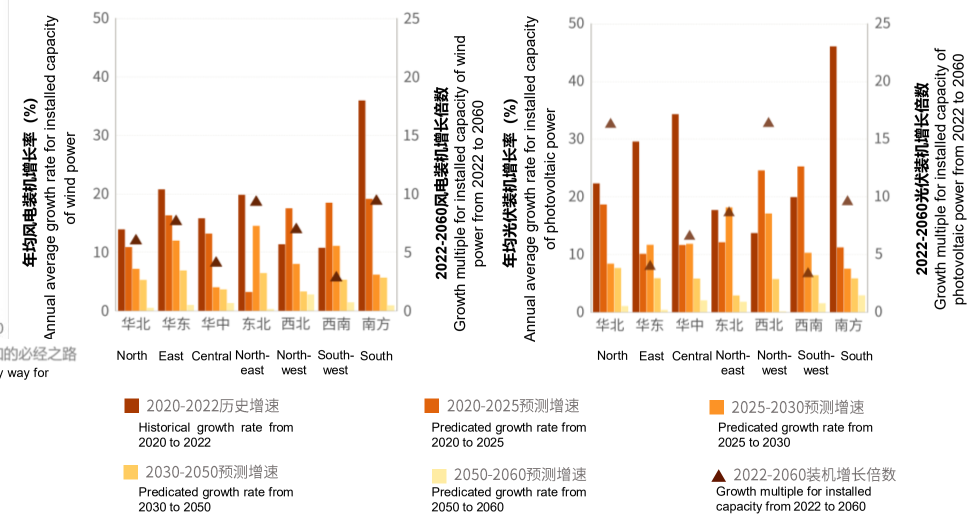
- ✓ **风光发电成为电力系统电源主体，并实现高效稳定利用与跨区域输送**
- ✓ WSP generation is the main sources of electricity in the power system, and has achieved efficient and stable utilization as well as cross-regional transmission.
- ✓ **"风光+"融合发展的新模式与新业态的市场与技术成熟，并广泛应用**
- ✓ The mature market and technology of the new model and new formats of integrated development of "WSP+ other industries" are widely applied.
- ✓ **全面实现风光产业链零碳绿色发展和退役材料的循环利用**
- ✓ Achieve comprehensive zero-carbon green development of WSP industry chain and the recycling of retired materials.
- ✓ **全面实现风光与生态环境的协调发展**
- ✓ Achieve comprehensive coordination between WSP development and the ecological environment.

发展愿景
Development vision

未来风光发展装机路线
Roadmap for installed capacity of WSP in the future



中国风电和光伏未来装机路径
Future installed capacity path of wind power and photovoltaic power in China



中国分区域风电与光伏装机预测及未来装机增长率及倍数
Predication on installed capacity of wind power and photovoltaic power in China by region and the growth rate and multiple of installed capacity in the future

清華大學 碳中和研究院
Institute for Carbon Neutrality, Tsinghua University

清華大學环境学院
School of Environment, Tsinghua University

ENERGY FOUNDATION
能源基金会

扫一扫 了解更多
Scan to learn more