Tracking Clean Energy Innovation

Focus on China

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Abstract

In the last 20 years, the People's Republic of China (hereafter, "China") has strengthened its position on the global stage as an energy innovator, as illustrated by the stories of solar power and, more recently, electric mobility. This is the result of several decades of increasing policy focus on technology innovation, which underpin China's ambitions to become a producer of knowledge and foster innovation-driven socio-economic development. Looking forward, clean energy innovation will play a crucial role to achieve China's objectives of carbon peaking by 2030 and neutrality by 2060, and ranks among core government priorities for the 14th Five-Year Plan period (2021-2025).

This report builds on the IEA Energy Sector Roadmap to Carbon Neutrality in China chapter on "Innovation for carbon neutrality", and provides complementary and new analysis and information. It maps the institutional and policy landscape of clean energy innovation in China and shows trends for selected metrics to track and explain progress of technology development.

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Introduction

Innovation for clean energy transitions

Achieving global energy and climate policy goals will require more, better and cheaper low-carbon energy technologies. Most energy technologies are not on track to provide the clean energy transitions targeted by governments, according to IEA annual monitoring. Many technologies required to lower emissions to so-called "net zero" levels are not ready for markets, notably in sectors hard to decarbonise such as heavy industry and long-distance transportation, for which large-scale low-carbon solutions are not widely available.

Governments are central to the success of clean energy innovation, and global policy support needs strengthening. In the People's Republic of China (hereafter, "China"), support for innovation has significantly increased in the last two decades, as the country became the world's manufacturing powerhouse for several key energy technology areas, such as solar photovoltaics (PV), wind turbines and batteries for electric vehicles (EVs). Looking forward, China's focus on technology innovation and development is expected to strengthen, notably to deliver on long-term carbon neutrality objectives and position the country in global value chains for clean energy technologies. This has important implications for global policy discussions, as China's ability to innovate effectively will have implications for global energy transitions.

Mapping China's innovation landscape

This report serves as an extension to the chapter on "Innovation for carbon neutrality" in the IEA Energy Sector Roadmap to Carbon Neutrality in China and provides complementary analysis and information. It seeks to map the landscape of clean energy innovation in China, in a similar way to the technology innovation sections of energy country reviews for IEA member countries. It aims to identify key developments in recent years, notably since the IEA last published on the topic in 2015, and to show trends for selected metrics that may be used to track progress of innovation. This report is part of broader IEA work to support China's vision of a carbon-neutral future, and aspires to summarise insights from China's energy innovation story in recent years and key announcements to date for the coming period to illustrate the foundation upon which the 14th Five-Year Plan (FYP) (2021-2025) might build.

This report takes a systemic approach to innovation, based on a four-pillar framework used to describe successful innovation systems: 1) resource push; 2) knowledge management; 3) market pull; and 4) socio-political support. This approach acknowledges that the innovation journey is complex and uncertain, involves a wide range of actors, and can be influenced by external factors such as past policy choices, history and culture, and macroeconomics. The report focuses on selected core components and features of China's energy innovation system, and draws on a small number of key innovation metrics. The authors note that further work would be required to provide a more complete picture and collect data for additional indicators to track progress.

Specifically, this report includes:

- Snapshots of recent trends in energy patenting, illustrating improvements in outputs of China's innovation system, and in solar PV, a technology area in which China's contributions to cost reductions have changed the way the world thinks about energy innovation.
- A mapping of the institutional framework for energy innovation, including key actors, priorities, policies and programmes, with a focus on FYP decision-making and energy-specific plans.
- The latest IEA estimates relating to inputs for innovation (e.g. spending in research and development [R&D], venture capital investments in energy start-ups).
- An overview of the country's approach to knowledge management and networks, including international collaboration.
- Insights on the role of market-oriented policies in pulling innovation.

What do we mean by energy innovation?

This report is concerned with how energy technologies are invented, turned into products and modified throughout their lives. Technology innovation is defined as "the process of generating ideas for new products or production processes and guiding their development all the way from the lab to their mainstream diffusion into the market". Equipment and processes that change how or how much energy is consumed are included, ranging from energy supply, transformation and distribution, digitalisation, to end-use sectors including in buildings, industry and transport.

There are four main stages of technology development: prototype, demonstration, early adoption and maturity. Technologies are not uniform in size, time to market, consumer value or type of owner. Each stage and technology type require tailored policy support as a result. The ETP Clean Energy Technology Guide tracks progress of over 400 energy technologies (e.g. stage of development, ongoing activities).

Patents and solar PV: Cases illustrating improvements in China's energy innovation

Introduction

This section introduces two snapshots of recent trends in outputs of China's energy innovation as background stories for the following sections, which will examine the innovation system itself. First, this section examines trends in low-carbon energy patenting activity as a proxy for new knowledge created by Chinese inventors in fields relevant to energy. Second, it summarises the unique case study of solar PV development in China, which has changed the way the world thinks about energy innovation, with a focus on component performance improvements brought about by Chinese institutions and companies. While many more metrics and cases could be explored to track progress, these two snapshots well illustrate improvements in China's clean energy innovation.

Key takeaways

- China has become a key player in energy patenting in a short period, especially in a few strategic areas where Chinese inventors account for an increasing share of global activity, including solar PV, EV technologies and lighting.
- About 80% of Chinese patents in climate-change mitigation technologies relating to energy are also protected abroad today, suggesting that quality has improved.
- China's solar PV innovation story suggests a progressive shift from sheer technology manufacturing to innovation. In just two decades, China has built a solar PV industry leading global manufacturing and now breaking efficiency records in some instances.

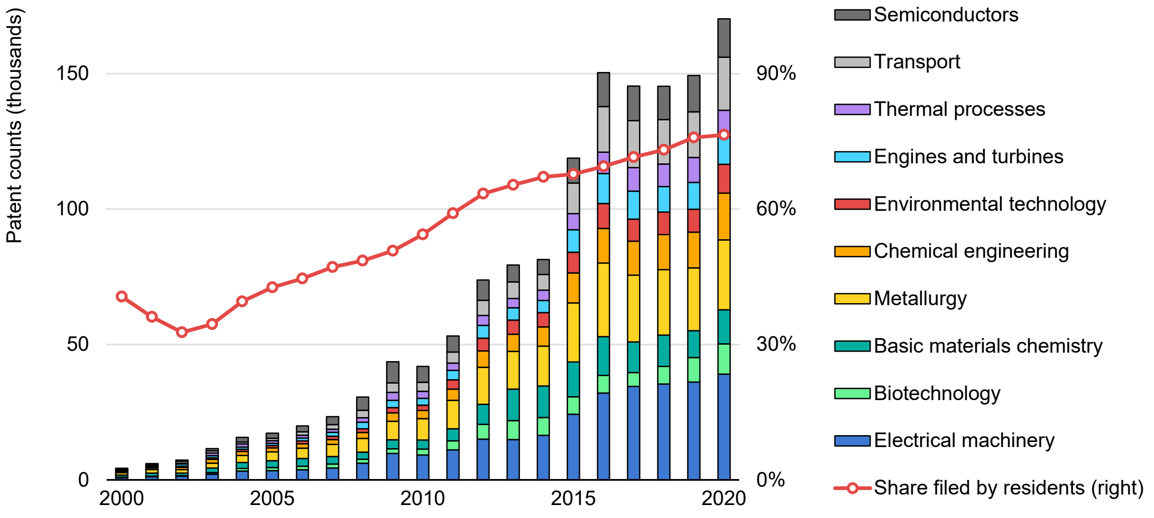
Increasing energy patenting activity

Patenting has been doubling every five years since 2000

Before the 1990s, Chinese inventors mostly protected new knowledge with "utility models" of patenting, which are easier and cheaper to file, and have lower novelty requirements than patents of invention but shorter protection periods. One of the reasons for using utility models is that these can be used to protect minor improvements of existing products that do not fulfil patentability requirement.

Since the 1990s, inventors have been increasingly filing patents of invention, including under international intellectual property (IP) regimes. In 2020, 1.5 million applications for patents of invention were filed, which is approaching the number of utility model applications, still 2.9 million in that year. Foreign actors such as multinationals have also increasingly protected IP in China. The number of patent grants in energy-relevant industry segments in China increased nearly 40-fold between 2000 and 2020. The share of residents among these filings increased from about 45% to 80%, which ranks above the world average of 60% for these technology areas.

Patent grants in China in selected technology areas and share of these filed by resident inventors (2000-2020)



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Source: IEA analysis based on WIPO data (Patent grants by technology, Resident and non-resident count by filing office).

Low-carbon energy patenting has boomed, led by batteries, electric vehicles and solar

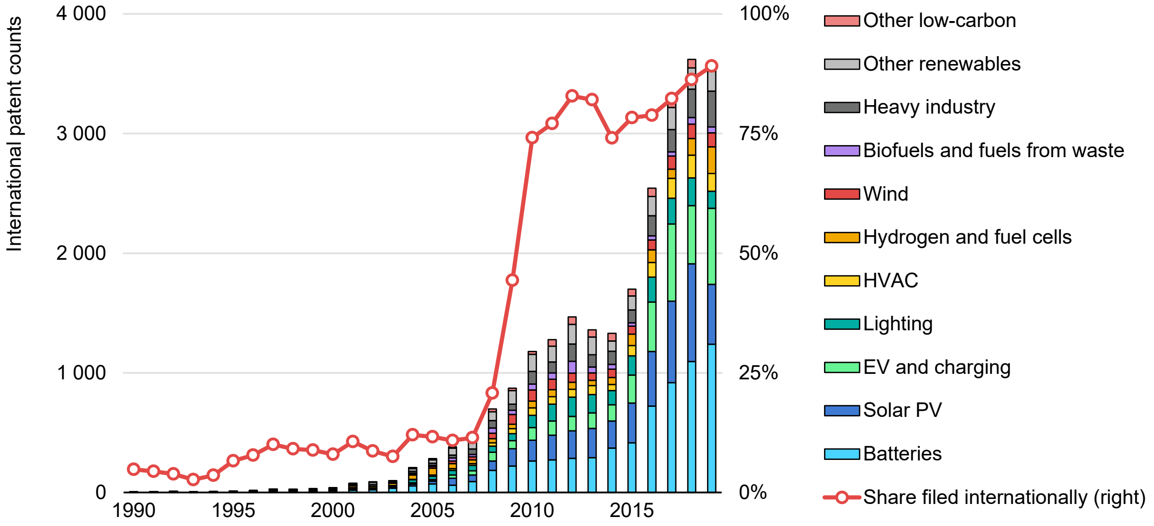
In the last 20 years, China has become a key player globally in energy patenting nearly from scratch, as suggested by trends in international patenting, especially in a few strategic technology areas.

Trends in a broad selection of low-carbon energy technologies – climate-change mitigation technologies relating to the energy sector – show that the number of international patents granted to Chinese inventors in 1990 was close to zero. Between 1990 and 2000, this number increased quickly, but overall activity remained low relative to international peers. Between 2000 and 2012, patenting activity increased more quickly at a cumulative annual growth rate of about 35%, primarily led by batteries, solar PV and EV technologies. After a slight decrease between 2012 and 2014, activity skyrocketed again from 2015 onwards and reached levels twice as high as 2012 already in 2017. In 2018-2019, Chinese inventors filed about six times the number of international patents they had filed in 2008-2009 for batteries and solar PV, and eight times for EV technologies.

Chinese international energy patenting was almost non-existent before the 2000s and rose rapidly. Between 2007 and 2010, the share of Chinese inventions that were also protected internationally increased from 10% to 75%. The internationalisation of patents suggests an increase in quality, given the constraints and expenses associated with filing for protection in several national or regional patent offices. China's rate of international patenting has now surpassed that of the United States and Europe, and ties up with Japan. The increase in the share of international patents coincided with a drop in overall activity between 2008 and 2010. While the total number of patents decreased, the number of patents that were filed internationally continued to increase steadily over the period, reflecting a decrease in lower-quality patenting activity. In 2019, Chinese inventors represented a significant share of the world's patenting in lighting (25%), heating and cooling (21%), renewables (19%), and EV technologies (11%). On average, China's share of global patenting activity remains lower for climate change mitigation than for all technologies, suggesting there remains room for Chinese inventors to increase their global presence.

It should be noted that a drop in patenting activity for climate-change mitigation technologies was also observed globally over the 2010-2015 period and is not specific to China. Meanwhile, global activity in low-carbon energy technology patenting has been steadily growing since the 2000s, with a small dip between 2014 and 2018.

International patents in selected low-carbon energy technology areas filed by Chinese inventors, and share of these patents that are international (1990-2019)



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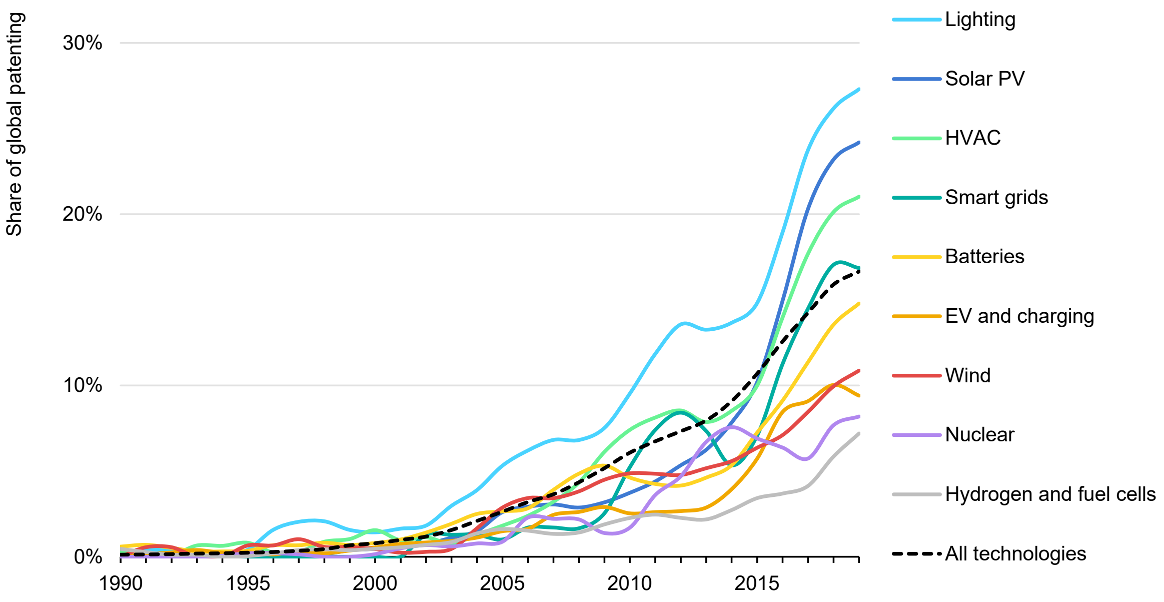
Notes: Patent counts in climate-change mitigation technologies relating to energy, filed in at least two geographical offices. HVAC = heating, ventilation and air conditioning. "Other renewables" includes the integration of renewables in buildings, geothermal, hydro, marine, solar thermal and hybrid thermal-PV energy sources. "Heavy industry" includes the production and/or processing of chemicals, cement, lime and metals. "Other low-carbon" includes technologies relating to air and maritime transport, capture or disposal of carbon dioxide, nuclear power generation and smart power grids. The share of patents filed internationally refers to the ratio of patents filed by Chinese inventors in at least two patent offices relative to all patents filed.

Source: IEA analysis based on OECD data on innovation in environment-related technologies.

China's share of global patenting in selected low-carbon energy technology areas and for all technologies (1990-2019)



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Notes: Patent counts in climate-change mitigation technologies relating to energy, filed in at least two geographical offices. Three-year moving averages are used.

Source: IEA analysis based on OECD data on innovation in environment-related technologies.

Over the 1990-2019 period, renewables accounted for 29% of all patenting activity in the sample at hand, including 17% for solar PV and 4% for wind. Chinese inventors were most active in battery technologies, which accounted for over 27% of activity. EVs and charging accounted for 13%, lighting 8%, hydrogen and fuel cells 5%, heating and cooling 5%, and biofuels 3%. Technologies relating to heavy industry accounted for about 7%, primarily for chemicals and metal processing and production, whereas there was limited activity in cement and lime. Over the 2017-2019period, the last three years for which data are available, battery, EV and solar PV technologies aggregated to the two-thirds of patenting activity in the sample at hand. Some areas have seen relatively less active patenting activity in general, such as air and maritime transport; carbon capture, utilisation and storage (CCUS); nuclear; and smart power grids.

In the case of nuclear, it is acknowledged that industrial confidentiality generally leads to underreporting of new knowledge created through R&D, which limits the use of patents as a good proxy for innovation activity. In fact, China's first home-grown third-generation nuclear power plant – Hualong One – started operations in 2021, and the government plans to expand nuclear capacity based on domestic concepts – including Hualong Two and small modular reactors – looking forward, which illustrates tangible technological progress not captured by patenting trends.

China's transformation from a solar PV technology importer to innovator

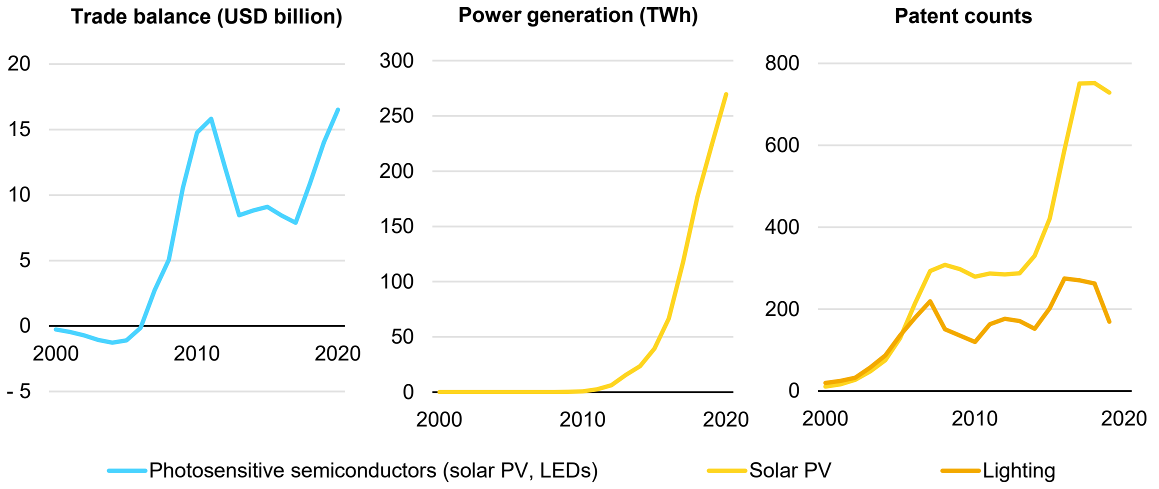
From solar PV manufacturer to innovator

It is common knowledge today that China is a global manufacturing powerhouse for solar PV technologies. In recent years, it has also become a major source of PV cell- or module-level innovations, and accounts for an increasingly important share of global patenting. This transition from having almost no technological competences in PV to being a frontier innovator did not happen overnight, although it was quick by historical standards.

The story of solar PV innovation in China starts in the 1950s with the first publicly funded R&D in the field, which primarily focused on space applications. In the 1980s, despite R&D projects focusing on crystalline silicon cells, overall manufacturing capacity, performance and quality remained low. Innovation efforts really took off in the early 2000s. In 2002, PV cells co-developed by a Chinese researcher at an Australian university began production in a factory owned by the researcher's company, Suntech, in China. A combination of low manufacturing costs, ambitious scale and cheap capital – Suntech was backed by a municipal government in Jiangsu province – gave the factory an edge in export markets just as public support for PV deployment was starting to expand in Europe.

Over the following decade, corporate partnerships and joint ventures helped achieve economies of scale and cost-based competition for export markets. Other Chinese firms built on this model of attracting world-leading companies to manufacture in China, gaining access to technology and global value chains. In 2008, Shandong Solar Technology licensed technology from Johanna Solar Technology, a German company. In 2012, Tianjin Zhonghuan Semiconductor formed a joint venture with Sunpower, a US company that went on to form other joint ventures with Dongfang Electric Company and two other Chinese companies.

Trade balance in solar PV and LEDs, power generation from solar PV and patenting trends in solar PV and lighting technologies (2000-2020)



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Note: LEDs = light-emitting diodes.

Source: IEA analysis based on United Nations Comtrade data on global trade (Harmonized System code 854140, three-year moving averages), IEA data and statistics for solar PV electricity generation, and OECD data on innovation in environment-related technologies (patent counts in climate-change mitigation technologies relating to solar PV and lighting, domestic and international filings, three-year moving averages).

Some Chinese companies also acquired foreign competitors and absorbed their R&D activities and transferred technology and knowledge. For example, Hanergy Group acquired Alta Devices, a US company, in 2013. Given the commanding position of Chinese manufacturing in global markets, raising capital for such purchases was not difficult. Several Chinese companies established partnerships with universities overseas, such as Trina Solar's tie-up with the Australian National University in 2011, and put in place special programmes to hire skilled labour and executives with foreign experience, especially Chinese nationals working abroad. Corporate partnerships and joint ventures brought about manufacturing and engineering improvements through learning-by-doing and economies of scale, paving the way for more novel technology innovation later on.

As competition with manufacturers in the rest of the world diminished over the 2010s, it intensified within China with the introduction of policies to support domestic deployment in the 12th FYP (2011-2015). Domestic market support was implemented to boost industry and take advantage of cheap panels, in a context of thin margins for manufacturers and boom-and-bust policy support abroad that triggered excess capacity. Typical policy support included deployment targets, financial incentives, subsidies and loans (e.g. Rooftop Subsidy Programme; Golden Sun programme; solar applications in agriculture), feed-in tariffs, creating local champions, and promotion of foreign direct investments in manufacturing. Competition for market share, often between companies backed by different municipalities, helped to drive impressive manufacturing innovations. Without innovations in silicon processing and cell assembly, the large cost reductions achieved for solar PV would not have been possible despite economies of scale. Progress in this area has been attributed to the fact that Chinese solar companies are organised in industrial clusters with exchange of knowledge and expertise.

In the last FYPs, market-pull factors have been strategically complemented by resource-push support, which has contributed to strengthening solar PV R&D. For example, R&D investments along the solar PV manufacturing value chain increased (e.g. in different components, resources and materials, manufacturing equipment, recycling). The government also provided research infrastructure and established key laboratories, set incentives to create corporate R&D labs, launched demonstration zones for emerging concepts such as distributed solar PV, and promoted the exchange of skilled labour. Since around 2010, Chinese companies and laboratories have become more active in developing new concepts and improving performance of solar PV technologies at the component level. These developments suggest that Chinese innovators are playing a more important role in global efforts beyond that of sheer manufacturing. The gap between the performance of Chinese firms and overseas competitors has shrunk rapidly. However, many cutting-edge modules with high efficiencies developed recently still come from countries with longer solar R&D history (e.g. Australia, Germany, Japan and the United States).

Chinese policy makers have indicated an ambition to remain the leading manufacturer of solar PV and the leading developer of new PV technologies in the 14th FYP (2021-2025) period and beyond. Chinese government laboratories and universities have already shifted their focus to next-generation PV designs, with corporate labs increasingly moving in the same direction.

Selection of solar PV technologies developed in China or acquired by Chinese groups from foreign R&D centres and companies

Institution	Cell and module family, type and efficiency
Advanced Solar Power Hangzhou Inc. Founded in 2008 in Hangzhou	**Chalcogenide cadmium-telluride modules** • 2010: 12.5% (eight-cell mini module), above ANTEC Solar's 10.6% record from 1995 for mini modules (Germany) and BP Solarex's 10.9% record from 2000 for larger modules (United Kingdom) • Current global record: 19% by First Solar (United States) since 2019 for larger modules
Alta Devices Founded in 2007 in California Acquired in 2013 by Hanergy Group (Beijing) R&D operations continued in the United States until 2019	**Gallium-arsenide single-junction thin film crystal cells** • 2010: 27.6%, above Radboud University's 26.1% record from 2008 (Netherlands) • 2011: 28.1%, then 28.3% • 2012: 28.8% • 2018: 28.9%, then 29.1%, current global record **Two-junction non-concentrator cells** • 2013: 30.8% (gallium-arsenide), above Japan Energy's 30.3% record from 1996 • 2016: 31.6% (gallium-indium-phosphide/gallium-arsenide), above the National Renewable Energy Laboratory's 31.1% record from 2013 (NREL, United States) • Current global record: 32.9% by NREL since 2020 **Gallium-arsenide III-V single-junction modules** • 2011: 21.1%, then 23.5%, above ECN Petten's 7.1% record from 2008 for a sub-module (Netherlands) • 2012: 24.1% • 2016: 24.8% • 2017: 25.1%, current global record
China's Academy of Sciences and **Chinese universities**	**Emerging PV organic cells** • 2018: 12.3% (thin film) by the State Key Laboratory of Polymer Physics and Chemistry of the Chinese Academy of Science • 2018: 15.6% (thin film) by the collaboration between South China University and Central South University • 2019: 17.35% (thin film) by Shanghai Jiao Tong University, in collaboration with University of Massachusetts (United States) • 2020: 18.2% (cell), in collaboration with Beihan University (China), the current global record **Emerging PV organic tandem cells** • 2019: 13.2% by Shanghai Jiao Tong University • 2020: 13.5% by the Institute of Chemistry at China's Academy of Sciences, the current global record **Emerging PV perovskite modules** • 2016: 12.1% (first-ever ten-cell mini module), in collaboration with the National Institute for Materials Science (Japan) • Current global record: 17.9% by Panasonic (Japan) since 2020
Jinko Solar Founded in 2006 in Shanghai	**Multicrystalline silicon cells** • 2020: 24.4%, current global record **Single crystal silicon cells** • 2021: 25.4% (n-type), current global record

Institution	Cell and module family, type and efficiency
LONGi Founded in 2000 in Xi'an (Shaanxi)	**Single crystal silicon cells** • 2019: 24.06% (p-type) • 2021: 25.09%, then 25.21% (n-type), 25.19% (p-type) • 2021: 25.26%, 25.82% and then 26.3% (heterojunction), current global record
MiaSolé Hi-Tech Corp Founded in 2004 in California Acquired in 2012 by Hanergy Group (Beijing)	**Copper-indium-gallium-selenide cells** • 2019: 20.56% (flexible) • 2021: 26.5% (perovskite tandem), in collaboration with the European Solliance Solar Research **Chalcogenide copper-indium-gallium-selenide modules** • 2010: 13.8%, then 15.7%, above Showa Shell's 13.5% record from 2002 (Japan) • 2019: 17.4% (thin film), second-highest globally • 2019: 17.44%, then 18.64% (flexible module) • Current global record: 19.2% by Solar Frontier (Japan) since 2017, and 19.6% for sub-modules by Avancis (Germany) since 2021
Microquanta Semiconductor Founded in 2015 in Hangzhou	**Emerging PV perovskite modules** • 2017: 16.0% (six-cell), above Shanghai Jiao Tong University's 12.1% record from 2016 (China) • 2018: 17.25% (seven-cell), breaking its own record • Current global record: 17.9% by Panasonic (Japan) since 2020
Solarmer Energy Inc. Founded in 2006 in California **Solarmer Materials Inc.** Founded in 2009 in Beijing	**Emerging PV organic cells** • 2009: 6.8%, 7.6% and then 7.9%, above Konarka's 6.4% record from 2008 (United States) • 2010: 8.1%, breaking its own record (beaten by Konarka at 8.3%) • Current global record: 18.2% by Shanghai Jiaotong University (China) since 2020 **Emerging PV organic modules** • 2009: 3.5% (sub-module), above Plextronics' 2.1% record from 2009 (United States) • Current global record: 11.7% by ZAE Bayern (Germany) in 2019
Trina Solar Founded in 1997 in Changzhou	**Single crystal silicon cell (non-centrator)** • 2019: 23.2% (n-type single crystal), below the Institute for Solar Energy Research Hamelin's record from 2018 at 26.1% (Germany), the current global record **Multicrystalline silicon cells** • 2014: 20.8% (p-type), above Fraunhofer Institute for Solar Energy Systems' 20.3% record from 2004 (Germany) • 2015: 21.25%, breaking its own record • 2020: 23.2% (n-type), above Canadian Solar's 22.8% record from 2019 (Canada) • Current global record: 24.4% by Jinko Solar (China) since 2020 **Multicrystalline silicon 120-cell large modules** • 2015: 19.2%, above Hanwha Q-Cells' 18.5% record from 2012 (Germany-Korea) • 2016: 19.9%, above Hanwha Q-Cells' 19.5% from 2015 • Current global record: 20.4% by Hanwha Q-Cells since 2019, first new high since Trina Solar's performance in 2016

Primary sources: Champion Photovoltaic Module Efficiency Chart and Best Research-Cell Efficiency Chart. Secondary sources: Solliance, MiaSolé hit 26.5% efficiency on tandem CIGS/perovskite solar cell; Longi achieves 25.21% efficiency for TOPCon solar cell; Longi improves efficiency of its heterojunction cell from 25.82 to 26.30% in just one week; JinkoSolar sets new record for n-type solar cell efficiency; Longi claims 25.19% efficiency for p-type TOPCon solar cell; Miasolé hits 20.56% efficiency with flexible CIGS technology; MiaSolé breaks its own record for flexible CIGS; Solarmer breaks organic solar PV cell conversion efficiency record.

Learnings from China's solar PV innovation story

The development of China's solar PV industry is a unique case study and may not be easily replicated, but it provides valuable innovation policy learnings. The impact that China has had on cost reductions and now performance improvements in solar PV has changed global conversations around energy innovation, and laid the foundation for what is happening in batteries and EVs.

In summary, the transition from a technology importer to an innovator was the result of a unique approach to joint ventures and corporate partnerships, a large domestic market, market-pull policies, resource-push support, and strong inter-company technology-based competition. China's solar story illustrates the need to consider innovation from a systemic perspective. Market-creation interventions alone were not enough to stimulate innovation. Overall, China aspired to cover all four pillars of successful innovation systems, although this was not the case from the beginning but rather progressive and particularly in the 13th FYP:

- sustained flows of resources for solar energy innovation activities, including increasing funding for R&D and developing human capital
- proactive knowledge management schemes including to share information and acquire IP from abroad, and to build domestic networks along solar supply chains
- strong industrial and market-pull policies to build integrated local champions, create domestic markets and boost exports
- efforts to promote socio-political support for solar PV technologies, such as through ensuring buy-in from industry, subnational governments and citizens with producer and consumer incentives.

The next sections of this report explore further some of these core components, starting with China's institutional landscape, which has enabled the progressive strengthening of innovation and changed over time thanks to policy learnings including from the case of solar PV.

China's institutional landscape for energy innovation

Introduction

This section maps China's landscape for energy innovation, including key stakeholders involved from priority setting to implementation of R&D and demonstration activities. It presents the country's key decision-making processes, notably through FYPs and associated action plans and guidelines, and tracks their focus on technology innovation in the last decades. It includes preliminary insights from the 14th FYP (2021-2025) with a focus on energy priorities, based on recent announcements and expectations relating to carbon neutrality targets.

Key takeaways

- The FYPs set the direction for China's energy innovation activities. In the last decade, they have increasingly focused on technology innovation, including in the energy sector. General guidelines set by central government agencies are translated into action plans and R&D programmes – many under the supervision of the Ministry of Science and Technology.
- Expectations for energy innovation from the 14th FYP (2021-2025) point to priority technology areas including new energy vehicles and associated components including batteries, hydrogen, bioenergy, energy storage and CCUS.
- The landscape of energy innovation in China is complex, with many actors and institutions involved in priority setting, decision-making and R&D execution, including at the subnational level and in state-owned enterprises.

Who are the key actors shaping innovation?

The ecosystem of stakeholders shaping China's energy innovation under the leadership of the State Council is complex.

Since its dissolution in 1993, there is no unified Ministry of Energy in China. Energy management is decentralised and relies on inter-ministerial collaboration and negotiation. In 2008, China established the National Energy Administration (NEA) as a co-ordinator of energy policy making, and in 2010, the National Energy Commission (NEC) as an umbrella mechanism for high-level energy decision-making. The NEC gathers representatives from all relevant ministries and public bodies, such as the NEA and the National Development and Reform Commission (NDRC), the country's top economic planner and policy maker.

Several government bodies and agencies have an official role in China's energy innovation decision-making process. In terms of priority setting, the Ministry of Science and Technology (MOST) plays an important role and collaborates with the NEC and its members (see table below), based on high-level policy guidelines set by the State Council. In 2018, a cabinet reshuffle created new bodies, such as the Ministry of Ecological Environment (MEE), and adjusted the responsibilities of others. For example, MOST incorporated the Administration of Foreign Experts Affairs and started overseeing the National Natural Science Foundation of China, which was previously independent.

In terms of funding for energy innovation, MOST oversees the country's major R&D projects, and several other ministries, public bodies and state-owned enterprises (SOEs) are mobilised as well (e.g. Ministry of Education with universities and affiliated research institutes). Subnational governments and provinces are also solicited, particularly for local policy support and implementation. After high-level priorities are set, a broad range of research institutions, universities and SOEs across the country is involved in implementation through dedicated R&D and demonstration programmes. The members of the NEC are in charge of co-ordinating, auditing and evaluating these activities in order to feed back into subsequent FYP priorities.

Overall, energy innovation responsibilities are shared among a broad range of actors reporting to the State Council (e.g. high-level strategy; R&D project design, funding, management and evaluation; support for diffusion of new technologies). Effective collaboration among these actors is key to ensure energy policy and innovation policy support each other.

An increasing role for China's SOEs in energy innovation following carbon neutrality pledges and the 14th FYP

China's carbon neutrality pledge mandates SOEs to be at the forefront of the country's low-carbon transition.

By mid-2021, about 30 SOEs had initiated discussions over carbon neutrality plans and strategies, including Sinochem, China National Offshore Oil Corporation (CNOOC) and Baowu Steel. Although few have announced specific timelines to date, most have announced changes to their strategy to deploy new technologies and devote more resources to R&D activities.

Furthermore, the State-owned Assets Supervision and Administration Commission (SASAC), the SOE regulator, issued draft rules to supervise and administer SOE energy conservation and environmental protection practices. Specifically, it instructed SOEs to build targeted action plans, increase relevant budgets, and carry out R&D in and accelerate deployment of low-carbon technologies. It is expected that under the 14th FYP (2021-2025), as in previous cycles, SOEs will be tasked with specific projects such as developing key technologies that are still at the pre-commercial stage in China, such as in CCUS.

In July 2021, Sinopec claimed to start the construction of China's first megatonne CCUS project to capture CO_2 at the Qilu Petrochemical plants, and transport and store it in over 70 wells in the Shengli oilfields. This project is one of several CCUS projects planned by Chinese SOEs in the 14th FYP period. In November 2021, Sinopec also announced the launch of the Xinjiang Kuche Green Hydrogen Demonstration Project, with total investment of CNY 3 billion (Yuan renminbi, about USD 450 million, market exchange rate basis). The project involves building 300 MW of solar PV powering electrolysers to produce an annual 20 000 tonnes of hydrogen starting mid-2023. The supply will fuel Tahe Refinery to replace its existing fossil fuel-produced hydrogen, reducing CO_2 emissions by about 500 kt annually. In December 2021, Sinopec and China National Petroleum Corporation (CNPC) also signed an agreement for deeper co-operation in new energy fields.

Public institutional landscape of energy innovation in China

Institution	Priority setting and strategic planning	Funding research and overseeing programme execution	Research execution or contribution to market-pull levers
National Energy Commission (NEC)	• The NEC is China's inter-ministerial mechanism for high-level energy decision-making within the State Council. It formulates national energy development strategies by gathering all key actors. • The NEC is chaired by the prime minister, with a responsibility to draft the national energy development strategy, review major issues in energy security and energy development, and co-ordinate tasks of domestic energy development and international collaboration. • As of 2020, NEC included 23 members, including the NDRC, NEA, MOST, Ministry of Finance (MoF), Ministry of Industry and Information Technology (MIIT), MEE, and Ministry of Foreign Affairs.		
National Development and Reform Commission (NDRC)	• NDRC is China's top economic planner and policy maker. It plays a key role in drafting the FYPs and related policies, which are the basis for the country's energy innovation strategy. • NDRC formulates high-level policies and support mechanisms for national research infrastructure, as well as for the demonstration and commercialisation of technologies in strategic sectors.	• NDRC manages four National Comprehensive Scientific Research Centers, each carrying out scientific research or providing test and analysis services to researchers, in Beijing (e.g. clean energy materials for energy storage, solar and lighting), Shanghai (e.g. thermal turbines), Hefei (e.g. renewables, smart grids, coal, nuclear fusion) and Shenzhen. • NDRC manages the State-accredited Enterprise Technology Centres programme, which certifies R&D centres of major SOEs and private enterprises and enables them to receive local government support. • NDRC oversees the Zhangjiakou Renewable Energy Pilot Zone. The programme features R&D and demonstration in energy technology areas including wind power, transmission and hydrogen. • NDRC's Department of Resources Conservation and Environmental Protection oversees the development of green technologies and a circular economy, and co-leads the Inter-agency Mechanism on Green Technology Development with MOST.	• NDRC's Energy Research Institute primarily conducts policy research, and the National Energy Conservation Centre manages energy standards and labels for various products.

Institution	Priority setting and strategic planning	Funding research and overseeing programme execution	Research execution or contribution to market-pull levers
National Energy Administration (NEA)	• NEA is China's main energy policy maker. It works with NDRC to translate the FYP into energy-specific plans and policies. It runs the office of the NEC and plays a crucial role in inter-ministerial collaboration in the energy sector. • NEA oversees nuclear power technology development, develops related support policies and standards, and co-ordinates deployment of nuclear technologies under the leadership of the State Council.	• NEA oversees the National Energy R&D Innovation Platform, which encompasses centres and laboratories affiliated with universities, institutes or SOEs that carry out innovation in a broad range of energy technology areas (e.g. renewables, nuclear, transmission and smart grids, storage, hydrogen, transport, fossil fuels). While NEA does not directly provide funding, it can certify institutions to facilitate access to funding from other state sources, and takes part in monitoring and evaluation. • NEA supports demonstration projects in energy storage (e.g. provides preferential access to the grid) with the view to set technological standards in the future.	• NEA sets standards in all energy technology areas (e.g. fossil fuels, renewables, nuclear power, power grid and storage) through dedicated committees gathering government, industry and sectoral experts.
Chinese Academy of Sciences, Chinese Academy of Engineering (CAS, CAE)	• CAS and CAE are China's top science and engineering academies at the ministerial level and reporting directly to the State Council. • CAE performs an advisory role for policy makers on technology development. Its members count experts from various sectors including transport, chemicals, the environment and energy. It produces sectoral technology reports and roadmaps for public R&D activities.	• CAS is China's most prominent natural science research institution. It directs over 100 institutes with an annual budget of CNY 90 billion (USD 13.7 billion). • Several affiliated institutes cover energy: the Guangzhou Institute of Energy Conversion (e.g. bioenergy, solar, marine energy, fossil fuels); the Institute of Physics – Key Laboratory for Renewable Energy (e.g. storage, solar); the Beijing Institute of Nanoenergy and Nanosystems (e.g. nano power and high-voltage systems); and the Institute of Engineering and Thermal Physics (e.g. wind and thermal turbines, distributed energy, renewables, storage).	

Institution	Priority setting and strategic planning	Funding research and overseeing programme execution	Research execution or contribution to market-pull levers
Ministry of Science and Technology (MOST)	• MOST is the top planner and policy maker for science and technology (S&T). It formulates the national S&T strategies and plans, including the S&T FYP and the Mid- and Long-term S&T Development Plan every 15 years, the next one covering the 2021-2035 period. • MOST leads the National S&T Major Projects (e.g. in nuclear, semiconductors, drilling equipment) and the National Key R&D Projects (e.g. in coal, renewables, hydrogen, nuclear, low-carbon transport, materials, smart grids).	• MOST manages the National Natural Science Foundation of China, a major funding source of China's scientific research with an annual budget of over CNY 30 billion (USD 4.5 billion). In 2019, the fund provided grants to over 18 000 research projects, including in energy technology areas such as solar power and hydrogen electrolysis. • MOST runs the National Guiding Fund for the Conversion of Scientific and Technological Achievements, which mobilises public and private funding for R&D, demonstration and commercialisation of emerging technologies. By 2019, it had notably set up 20 venture capital funds with other co-investors, several of which list low-carbon energy and transport technologies in their investment priorities. • MOST oversees resource allocation for R&D, demonstration and S&T prizes. It supervises project evaluation and the certification of National Scientific Laboratories.	
Ministry of Finance (MoF)	• MoF oversees annual budgets for S&T and sets management rules for public S&T spendings.	• MoF provides general tax credits for R&D expenses to encourage R&D activities, and specific subsidies to high-tech sectors.	• MoF works with relevant agencies to set subsidy policies in demonstration and deployment of new energy technologies, including renewables and low-carbon transport. It oversees the latest research and pilot programmes for fuel cell vehicles.

Institution	Priority setting and strategic planning	Funding research and overseeing programme execution	Research execution or contribution to market-pull levers
Ministry of Industry and Information Technology (MIIT)	• MIIT is the planner and regulator of China's wide-ranging industry and information technology sectors. Its portfolio includes automobiles, civil aircraft, shipbuilding and traditional industries. • MIIT’s State Administration of Science, Technology and Industry for National Defence oversees military and dual-use technologies such as civil nuclear technology. • In 2021, it published the 14th FYP Industrial Green Development Plan, covering most industrial sectors.	• MIIT directly manages and provides funding for seven top-quality engineering universities.	• MIIT designs standards and industrial policy for energy-saving technologies and green manufacturing, and is responsible for the promotion and deployment of green technology in traditional industries such as steel making. • In the automobile sector, MIIT formulates development plans and technical standards for low-carbon vehicles, and manages licences for manufacturers and new models.
People’s Bank of China – and other financial regulators		• China’s financial regulators can set specific policies or regulations that support R&D activities, such as bank financing for innovative firms and start-ups. • The China Banking and Insurance Regulatory Commission shares the responsibility of managing and regulating venture capital (VC) funds with NDRC. • Banks may directly support major public R&D programmes, such as through the partnership between MOST and the Industrial and Commercial Bank of China to improve the country’s technological self-reliance.	
Ministry of Ecology and Environment (MEE)		• MEE oversees environmental technology, including its standard and demonstration projects.	

Institution	Priority setting and strategic planning	Funding research and overseeing programme execution	Research execution or contribution to market-pull levers
Ministry of Housing and Urban-Rural Development (MOHURD)		• MOHURD takes the lead for sectoral FYPs relating to buildings energy efficiency. It designs standards, labels and policies for green buildings, materials and other related technologies, and collaborations with NDRC and other ministries for demonstration and deployment projects as well as certification. • Through market-oriented programmes to stimulate deployment (e.g. the Rooftop Subsidy Programme for solar PV), MOHURD contributes to China's market creation policies for energy technologies and can be an enabler for emerging technologies.	
Ministry of Education – and affiliated public universities (MoE)		• MoE manages 75 public universities including Tsinghua, Peking and Shanghai Jiaotong University. While universities are given some autonomy in setting R&D budgets, MoE's Department of S&T audits innovation funding streams and co-ordinates research activities.	• In 2019, the public universities that MoE oversees spent over CNY 50 billion (over USD 7.25 billion) of R&D funding, accounting for more than half of the total R&D budgets of the nearly 2 000 universities across the country.

Sources: IEA analysis based on exchanges with MOST.

How does China set innovation priorities?

High-level strategy and decision-making is through FYPs

China’s overarching priorities are formulated and updated over time in the successive FYPs. The State Council sets an overarching vision for the country’s economic and social development in a general FYP covering all sectors of the economy. Afterwards, several ministries collaborate – supported by bodies such as the NEC to co-ordinate – to formulate sector-specific FYPs, set common priorities, align objectives, and avoid duplication or omission. The three core high-level steps relevant to energy innovation decision-making are listed below.

High-level strategy and decision-making process relevant to energy innovation

Step	Description
1. Vision for the country	• The State Council first develops the FYP for National Economic and Social Development, an overarching plan including high-level priorities for the country across all sectors of the economy. In March 2021, for example, it issued the 14th FYP (or Fourteenth Five-Year Plan for the National Economic and Social Development and Outline of the Long-term Goals for 2035). • The general FYP may include specific points related to the energy sector and technology innovation when these are considered strategic drivers for economic and social development. Energy technology innovation has been increasingly present in this overarching FYP in the last two decades.
2. High-level strategy for energy	• The NDRC and NEA develop a FYP for Energy Development, the blueprint to deliver the energy objectives of the general FYP. This FYP covers the whole energy system and is based on guiding documents such as the Energy Development in the New Era white paper (December 2020). • The energy-specific FYP includes guidelines related to energy technology innovation and development of priority emerging technologies. Key performance indicators are also included to track progress with the running year selected as a baseline and five-year targets (e.g. energy production or consumption, energy security, energy efficiency, environmental protection).
3. High-level strategy for science and technology	• In parallel to the FYP for Energy Development, MOST develops a FYP on Science, Technology and Innovation to deliver the objectives of the general FYP and of the several sectoral FYPs including the FYP for Energy Development. • This FYP includes (but is not limited to) aspects related to the energy sector, such as priorities and objectives for new energy technologies, materials and vehicles. In the case of the 14th FYP, it will be complemented by a Carbon Peak and Carbon Neutral Technological Innovation Action Plan.

To formulate FYPs, Chinese decision makers capitalise on learnings from previous FYPs and collect information from a range of experts, officials, academics and subnational levels of government. About halfway through the FYP, a mid-term evaluation helps update priorities and prepare the following plans. For example, the elaboration of the 14th FYP (2021-2025) started in 2019 with a research prophase aiming to take stock of achievements of the 13th FYP, identify major outstanding issues and possible future priorities for China, and formulate guiding recommendations. Since mid-2020, the core themes of the 14th FYP have been further fleshed out, debated and refined through several rounds of consultation, before being approved by the National People's Congress in March 2021. The government aims to publish sectoral plans in 2021-2022, as well as goal-specific or thematic strategies such as the Carbon Peak Action Plan by 2030.

General guidelines and expectations for innovation in the 14th FYP (2021-2025) are already in place

Innovation is expected to be core to China's economic and social development strategy under the 14th FYP as first introduced by Premier Li Keqiang, and is featured in the first chapter of its guiding policy document (March 2021). In May 2021, President Xi Jinping shared a vision for China to become "the top innovation-oriented country by 2035" and "the world's major science centre and a highland of innovation", with the view to achieve a high level of technological self-reliance and drive innovation-led growth.

Beyond economic development, innovation should help tackle environmental challenges and build an "ecological civilisation". In February 2021, Minister Wang Zhigang (MOST) said innovation would support "achieving the goal of carbon peak and carbon neutrality", environmental protection and the "response to climate change". In August, NEA Director Zhang Jianhua called for a strengthening of low-carbon technology innovation. In October, the State Council issued the Carbon Peak Action Plan by 2030 and accompanying working guidance to achieve carbon neutrality. Accelerating "green and low-carbon technological innovation" ranks among the plan's "Top 10 Carbon Peaking Actions". The CAS, CAE, and Association for Science and Technology have all stressed the importance of S&T innovation to achieve climate ambitions and are joining forces to strengthen China's technology leadership. In 2019, MOST and the NDRC had published guidelines to build a "market-oriented green technology innovation system", notably to strengthen enterprise innovation and establish an "inter-ministerial coordination mechanism for green technology innovation". These will continue to inform policy in the next period.

To accelerate innovation, Chinese decision makers have identified areas for possible improvement in the coming years, including:

- Improving original and breakthrough innovation capability.

- Allocating budgets and resources to strategic and emerging areas.
- Further involving enterprises in technology innovation and major national projects.
- Improving the effectiveness of R&D institutions and input-to-output efficiency.
- Modernising S&T governance structures.
- Modernising central funds management, notably following warnings by CAS of funding gaps, and reviewing the ability to raise external funds.
- Strengthening evaluation mechanisms.

These recent policy announcements are in line with the last few FYPs, which also defined science and technology as drivers of China's modernisation towards a high-tech innovation economy, and with reference to deploying new energy technologies. More than in previous cycles, however, the 14th FYP puts emphasis on China's technological self-reliance, notably to mitigate exposure of Chinese firms to foreign equipment.

Proposals in the innovation sections of the 14th FYP or in complementary announcements include:

- Increasing all public R&D spending by over 7% every year over the 2021-2025 period, which is in the ballpark of average GDP growth rates in recent years and slightly above the indicative 6% GDP growth target for 2021. This would bring China's public R&D spending to about USD 580 billion in 2025, surpassing budgets in the United States (2018) and Europe (2019). Basic research has also received particular emphasis, with a target to reach over 8% of total R&D. In 2021, the Ministry of Finance cancelled import taxes until 2025 on S&T equipment purchased for R&D or teaching and that cannot be produced in China, in an effort to free up budgets for research and academic institutes.
- Concentrating resources on strategic and emerging energy areas, strengthening R&D and demonstration in disruptive technology development, with long-term budgets – including CCUS, hydrogen, industrial decarbonisation, digital and smart energy, and advanced biofuels for transport.
- Granting more autonomy to research institutions and personnel, and promoting open competition mechanisms by broadening access to publicly funded R&D programmes, including for younger and more diverse scientists, such as through the new "bounty system" and "disruptive technology innovation competitions".
- Setting up national, regional and international innovation centres, and platforms for the joint participation of research institutes, enterprises and universities. In April 2021, for example, the province of Sichuan announced establishing the country's first carbon-neutral innovation centre, focusing on carbon emissions reduction and zero-emission and carbon-negative technologies. The centre is expected to carry out basic and applied research projects, develop an industrial technology development platform and export-oriented industrial parks, implement technology upgrading programmes for traditional industries in the province, and provide support to innovation networks and information sharing and library resources.

Other examples include a strategic co-operation partnership between MOST's Administrative Centre for China's Agenda 21 (ACCA21) and Tsinghua University's School of Environment to strengthen research in carbon neutrality, climate change and other sustainable development areas.

- Encouraging enterprises to increase R&D spending and strengthen linkages between innovation and industrial chains to capture a share of growing clean energy supply chains. The government may continue using tax incentives or other non-traditional fiscal policy tools such as "innovation points" systems that reward innovative firms located in official National High-Tech Zones with financing. The government also plans to devolve leadership to enterprises of over 55% of major S&T projects and national key R&D programmes supporting green technologies.
- Proceeding with major institutional reforms to cut red tape, streamline administrative processes, and improve evaluation mechanisms for task- and results-oriented S&T projects.
- Enhancing protection under IP regimes (see next sections).
- Promoting international collaboration with China-initiated S&T plans and projects, and establishing a China-based international S&T organisation.
- Accelerating the development of China's innovation culture.

The energy technology areas of focus in the 14th FYP are broad in scope, but signal some new directions

Innovation has become more central to Chinese energy policy discussions following the climate pledges of peaking carbon emissions by 2030 and achieving carbon neutrality by 2060. From China's perspective, the clean energy transition presents opportunities to seek global leadership, learning from the experiences with solar PV and, more recently, EVs.

The objectives laid out in the 14th FYP and accompanying documents determine which energy technologies will receive most focus over the five-year period and which R&D programmes and demonstration projects could start. A number of official policy documents – already published or announced – provide indications of China's priorities for energy technology development and innovation. These plans include, in the chronological order of publication:

- NEA's notice on Administrative Measures for the National Energy R&D and Innovation Platform (September 2020), which are broad in scope and include details relating to R&D operations, monitoring and evaluation.
- The State Council's Energy Development in the New Era white paper (December 2020), which fleshes out high-level guidelines for energy under the 14th FYP, takes stock of recent progress and lists reforms to strengthen the "driving force of technology innovation". Three overarching policy goals are set for the energy sector: 1) address growing energy security concerns; 2) develop emerging strategic industries; and 3) meet the carbon neutrality pledge.

- MOST's upcoming Carbon Peak and Carbon Neutral Technological Innovation Action Plan, in the making since 2020 and based on regular expert meetings and seminars. A technology roadmap and a list of R&D projects for "key carbon neutral technologies" are expected to accompany the plan.
- The NDRC's Green Technology Promotion Catalogue (January 2021), which lists priorities for cleaner technology development across the economy. These include:
  - 63 areas for "energy saving and environmental protection" and 26 for "cleaner production" (e.g. transport and new energy vehicles; buildings; power and grids; CCUS; steel, cement and chemicals; rare earth mining).
  - 15 areas for "clean energy" (e.g. renewables such as offshore wind and advanced solar designs; energy storage; fossil fuels).
  - 8 areas for "green upgrade of infrastructure" (e.g. grids and storage; rail).
- The NDRC's Pollution Control, Energy Saving, and Decarbonisation Special Funds Budget Management Guidelines (May 2021) set out conditions for central funding of technology development and infrastructure. Eligible areas in energy saving and carbon reduction include power, steel, building materials, chemicals, energy efficiency in transportation and buildings, and battery recycling, as well as fossil fuels including coal. The document also specifies support for promotion and demonstration of "low-carbon, zero-carbon and carbon-negative technologies".
- The State Council's Carbon Peak Action Plan by 2030 (October 2021), already mentioned above, also lists priority areas for energy technology and innovation.
- MIIT published the 14th FYP on Green Industry Development (November 2021), covering most industrial sectors from heavy industry to transportation, and energy technologies from hydrogen to CCUS and rare earth minerals.

While there is no indication of ranking and although specific projects are yet to be fleshed out for most of them, the list of priority areas for the 14th FYP includes:

- New energy vehicles, with an emphasis on electric mobility and associated components such as next-generation batteries, as well as hydrogen and fuel cells. The Ministry of Transport's 14th FYP for Comprehensive Transportation Services, 14th FYP for a Modern Integrated Transport System and 14th FYP for Green Transportation also mention possible innovation focus on freight (road, shipping).
- Hydrogen production, notably through low-carbon electrolysis, transport, storage, distribution and use, with large-scale applications including in industry, transportation and construction.
- Bioenergy technologies, such as advanced biofuels for use in aviation, shipping and trucks; bio-based hydrogen production (e.g. biomass gasification); bio-based materials and chemicals production and refinery; bio-based CCUS; and co-power generation in large fossil fuel plants.
- Energy storage and power batteries, including at grid scale and molten salt storage for heating and power generation. In April 2021, NDRC and NEA also

issued for consultation plans on "Accelerating the Development of New Energy Storage", which would include support for new technology development.

- CCUS technologies, such as for coal-based hydrogen production and applications in heavy industry, within a National CCUS Innovation Centre benefiting from more support and funding than CCUS under the 13th FYP, and new major demonstration projects. In April 2021, the National Natural Science Foundation also identified over 20 "major basic science issues" in fields relating to CCUS.
- Technologies to decarbonise heavy industry, including iron and steel (e.g. non-blast furnace ironmaking technology demonstrations, all-scrap electric furnace processing) and building materials and cement (e.g. R&D for new cementitious materials, low-carbon concrete, wood, bamboo and other low-carbon building materials), in addition to hydrogen, CCUS and low-grade waste heat applications.
- Renewables, such as high-efficiency solar PV and "PV+" models, offshore wind, ocean, wave and tidal energy, and geothermal.
- Nuclear power including fusion.
- Basic materials including carbon fibre and aerogel.
- Digital technology applications in energy, such as for smart grids, grid stability and flexibility in anticipation of higher shares of renewables, and intelligent buildings.

Key energy innovation priorities outlined in China's recent five-year plans

	11th FYP (2006-2010)	12th FYP (2011-2015)	13th FYP (2016-2020)	14th FYP (2021-2025)
General innovation approach	Ramp up technology manufacturing to boost exports	Prime domestic markets and manufacturing innovations	Seek novel innovations in priority technology areas	Keep edge in manufacturing and prime breakthrough innovations
Key focus areas for energy innovation	Nuclear, coal, automobiles and new materials	Solar, wind, EVs and charging	Next-generation renewables, energy storage, new energy vehicles and batteries, smart power grids, and buildings energy efficiency	Next-generation batteries and new energy vehicles, hydrogen and fuel cells, advanced biofuels, CCUS, industry, and smart digital systems

Notes: Key focus areas correspond to those technologies for which innovation is mentioned in high-level policy documents and guidelines. As priorities typically roll over in five-year plans, the table focuses on additions relative to previous FYPs.
Source: Adapted from An Energy Sector Roadmap to Carbon Neutrality in China based on official documents.

Notably, innovation for the decarbonisation of heavy industry is present in the 14th FYP more than in previous cycles. For example, there are plans to develop a "comprehensive reform pilot zone for the energy revolution" in Shanxi province to strengthen innovation in greening heavy industries, in a region traditionally reliant on coal with a dynamic coal-based innovation ecosystem. In the iron and steel sector, three of the top five companies in the country including Baowu have put forward plans to achieve carbon peaking before 2025 and neutrality by 2050 ahead of national schedules, strengthen R&D, set up innovation centres in existing facilities such as in Xinjiang, and "create a global low-carbon metallurgical innovation alliance" to foster collaboration. The special central funds put in place in May 2021 by the NDRC also support energy saving and decarbonisation through technology upgrading, development and demonstration in industrial sectors including steel, non-ferrous metals, building materials, petrochemicals and chemicals, textile, paper, and machinery, among others.

Given the importance of critical minerals in clean energy transitions, it is notable that these rank among central national priorities in the 14th FYP. China already has a strong presence across the board, such as for cobalt, lithium, nickel and rare earth elements. Critical minerals and new rare earth materials are mentioned throughout high-level policy documents – such as MIIT's 14th FYP for Raw Material Industry Development – and are the focus of new R&D projects proposed by MOST in 2021. In this area, global co-operation and more innovation will be needed to ensure recycling, supply chain resilience and sustainability.

Fossil fuels are expected to remain an important aspect of China's energy security in the 14th FYP, with a likely continuation of innovation activities for a cleaner and more efficient use of these resources. Examples include coal use, coal-derived chemicals, coal-biomass mixed power generation, oil and gas exploration and production including of unconventional resources (e.g. shale gas, coalbed methane and tight oil), deep-sea technologies, and large liquefied natural gas ships and engines. For many of these energy technology areas, as well as for nuclear, improving technological self-reliance and reducing exposure to trade fluctuations are also drivers for strengthening innovation and domestic capacity.

How are innovation priorities implemented?

FYPs are translated into guidelines and then action plans

China's overarching FYP provides high-level directions but partial understanding of specific activities (see table). Priorities are further detailed in additional policy documents, strategies and plans such as the Carbon Peak Action Plan by 2030, and later translated into concrete R&D activities. For the 14th FYP period (2021-2025), most R&D projects are yet to be launched.

In 2016, NDRC and NEA drafted the Energy Technology Revolution and Innovation Action Plan (2016-2030), laying out a strategy to "build a complete energy technology innovation system". In 15 broad energy technology areas – three each for fossil fuels and renewables, two for nuclear, and one for each CCUS, hydrogen, gas turbines, energy storage, power grids, digital and energy efficiency – the document lays out a roadmap with key goals for 2020 and 2030, a vision for 2050, and more detailed lists of priority technologies. For example, the plan sets four directions for nuclear: 1) exploration, development and use of nuclear resources; 2) advanced nuclear fuel components; 3) new generations of reactors; and 4) fusion power. For new designs, the plan includes a focus on small modular reactors with goals to launch demonstration projects by 2020 and reach larger-scale production by 2030, and to explore offshore nuclear power platforms. For fusion power, the plan sets a target to "master the experiment, operation and control technology of plasma combustion in the fusion reactor core" by 2030 and the vision to "build a million KW-level fusion prototype power station" by 2050.

Building on this action plan and the 13th FYP for Energy Development, the NEA developed the 13th FYP on Energy Technology Innovation (2016-2020). This FYP mapped 21 focus areas covering five broad fields: 1) efficient use of fossil energy; 2) new energy power systems; 3) advanced nuclear; 4) strategic energy technologies; and 5) energy materials. It proposed specific tasks for each area in R&D, demonstration and industry applications (see table). Although the breakdown is not exactly similar, the focus areas broadly match that of the Energy Technology Revolution and Innovation Action Plan (2016-2030), with a greater level of details for the 2016-2020 period, with a number of projects running up to 2025. Special plans and other sectoral documents may further specify these tasks.

Other strategic documents fleshing out China's vision regarding technology innovation include Made in China 2025 plans from 2015, which focus on enhancing innovation capability in the manufacturing industry, and its longer-term complement, China Standards 2035.

Selection of low-carbon energy technology priorities from NEA’s 13th FYP on Energy Technology Innovation

Focus area	R&D	Demonstration	Industry use
Efficient use of renewable energy	• New, high-efficiency and low-cost solar PV • Large-scale hydro in complex conditions • Comprehensive management of cascade hydropower stations • Environmental protection and soil and water conservation in hydropower projects	• Large offshore wind of 8-10 MW • Large-scale solar thermal power • Use of biomass and efficient co-generation* • Large-scale pumped storage power stations • Marine energy use • Dry heat rock use	• Carbon fibre composite wind turbine blade and anti-icing technology • Large and intelligent offshore wind of 5-6 MW • High-efficiency, low-cost crystalline silicon battery industrialisation
Integration of high shares of renewables on the grid	• Key technical equipment of direct current (DC) grid • Development of ± 500 kV DC transmission cable • New ultra-high voltage alternating current (AC) transmission • Power dispatching control system with cloud technology • Smart grid information collection and communication	• Intelligent control, dispatch and energy efficiency evaluation of wind farms • Flexible DC transmission • Fault current limitation of high-voltage and large-capacity AC grids • Grid security and stability protection system	• Large-scale ultra-high-voltage DC transmission and dispatch operation • Multilevel dispatch control system for smart grids • Real-time simulation technology for AC and DC grids
Energy storage	• New high-efficiency battery storage • Large, distributed power grid integration and control • Interconnection system operation and transaction	• Large-capacity and long-life lithium-titanate battery storage • Large-capacity sodium-sulphur battery storage at MW level • 10 MW/100 MWh advanced compressed air energy storage • AC/DC distribution network to adapt to various power sources and consumer activity	• Industrialisation of vanadium flow battery storage technology • Multi-energy distributed generation and microgrid • Interactive intelligent power consumption and demand response
Hydrogen and fuel cells	• Hydrogen fuel cell catalyst materials • Hydrogen storage and transportation	• Renewable energy-produced hydrogen • Fuel cell distributed power generation	

Focus area	R&D	Demonstration	Industry use
Clean energy materials	• Solar cells with perovskite materials • Polymer film materials for high energy density batteries • Electrode materials production with micro-nano manufacturing • New energy storage materials	• Polymer materials for PV modules • Silver electrode paste for crystalline silicon solar cells • Compound semiconductor material	
Superconducting power transmission	• Superconducting DC transmission	• 2.5 MW/5 MJ high- temperature superconducting energy storage device	
Advanced nuclear power technologies	• Ultra-high temperature gas-cooled reactor • Fast neutron reactor operation and control • Lead-based alloy cooling reactor • 5-10 MW class manufacturing module stack based on highly safe fuel • Thorium-based molten salt reactor • New generation of advanced nuclear fuel • Radioactive waste minimisation • Controllable fusion frontier technology	• CFR600 fast reactor • Modular small reactor • Key technologies for extending life in nuclear power plants • Smart design and construction technology for nuclear power engineering • Offshore nuclear power platform	• Third-generation large-scale advanced pressurised water reactor • 600 MW high-temperature gas-cooled reactor nuclear power plant • Advanced nuclear fuels assembly • Advanced nuclear power monitoring and testing equipment • Digital instrumentation control platform technology

* Co-generation refers to the combined production of heat and power.

Source: 13th Five-Year Plan on Energy Technology Innovation.

Overview of China's FYPs and focus on energy innovation in cycles preceding the 14th FYP

Policy	Framing for innovation and targets	Focus on energy priorities	Policy approach to implementation
13th FYP 2016-2020 Link	• The 13th FYP (2016-2020) further strengthened China's focus on technology innovation, "the primary driving force for development", which ranked first in the FYP's development philosophy and policy guiding principles. • This was in line with the issuance in 2016 of the National Innovation-Driven Development Strategy. • Key objectives included reaching 12 patents per 10 000 people in 2020 (up from 6.3 in 2015) and a contribution of scientific and technological advances to economic growth of 60% (up from 55%). Latest estimates suggest China reached 15.8 patents per 10 000 inhabitants in 2020, surpassing its target. • The 13th FYP was rooted in the concept of "four revolutions", among them the energy revolution aiming to "build a modern energy system that is clean, low-carbon, safe, and efficient, and will safeguard the country's energy security". As such, energy was made core to China's science and technology development ambitions.	• Two energy technology areas were listed among the plan's six strategic emerging industries: energy storage and distributed energy (e.g. next-generation renewables, hydrogen power and fuel cells, smart grids, new energy storage) and new energy vehicles (e.g. EVs, batteries, charging). While R&D for electric mobility had already been mentioned in the 12th FYP, additional focus was put on developing battery technology. • Innovation in long-distance transport technologies was also mentioned (e.g. cruise ships and high-tech vessels, aircraft engines), although not specifically geared towards low-carbon development, as well as ambitions to exceed international energy efficiency standards in heavy industry (e.g. iron and steel, cement, chemicals).	• The FYP explicitly aimed for "the development of a national innovation system" and proposed support not only for publicly led R&D programmes, but also for business innovation, start-ups and innovative small and medium-sized enterprises (SMEs), education and academia, research infrastructure, and domestic and international knowledge networks. • The FYP also proposed to leverage China's large domestic market to support major innovation programmes – that is, to put in place market-oriented mechanisms setting incentives for innovators and promoting domestic diffusion of emerging technologies, thereby pulling product development along the innovation value chain. • A reform to the S&T management system was also proposed, in which the government would provide greater autonomy to innovation actors such as research institutes and enterprises, as well as strengthen IP rights.

Policy	Framing for innovation and targets	Focus on energy priorities	Policy approach to implementation
13th FYP for Energy Development 2016-2020 Link	The 13th FYP for Energy Development, which was finalised in December 2016, contained a number of innovation elements. These were aimed at accelerating China's transition from a large energy producer and consumer to a strong innovator in technology and equipment.	The 13th FYP for Energy Development put forward innovation tasks for a broad range of energy fuels and technologies, in both low-carbon and fossil fuel-related fields without clear indications for which should be prioritised over the others. In addition, it did not set performance indicators for the innovation objectives.	• The plan included special sections listing high-level guidelines to strengthen scientific and technological innovation capabilities, establish research centres and laboratories, promote indigenous technology development and entrepreneurship, stimulate the innovation potential of major energy companies including SOEs, provide equipment and infrastructure for R&D, and carry out demonstration projects, among others. • The plan's guidelines aspired to address technology innovation in a systemic way, including components relevant to resource push (e.g. funding, human capital), knowledge management (e.g. developing talents) and market pull (e.g. market-creation support for emerging technologies and industries).

Policy	Framing for innovation and targets	Focus on energy priorities	Policy approach to implementation
13th FYP for Science and Technology Innovation 2016-2020 Link	• The 13th FYP for Science and Technology Innovation was put forward in mid-2016 and aims for China to enter the ranks of innovation-driven countries, specifically, reach 15th position in global rankings for innovation capacity. • The plan tracks progress with over 10 metrics, including: the contribution of S&T progress to economic development; R&D funding intensity; R&D personnel; operating revenue of high-tech firms; value added in knowledge-intensive service industries per GDP units; R&D-to-revenue ratios in industry; citations of scientific papers; and patents.	The 13th FYP for S&T Innovation includes project proposals across the economy including in fields relevant to energy, such as: oil and gas, coal, nuclear, smart power grids, materials, energy-efficient buildings.	• Similarly to other 13th FYP documents, the 13th FYP for S&T Innovation takes a systemic approach to innovation and covers resources for major S&T innovation projects in strategic industries, talent management and human capital, entrepreneurship, market-oriented R&D, and ways to promote and develop a culture of innovation in China. • Subnational government has a role to play, such as with municipal or provincial innovation centres. • The plan aims to support the National Innovation-Driven Development Strategy, Made in China 2025, Internet+, and other high-level strategies.
12th FYP 2011-2015 Link	In the 12th FYP (2011-2015), "scientific progress and innovation" were core guiding principles for China's economic transformation, and key performance indicators included "patents per 10 000 people", illustrating State Council objectives to "speed up the construction of an innovation country".	In contrast to the 11th FYP, several key low-carbon energy technologies benefited from an explicit focus on innovation in the 12th FYP, notably solar, wind and EVs.	
11th FYP 2006-2010 Link	The 11th FYP (2006-2010) generally mentioned innovation and talent development as an enabler of growth, with goals such as reaching R&D expenditures of 2% of GDP in 2010, up from 0.9% in 2000 and 1.3% in 2005.	While some of the FYP's guidelines addressed several energy technology areas (e.g. fossil fuels with a focus on coal, hydropower, solar and wind energy), it mostly focused on deployment, with some exceptions where innovation activities were mentioned (e.g. nuclear, automobiles, coal, new materials).	

What are the central government's core energy R&D programmes?

Based on the guidelines set out in the various FYPs and associated strategy documents, MOST is responsible for designing and managing China's central government research programmes. Since 2015, there are five main types of national science and technology projects, and MOST's National Science and Technology Management System supports with resource allocation across them. These include:

- National Major Science and Technology (S&T) Projects, which match the country's top priorities and pool extended resources for a limited duration (e.g. running up to 2030 for some projects launched under the 13th FYP).
- National Key R&D Projects, broad in scope and addressing all economic areas.
- Projects under the Technology Innovation Guidance Fund, which uses market mechanisms to support innovation.
- Projects under the National Natural Science Foundation, mostly basic research.
- Talent development projects, supporting innovators and human capital.

China's National Major S&T Innovation Projects and National Key R&D Projects centralise the country's R&D activities. They incorporate previous programmes such as MOST's 863 Programme (or State High-Tech Development Plan) and 973 Programme (or National Basic Research Programme).

The Major S&T Innovation Projects rank among the world's largest funding programmes for energy technology demonstration, with selected SOEs carrying responsibility for a priority engineering challenge and supported with multi-annual funding, such as USD 1 billion over five years. Local governments and enterprises are also encouraged to take part. Among the 16 projects announced for 2020-2030 are turbines, coal use and smart grids. The Key R&D Projects account for much of the R&D funding disbursed by MOST. Around USD 200 million of this was allocated annually to EVs and smart grids in 2016 and 2017, often for basic research, and around USD 65 million was allocated to renewable energy and hydrogen in 2019. In 2016-2017, clean and energy-saving coal received USD 70 million per year. Throughout the 13th FYP period (2016-2020), MOST supported over 3 500 R&D projects with about CNY 76 billion (about USD 11 billion) in funding across all economic areas.

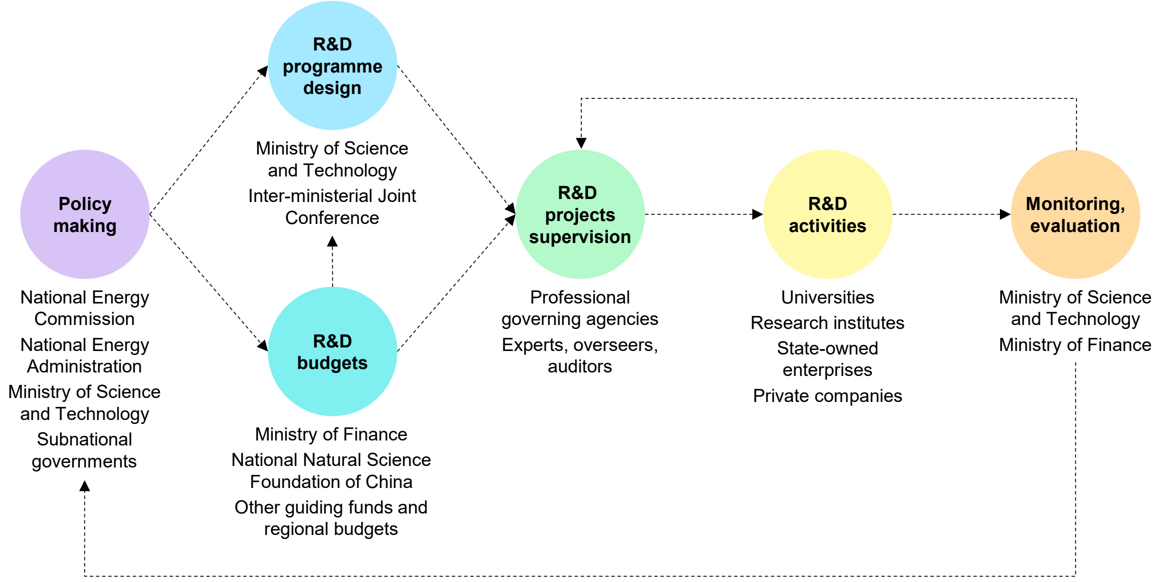
Out of the 15 National Major S&T Innovation Projects put forward in the 13th FYP for Science and Technology Innovation, at least four were directly relevant to energy and another on materials indirectly; over 20 out of more than 100 proposed Key R&D Projects were relevant to energy fields. Together, these research projects aspire to cover all technology areas mentioned in the FYPs. Given the high-level directions signalled in 14th FYP documents, many of the R&D projects running in the 13th FYP period are expected to continue in the next cycle.

In the first half of 2021, MOST opened 55 R&D project areas for consultation for National Key R&D and Key Special Projects, among them hydrogen, energy storage and smart grids, new energy vehicles, and rare earth materials. It announced that 784 R&D projects would be supported in the first year of the 14th FYP (2021-2025) with about CNY 20 billion (about USD 3 billion) in funding. The ministry issued specific guidelines for focus areas and eligibility requirements, such as for 18 R&D project areas in hydrogen technologies, 18 in new energy vehicles, 20 in energy storage and smart grids, and 33 in rare earth new materials with implementation periods of three to five years. In each area, several projects can run in parallel and benefit from state funding. Several plans have followed and others are yet to be published. Each includes budgets, procedural guidelines and requirements for applicants, possible focus areas, assessment indicators and reporting methods. Some roadmaps may also be supported by international knowledge partners, such as the CCUS demonstration and deployment roadmap developed in 2015 in collaboration with the Asian Development Bank.

Subnational levels of government are also involved. For example, MOST issued the framework for Hydrogen to Ten Thousand Homes project in Shandong in collaboration with the Shandong Provincial Science and Technology Department, which allocates state funding of up to CNY 150 million (up to USD 20-25 million) for projects in the region. Shandong province announced over CNY 30 billion (about USD 4.5 billion) of hydrogen industry investments this year, and the provincial capital Jinan plans to set up three hydrogen R&D platforms by 2022 as part of its Action Plan for the Development of Jinan Hydrogen Energy Industry (2020-2022). Similarly, Guangdong Province published the Action Plan for Accelerating the Construction of Fuel Cell Vehicle Demonstration City Clusters (2021-2025).

To design R&D programmes, MOST gathers an inter-ministerial joint conference, which partly overlaps with the members of the NEC and includes relevant administrations, an advisory board comprising science and industry experts, and professional governing agencies (PGAs), which are mandated with overseeing research activities and evaluating results. There are seven PGAs in total, including four under MOST, such as ACCA21. For the 14th FYP cycle, MOST kick-started high-level design of national programmes in the beginning of 2020 and collected information through consultations about 16 000 major R&D needs from 67 departments and 2 400 scientific research units.

Process from policy making to implementation and evaluation of R&D activities



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Programmes usually kick off in the year following the FYP and run for a period of five years. In the 13th FYP for Energy Technology Innovation, the majority of proposed energy R&D projects ran over the 2016-2021 period, with some larger projects notably for demonstration running until 2025. A few current R&D projects under the supervision of MOST run over the 2017-2022 and 2018-2023 periods. The Energy Technology Revolution and Innovation Action Plan (2016-2030) aims to provide continuity for programmes that span across multiple FYPs.

In practice, each project comes with dedicated implementation plans and performance objectives and targets to deliver on longer-term technology roadmaps. Additional guidance documents may be published every year to refine targets and update priorities based on progress. Projects are then broken down into research activities, each with a narrower focus and specific milestones. PGAs scope the projects and then issue calls for applications for interested parties (e.g. research institutes, universities, SOEs, private businesses, China-based affiliates of overseas entities) to implement and achieve the proposed targets. PGAs select which entities may lead activities on a given project, ultimately reporting to MOST. Halfway through the period, for example two years after implementation for a project spanning over the FYP, a mid-term assessment of progress may be carried out. Upon expiration of the project's period, PGAs evaluate outputs and whether targets have been achieved, feeding back into subsequent funding decisions.

Selection of R&D projects announced by MOST for the 14th FYP cycle (2021-2025)

Technology area	Possible project focus areas
Hydrogen *Planned state funding for national projects: CNY 795 million (USD 125 million)*	National projects: • Production of low-carbon hydrogen by electrolysis with renewables • Low-cost materials for proton exchange membranes, and high-efficiency electrolysers • Methanol production through electrolytic hydrogen and CO_2 • Ammonia production through electrolytic hydrogen and nitrogen • Hydrogen storage, transportation and distribution technologies • Hydrogen high-efficiency power systems and fuel cells
Planned state funding for Shanding projects: CNY 150 million (USD 25 million)	Projects in collaboration with Shandong province: • Production of low-carbon hydrogen by electrolysis with renewables • Hydrogen power systems and fuel cells for various applications (e.g. automobiles, ships, cargo, public transportation, buildings) • Hydrogen supply pipelines • Refuelling infrastructure for vehicles, on highways and in ports • Hydrogen production and use onsite in industrial parks
New energy vehicles *Planned state funding: CNY 860 million (USD 135 million)*	• Advanced battery designs (e.g. all-solid-state metal lithium) • Solid oxide fuel cells for vehicles • High-density and large-capacity gas and hydrogen storage and supply systems for heavy vehicles • Pure electric buses and heavy-duty vehicles • New electric drive systems • Hybrid engines and high-efficiency electromechanical coupling • Intelligent and autonomous driving technologies • Vehicle network integration and charging infrastructure
Rare earth materials *Planned state funding: CNY 347 million (USD 55 million)*	• Rare earth permanent magnet materials, for applications such as in electric motors for new energy vehicles • High-efficiency rare earth optical functional materials, for applications such as in photovoltaics • High-energy density rare earth materials, for applications such as in hydrogen energy and energy storage • Superlattice rare earth hydrogen storage electrode materials • Special rare earth functional allow, for applications such as in nuclear safety, vehicle lightweighting and motors • Rare earth recycling
Energy storage and smart grids *Planned state funding: CNY 667 million (USD 105 million)*	• GWh lithium-ion battery energy storage system for grid integration of high shares of intermittent renewables • MWh solid-state lithium-ion battery designs • Metal sulphur-based batteries • Short-term high-frequency energy storage • Grid technologies including flexible DC converter platforms for offshore wind, large AC/DC hybrid power grids, and low-frequency power transmission • Multi-user supply-demand interaction and flexibility, virtual power plants, distributed energy resources

Sources: Summary of 2021 project application guidelines; Summary of the requirements of the form review of key special projects; Notice for the key special projects on hydrogen; Notice for the "Hydrogen to Ten Thousand Homes" project; Notice for the key special projects on new energy vehicles; Notice for the key special projects on rare earth new materials; Notice for key special projects on energy storage and smart grids.

National Major S&T Innovation 2030 Projects relevant to energy under the 13th FYP for S&T Innovation developed by MOST (2016-2020)

Project scope	Focus areas
1. Large oil and gas fields and coalbed methane development (Major S&T Project)	• Deep-sea oil and gas exploration and development technologies and equipment • Shale gas equipment • Coalbed methane technologies • Recovery of complex oil and gas fields • Oil and gas industrial equipment
2. Large advanced pressurised water reactor and high-temperature gas-cooled reactor nuclear power (Major S&T Project)	• CAP1400 pressurised water reactor shielded main pumps, control systems, fuel components • High-temperature reactor steam generators, fuel systems, nuclear-grade graphite • 200 MW high-temperature gas-cooled reactor demonstration (2017) • CAP1400 demonstration project (2020)
3. Clean and efficient use of coal (Major Engineering Project)	• High-efficiency coal production (e.g. below 305 g CO_2/kWh) • Coal conversion • Coal pollution control (e.g. reduce emissions of conventional pollutants by 50% relative to current levels) • CCUS (e.g. demonstration of post-combustion capture to achieve 1 million tonnes/year) • Modern coal chemical and polygeneration technologies
4. Smart grid technology and equipment (Major Engineering Project)	• Large-scale renewable energy grid-connected control (e.g. with 250 GW of wind power and 150 GW of solar) • Flexible interconnection of large power grids • Demonstration of +/- 1 100 kV DC power transmission) • Multi-user interactive power supply and demand • Smart grid equipment and systems
5. New materials (Major Engineering Project)	• Carbon fibre and composite materials • High-temperature and special alloys for high-end equipment • Advanced semiconductor materials • New rare earth materials

Note: Projects are ranked in the order of appearance in the 13th FYP for Science and Technology Innovation (2016-2020).
Source: 13th Five-Year Plan for Science and Technology Innovation (2016-2020).

Selection of National Key R&D Projects relevant to energy under the 13th FYP for Science and Technology Innovation developed by MOST (2016-2020)

Project scope	Focus areas
1. Safe, clean and efficient coal development and utilisation and new types of energy conservation	See previous table
2. Renewable and hydrogen energy technology	• Solar • Wind • Biomass • Geothermal • Ocean energy • Hydrogen • Renewable energy coupling and systems integration technology
3. Nuclear safety and advanced nuclear energy technology	• Advanced nuclear fuel, spent fuel reprocessing and waste treatment • Nuclear safety, risk and severe accident management • Ultra-high temperature gas-cooled reactors • Advanced fast reactors • Supercritical water-cooled reactors • New modular small reactors
4. Smart grids	See previous table
5. Energy-efficient buildings	• Technical standards for ultra-low-energy buildings • Building energy evaluation systems • Energy-saving integration and high-efficiency cooling technology • Active/passive multi-energy systems • New types of daylighting and efficient lighting
6. New energy vehicles	• EV battery and battery management system • Motor drive and power electronics • EV smart technologies • Fuel cell power systems • Plug-in/extended hybrid system • Pure electric power system • Equipment for manufacturing and production chains
7. Rail transportation	• High-speed trains and associated equipment • Inter-European railway interconnection • Energy-saving technology
8. Marine transportation	• Cleaner and smart shipbuilding and associated equipment • Ship operation and maintenance smart systems
9. Air transportation	• New energy civil aircraft production and associated equipment • Air traffic control systems
10. Biomanufacturing	• Manufacturing of major chemical products • New bioenergy sources • Biotransformation of organic waste gaseous CO_2 resources • New sources of industrial materials and manufacturing processes

Project scope	Focus areas
11. Prevention and control of air pollution	• Dynamics of haze and ozone formation, and monitoring • Pollution control and relationship with public health • Technologies for desulphurisation, de-nitration, dust removal, volatile organic compound control, diesel engine emissions purification • Air pollution and quality monitoring and control systems
12. Cleaner production in manufacturing	Pollution emissions reduction from industry sources, with a focus on steel and chemicals production
13. Coal resources development	• Smart coal resource exploration • Large mine construction • Carbon emissions control in mining areas • Cleaner processing and more comprehensive utilisation of coal
14. Oil and gas resources development	• Drilling, production, storage and transportation equipment, tools, software and materials • Unconventional oil and gas resources
15. Urban development	• Electricity-gas-thermal energy systems and networks • Smart cities
16. Green and prefabricated buildings	• Near-zero energy building planning and design • High-efficiency heating solutions • Application of digital technologies in building design, construction and operation and management • Prefabricated buildings and concrete and steel structures
17. Deep-sea exploration	See previous table
18. Large-scale offshore engineering equipment	• Deep water semi-submersible drilling platforms and vessels • Floating liquefied natural gas production, storage, offloading and regasification equipment
19. Deep earth resource exploration	• Deep-earth mineral extraction equipment • Exploration for oil and gas resources at depths of 8-10 km • Exploration for minerals (including uranium) at depths of 1-3 km
20. Polar resource exploration	Oil and gas exploration and natural gas hydrate resource development in polar regions
21. Strategic basic research and major forward-looking scientific issues	• Physical and chemical bases for the efficient and clean utilisation and conversion of energy • Earth system processes and resources and environmental and disaster effects • New principles and new methods for the design and preparation of new materials • Synthetic biology • Scientific research on deep sea and deep ground • Development of magnetically constrained nuclear fusion energy

Note: Project proposals are ranked in the order of appearance in the 13th FYP for Science and Technology Innovation (2016-2020), and focus areas may overlap in some instances.

Source: 13th Five-Year Plan for Science and Technology Innovation (2016-2020).

Resources for energy innovation

Introduction

This section reviews the resources available for energy innovation in China. Specifically, it tracks a selection of innovation input metrics such as public energy R&D spending, energy R&D spending by Chinese globally listed companies, venture capital investments in clean energy start-ups, and human capital development including R&D personnel.

Key takeaways

- China has become the world’s second largest public spender in energy R&D (about USD 8.4 billion in 2020) after the United States, surpassing other established technology hubs such as Japan and Europe. Per units of GDP, China ranked eighth.
- While budgets allocated to low-carbon technology development have been steadily increasing in line with Mission Innovation pledges, and is second only to the United States in terms of clean energy R&D spending, China allocates a substantial part of its budget to fossil fuel research.
- In recent years, China has become a clean energy venture capital powerhouse, led by electric mobility start-ups. These have reaped the benefits of support from government including public funds, SOEs and universities.
- China is promoting a culture of innovation and seeking to develop a skilled workforce able to advance the country’s technology development ambitions. The number of R&D personnel is greater in China than in any other country – even though it still lags behind per capita – and youth is increasingly educated.

Public funding for energy innovation

Public spending for energy R&D in China significantly increased under the 13th FYP, from about USD 7.3 billion (CNY 49.0 billion) in 2015 to USD 8.4 billion (CNY 57.0 billion) in 2020, based on IEA tracking. This increase has enabled China to become the world's second largest energy R&D spender in absolute terms after the United States, and eighth globally per units of GDP. Energy accounted for about 5.5% of China's public expenditures for R&D.

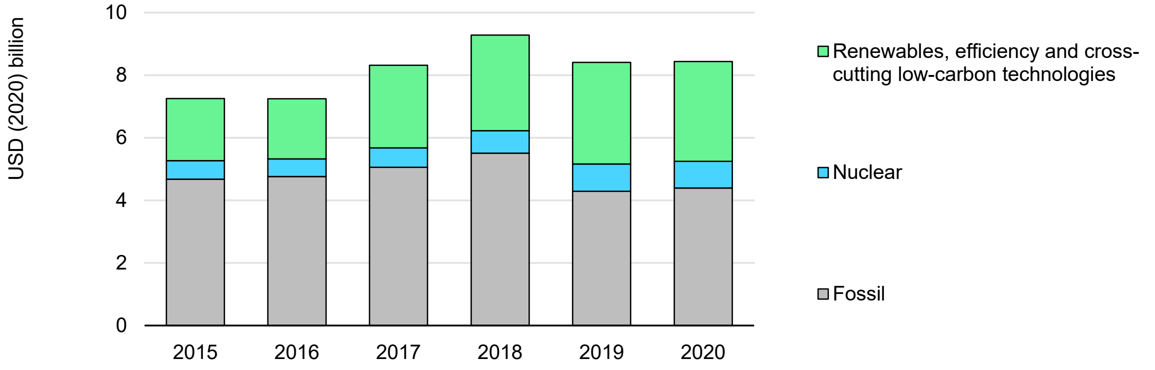
In 2015, China pledged under Mission Innovation to double clean energy R&D spending over a five-year period coinciding with the 13th FYP. This pledge included a substantial amount of R&D spending dedicated to a more efficient use of coal, including CCUS. The latest data suggest that China nearly met its target in 2020. Estimates based on reportings to Mission Innovation suggest China's low-carbon energy R&D spending steadily increased from USD 2.6 billion (CNY 17.4 billion) to USD 4.0 billion (CNY 27.3 billion) over the 2015-2020 period, which corresponds to a 60% increase, while GDP grew by about 30% over the same period. As a result, low-carbon budgets increased their share within overall energy R&D budgets from 35% to nearly 50%.

While total spending decreased in 2019, the slowdown was due to drops in non-low-carbon energy R&D spending – and reflects the end of the FYP period. Increasing budgets have enabled China to rank second globally in terms of absolute low-carbon energy R&D spending, behind the United States.

Until today, China's public energy R&D budgets have mostly been allocated to the development of fossil fuel-related energy technologies, such as the cleaner and more efficient use of coal, and oil and gas resource exploration and development. In fact, China is by far the world's top spender on fossil energy R&D. Trends during the 13th FYP – notably since Mission Innovation pledges in 2015 – and expectations for the 14th FYP suggest an increasing focus on low-carbon energy technologies, but this warrants further analysis over the 2021-2025 period.

Limited data granularity makes in-depth analysis and tracking challenging, particularly at the technology level. For example, flagship MOST funding (e.g. formerly 973 and 863 programmes) accounted for only about USD 800 million over the 2006-2010 period, leaving budget gaps that could be explained by demonstration projects, spending made by SOEs, or other programmes not managed by MOST. There are also uncertainties related to investments made by SOEs, which are estimated to account for about 80% of public energy R&D investments, particularly in the coal industry and power and heat sectors, in which most major companies are state-owned.

Public spending in energy R&D in China from 2015 to 2020



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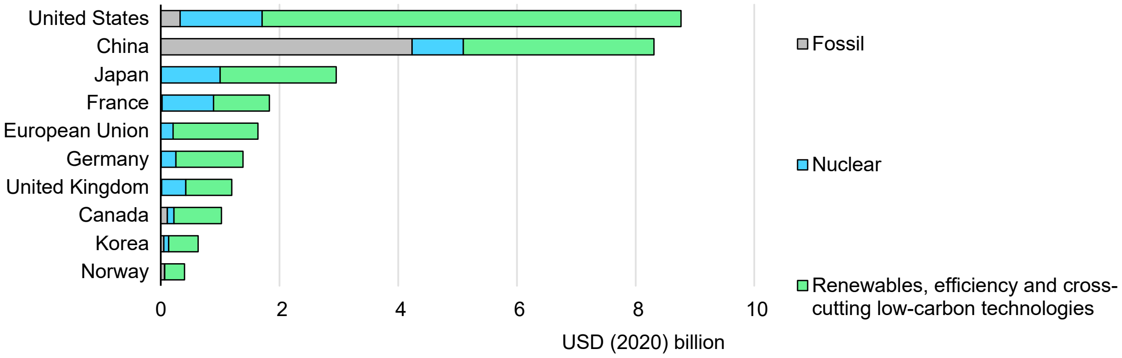
Note: Due to data availability limitations, CCUS spending is counted under "Fossil".
Source: IEA analysis based on official data and Mission Innovation reporting.

Top spenders globally in energy R&D in 2020



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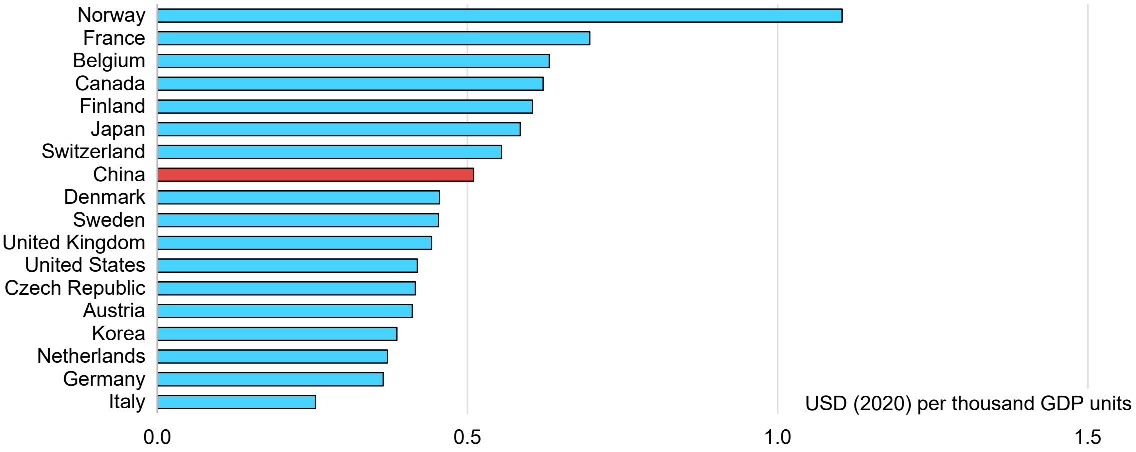
Note: Due to data availability limitations, CCUS spending is counted under "Fossil".
Source: IEA analysis based on country submissions to the IEA, official data and Mission Innovation reporting.

Public spending in energy R&D per thousand units of GDP in 2020



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Source: IEA analysis based on country submissions to the IEA, official data and Mission Innovation reporting.

Energy innovation in the business sector

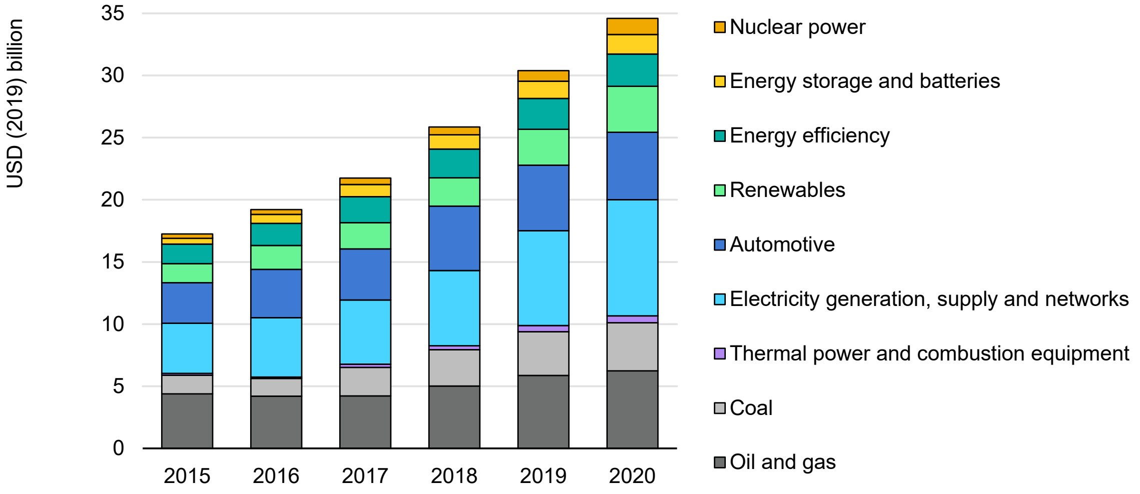
Energy R&D spending by global Chinese companies

IEA estimates of R&D spending by globally listed companies suggest that Chinese companies – either state-owned, private or with mixed ownership – spend more on energy R&D than in any other country.

In 2020, Chinese firms spent nearly USD 35 billion on energy R&D, a 15% increase relative to 2019, against about USD 30 billion in Europe, USD 17.5 billion in Japan and USD 15 billion the United States in the same sectors. Most of these budgets are allocated to the development of cleaner or more efficient use of fossil fuel technologies. Oil, gas and coal are estimated to account for about 30% of total investments, ahead of power and grids (27%) and far ahead of automotive (16%), renewables (11%), batteries, hydrogen and energy storage (5%), and nuclear (4%). Spending on fossil fuels has been steadily increasing in recent years. Spending on renewables more than doubled over the 2015-2020 period coinciding with the 13th FYP; tripled for batteries, hydrogen and energy storage; and quadrupled for nuclear.

In hard-to-decarbonise sectors such as heavy industry and long-distance transportation, Chinese companies have also steadily increased total R&D spending, although it is expected that only a fraction of these budgets will be allocated to the development of new low-carbon energy technology applications. Iron and steel attracted over USD 12 billion in R&D investments in 2020, about USD 11 billion in chemicals, and nearly USD 1 billion in cement. Companies developing drivetrains and other technologies for trucks and commercial vehicles spent about USD 2 billion, and USD 1.9 billion went for shipbuilding, USD 1.7 billion for aviation (up from virtually no spending in 2015) and USD 1.4 billion for rail. Expectations for the 14th FYP suggest that Chinese enterprises may accelerate energy innovation activities relevant to cement and steel production, such as through the private-led launch of demonstration projects for CCUS applications.

Estimated energy R&D spending by globally listed companies headquartered in China, by technology area, 2015-2020



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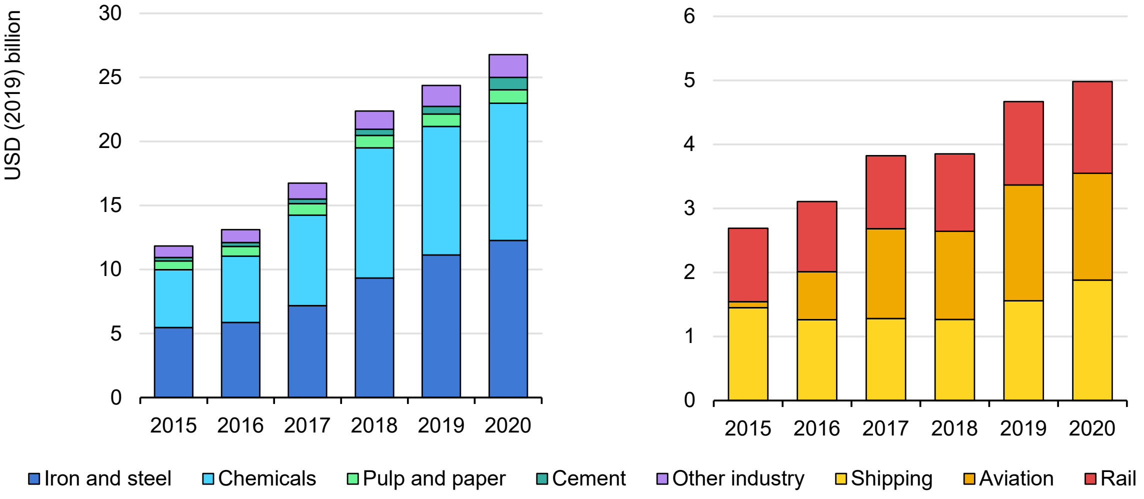
Notes: Fuel cells and hydrogen are included in “Energy storage and batteries” and account for only a fraction of the category. “Energy efficiency” includes appliances, lighting and heating and cooling technologies, but excludes electrical components. Corporate energy R&D spending includes reported R&D expenditure by companies in sectors that are dependent on energy technologies, including energy efficiency technologies where possible. Automotive includes technologies for fuel economy, alternative fuels and alternative drivetrains including trucks. To allocate R&D spending for companies active in multiple sectors, shares of revenue per sector are used in the absence of other information. Classifications are based on the Bloomberg Industry Classification System. All publicly reported R&D spending is included, hence companies that do not disclose R&D spending are underrepresented. Depending on the company, publicly reported corporate R&D spending can include capitalised and non-capitalised costs, from basic research to product development.

Source IEA calculations based on Bloomberg data.

Estimated R&D spending by globally listed companies headquartered in China with activity in heavy industry and long-distance transporation



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Notes: “Other industry” includes industrial furnaces and ovens, metalworking machinery, flow control equipment, industrial trucks, plastics and rubber, recycling and woodworking.

Source IEA calculations based on Bloomberg data.

The role of Chinese enterprises in innovation

Estimates of R&D budgets allocated by Chinese companies are in part blurred by the overlap between business and public sectors in China given the prominent role of SOEs, especially in the energy sector. Historically, there have been close links between SOEs and funding for R&D available by MOST, such as through the National Major S&T and Key R&D Projects. This has given a central role to SOEs in innovation alongside other publicly led institutions, universities and research institutes, while private companies typically played a smaller role until the 2010s. This is still the case today in certain fields of strategic importance such as nuclear power, coal and other fossil fuels. The close ties between SOEs and the government imply that R&D initiatives financed by SOEs often align well with national priorities. SOEs also benefit from stronger financial support and political connections relative to private firms (e.g. preferential costs of borrowing), especially from state-owned banks. Meanwhile, private companies have been central actors in solar PV, EV and battery technology development, illustrating a possible strengthening of their role in Chinese innovation.

Successive FYPs in the last decades have progressively encouraged companies, both public and private, to strengthen their role in energy technology innovation. In 2006, the National Medium and Long-Term Science and Technology Development Plan (2006-2020) already encouraged enterprises to become the “mainstay of technological innovation”. The 13th FYP (2016-2020) also aimed to “strengthen the position of enterprises as principal entities for innovation”, and planned to set up corporate technology centres, support public start-ups, and offer advantageous R&D tax credits and public procurement of innovative products.

In 2019, the NDRC published policy guidelines on Building a Market-Oriented Green Technological Innovation System, which underscore the “the main role of enterprises in green technology research and development, transformation of results, demonstration applications and industrialisation”, and aim to build “a group of leading enterprises in green technology innovation”. The notice also included specific targets for the 2019-2022 period, in collaboration with MOST, such as:

- Identifying 1 000 green technology innovation enterprises.
- Establishing 100 green enterprise technology centres.
- Supporting 10 leading green technology innovation enterprises with an annual output of over CNY 50 billion (about USD 8 billion).
- Increasing support for corporate green technology innovation, with the view to reach a share of Major National S&T Projects and National Key R&D Projects led by enterprises of over 55%.

The 14th FYP features a dedicated chapter on “Enhancing the enterprise's technological innovation capability”. In 2021, President Xi explained China’s goal to enhance innovation at all stages of the industrial chain and increase "technological self-reliance" by establishing enterprises as "the mainstay of innovation". Specifically, the government seeks to encourage all enterprises – and central SOEs in particular – to increase R&D spending through extra deductions for R&D expenses and tax incentives, and to take the lead in the implementation of Major National S&T and National Key R&D Projects. The strategy also involves setting up collaborative partnerships with other enterprises, universities and research institutes; promoting regional clusters with mixed ownership with local government; facilitating access to finance including through venture capital; and providing special support to small and medium enterprises. In 2020, the Chinese Securities Regulatory Commission also set stricter requirements for R&D spending – more than 5% of operating income – and ownership of patents of invention to list on the Shanghai Stock Exchange's Science & Technology Board.

As in many other countries and regions including the United States, Japan, South Korea and Europe, a large share of China's total R&D spending comes from business actors. In 2015, estimates suggested that over 60% of China's total energy budgets for R&D and demonstration came from private industry sources, against 35% from SOEs and government entities. According to data from the Organisation for Economic Co-operation and Development (OECD), in 2019 over 75% of Chinese R&D budgets came from business enterprises, against about 15% from government bodies and 10% from institutions of higher education. In comparison, business actors accounted for only 60% of total R&D spending in 2000, against 30% from government, illustrating their strengthening role.

While the business sector accounts for a large share of total and energy R&D spending, enterprises mostly focus on experimental development, product and manufacturing innovation, whereas public institutions and higher education focus on earlier stages such as basic and applied research. OECD data show that in 2019, over 95% of Chinese enterprises' R&D budgets were allocated to experimental development, much more than government bodies (50%) and institutions of higher education (10%), which spent greater shares on basic (15% for government, 40% for higher education) and applied research (30% government, 50% higher education). This difference suggests that the public and private sectors fund non-substitutable types of R&D. Under the right conditions, SOEs may be well placed within China's innovation system to bridge potential gaps between lab and market.

Venture capital activity in clean energy

In recent years, China has become a clean energy VC powerhouse, led by the transport sector. VC investments are an important source of funding for start-ups to develop new energy products and services and bring emerging technology concepts to markets. They represent a valuable complement to public and private energy R&D budgets. Tracking early-stage investments can help identify trends and investor appetite for relatively less mature technologies.

An increasing role for start-ups in China

Business innovation and start-ups have not always been core to China's innovation strategy to develop pre-commercial technologies. Since the 13th FYP, however, more emphasis has been put on supporting entrepreneurs, in complement to traditional publicly led R&D programmes. While the 12th FYP (2011-2015) only briefly mentioned the role of start-ups in China's innovation ecosystem, the 13th FYP (2016-2020) dedicated a full chapter to "Encourage public startups and innovations".

The 13th FYP for Science and Technology Innovation sought to develop VC investments, including government-backed VC such as through the China State-Owned Capital Venture Capital Fund, which targets investing over CNY 200 billion over time (over USD 30 billion), and the National Emerging Industry Venture Capital Investment Guidance Fund, which targets CNY 40 billion (USD 6 billion). The 13th FYP also aimed to provide public services for start-ups in all counties, improve employment conditions for innovators and establish demonstration areas for start-ups. This was in line with the National Innovation-Driven Development Strategy published in 2016, which included sections on entrepreneurship to promote "incubation + venture capital" models as well as innovation in micro and small enterprises.

China's "guidance funds" help support strategic industries and start-ups

In 2015, China established new special public funds to support new companies in strategic emerging industries, promote mass entrepreneurship and accelerate industrial upgrading. The government also published associated guidelines on ways to set up and operate such a fund. While this announcement came as part of a wave of launches of new funds, the concept of public "guidance funds" was not new and had been piloted since at least the 2000s, such as through the Zhongguancun Venture Capital Guidance Fund.

In practice, guidance funds are asset management companies selected after public bidding to operate and manage central, regional and local government funds, with the view to invest in companies and attract other investors. Guidance funds report to the government – a limited partner of the investor – but keep some independence in operational decisions. They may be overseen by ministries or directly managed by public institutions and SOEs. They are encouraged to collaborate with local actors and industry including through equity participations. Returns are distributed to all partners or reinvested in the fund.

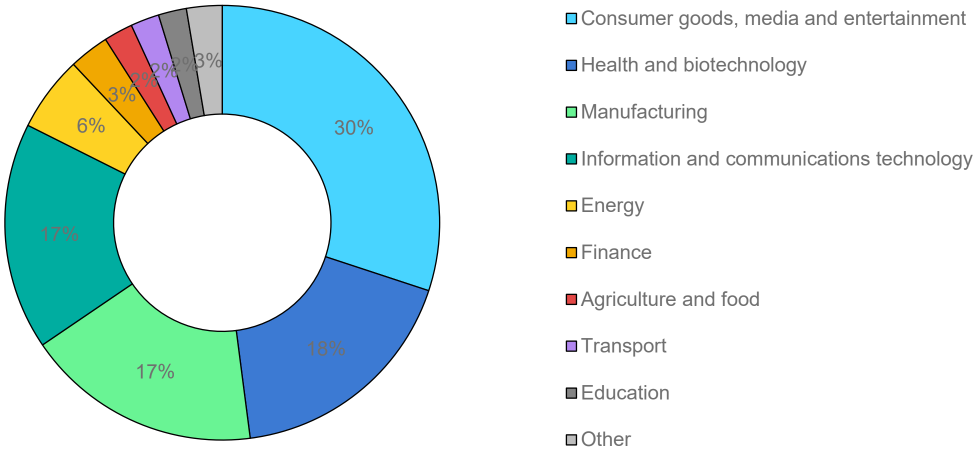
As of 2019, there were nearly 1 700 government guidance funds, managing over CNY 4.1 trillion (USD 650 billion) and aiming to invest over CNY 10.1 trillion (USD 1.6. trillion) over time. A small number of them account for a large share of total activity. In 2019, there were 18 guidance funds created between 2014 and 2018 accounting for about CNY 3.0 trillion (USD 470 billion) in funding targets – a third of the government's overall target. Some of the largest funds include the China State-owned Enterprise Structural Adjustment Fund, which targets over CNY 350 billion (USD 55 billion) and has invested in oil and gas and power projects, and the Yangtze River Economic Belt Ecological Fund, which targets over CNY 300 billion (USD 50 billion) of investments over time. Some funds focus on specific segments of the economy, such as the State-owned Enterprise Guochuang Investment Guidance Fund, which targets CNY 150 billion (USD 25 billion) of investments primarily in aerospace, nuclear energy, shipbuilding, high-speed rail, equipment for power and grids, clean energy, new energy vehicles, and other high-tech fields.

Although many of the guidance funds do not invest in start-ups specifically, an increasing number have been focusing on innovative, early- to mid-stage companies in recent years. The National Emerging Industry Venture Capital Guidance Fund was established in 2015 under the NDRC with three funds managed separately, and targets aggregate investments of CNY 40 billion (USD 6.5 billion). MOST, the Ministry of Finance and the Chinese Academy of Sciences oversee the National Science and Technology Achievement Transfer and Transformation Fund, which holds over 30 VC sub-funds with target investments of CNY 25 billion (USD 4 billion). The State-owned Assets Supervision and Administration Commission manages the China State-Owned Capital Venture Capital Fund, which targets CNY 200 billion (USD 30 billion). MIIT manages the National SME Development Fund, which targets CNY 60 billion (USD 9.5 billion) for seed and growth stages of start-ups and SMEs.

Ahead of the 14th FYP period in 2020, the Ministry of Finance reformed the mechanism to address inefficiencies identified in the 13th FYP period, such as risks of duplication across different funds, idle funds and fragmentation of resources. The new guidelines notably tighten conditions to access government funds in case of low performance and require clearer expectations in terms of exit strategies (e.g. duration, termination clauses). They also embed more rigorous tracking and reporting of performance with quantitative indicators.

China's start-up ecosystem has been burgeoning across all sectors of the economy, particularly since around 2015. Pitchbook data suggest that in 2020, Chinese VC-backed companies raised nearly USD 60 billion in total, recovering well from 2019 and reaching the second-highest point this decade. Urban tech hubs such as Beijing, Shanghai and Hangzhou account for much of the growth since 2015. Taken together, the three cities are home to 75% of Chinese unicorns, start-ups with a value of over USD 1 billion. Consumer goods, manufacturing, and information and communication technology (ICT) are sectors with highest activity recorded to date. In 2020, health was also on the rise – the only sector where growth was recorded from 2019. However, IEA estimates based on Crunchbase data suggest that energy (6% in cumulative investments over 2019-2020) and transport (2%) generally attract less early-stage funding. Official data show that energy in 2019 attracted as much VC as semiconductors or medicine and health.

Sectoral distribution of early-stage venture capital investments in Chinese start-ups in 2019 and 2020



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Notes: Includes angel, pre-seed, seed, series A and B financing rounds. Investments in 2019 and 2020 are cumulative, by primary field of company activity.
Source: IEA analysis based on Crunchbase data.

Large deals in EV start-ups dominate China's energy VC

In China, overall clean energy VC activity – focusing on early-stage deals such as seed, series A and B financing rounds – remained low until 2010-2011, when investments in clean technology start-ups increased. In 2012 and subsequent years, the bubble burst in China as in other areas of the world. However, clean energy VC investments recovered in China from 2015 onwards in an earlier wave than in other countries or regions, led by domestic investors and notably with a series of very big early-stage deals of above USD 150 million in a single financing round. While 2019 had been set for a promising trend in terms of volume and sectoral diversity, the Covid-19 pandemic slowed progress down. In 2020, investments fell drastically and China fared worse than other regions. There appears to have been a quick recovery in 2021, particularly in transportation, energy storage and batteries, hydrogen and fuel cells, and renewables.

Between 2015 and 2020, a cumulative USD 10 billion were invested, aggregating to 33% of global early-stage financing rounds against 40% in North America and 17% in Europe, and very big deals accounted for most of these investments. The typical early-stage deal size witnessed in China in recent years may indicate a different approach to seed and series A-B financing relative to other countries. Both public and private investors in China appear prepared to invest more capital faster – and take on more risk as a result – for a quick and direct scale-up, including in instances where there are already existing VC-backed domestic competitors, such as in electric mobility.

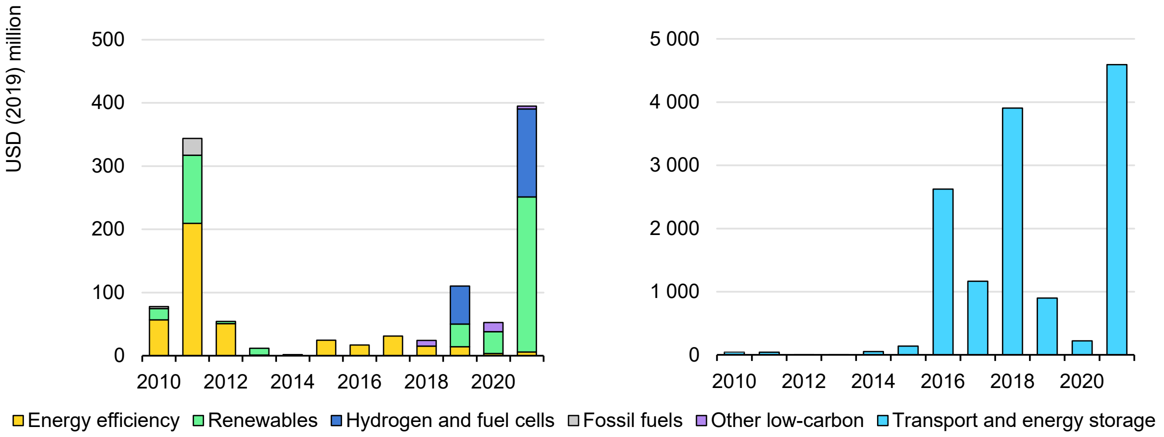
China's energy VC ecosystem has channelled most funding to companies developing low-carbon transport technologies such as EVs and charging. The importance of EV technologies relative to other areas (e.g. renewables, energy efficiency, storage and hydrogen) may reflect the confidence of investors in the market prospects for EVs in China and globally, and in the ability of Chinese companies to scale up and penetrate global markets faster than the competition.

Between 2016 and 2021, a series of VC mega-deals took place in China's electric mobility sector. Together, a small group of nine EV technology start-ups all founded since 2014 successfully raised over USD 15 billion over the period, from early-stage investments up to initial public offering (IPO) and follow-on financing. Years 2016 and 2018 were particularly active, and while appetite for large early-stage investments appears to have dried up by 2020, growth-stage financing remains strong.

For example, Xpeng Motors listed on the stock exchange in the United States, raising USD 1.5 billion; Enovate Motors announced pre-IPO financing of over USD 700 million; and WM Motor raised USD 1.5 billion in growth equity followed by USD 2 billion in debt. In 2021, battery innovator and manufacturer Svolt, a spin-off of Chinese automobile manufacturer Great Wall Motors, also raised over USD 3 billion, illustrating the progressive development of an EV and associated components ecosystem in China. Companies typically reported using the first rounds of financing for technology R&D and product development and to set up factories and manufacturing lines, and subsequent funding for scale-up, market expansion and to set up EV industry investment funds in some instances.

Electric mobility now accounts for a greater share of China's start-ups having reached unicorn status, which refers to a valuation over USD 1 billion. In 2020, EV technology start-ups accounted for 6% of these, equal to the share of other transport start-ups. This trend is notable for the energy sector, which typically generates few start-ups reaching such valuations, especially in only a few years.

Early-stage venture capital investments in energy start-ups in China, by technology area (2010-2020)



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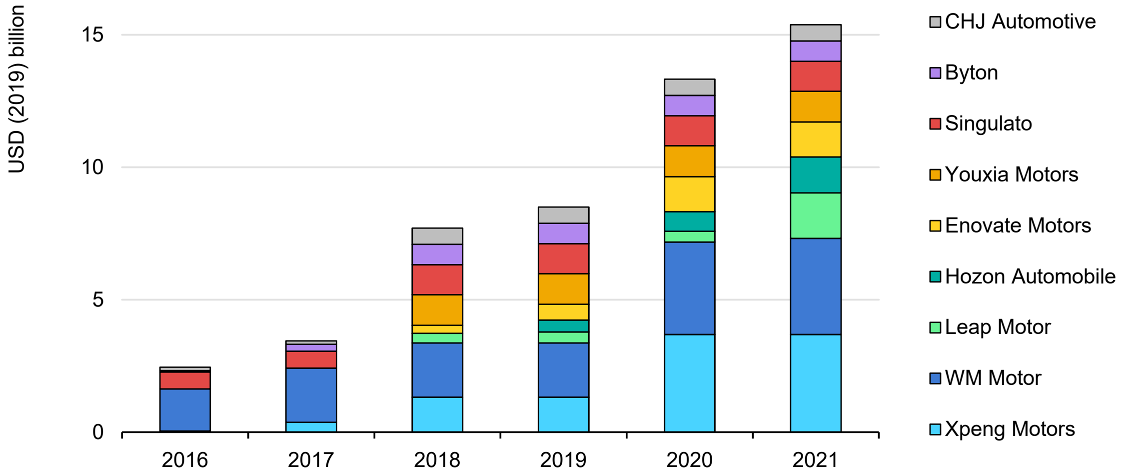
Notes: Includes seed, series A and B. “Energy storage” mostly includes battery manufacturers for EVs.
Source: IEA analysis based on Cleantech Group i3 database.

Venture capital investments in selected Chinese electric mobility start-ups (2010-2021)



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Source: IEA analysis based on Cleantech Group i3 database.

Public support was instrumental in bringing the selected EV companies to industrial scale in just a few years. The government typically provided financial support through the investment branches of large SOEs in the automotive, mining, power equipment or other energy-relevant industries, as well as public investment funds at national and subnational levels. Some start-ups also benefited from university-level support and funding, such as through Tsinghua University Holdings. In many cases, local government at the provincial and city levels played an active role in building R&D infrastructure and manufacturing capability to support industrial development, in addition to providing direct financial support.

Official data show that in 2019, SOEs accounted for about 15% of VC investments, about as much as government-led funds. Meanwhile, private companies in industry segments relevant to EVs (e.g. Contemporary Amperex Technology Co. Limited [CATL]) and non-traditional energy actors (e.g. Alibaba, Baidu, Foxconn, Tencent Technology) also provided funding.

China's start-up ecosystem has successfully built several large EV start-ups from the ground up in a matter of years. These success stories open significant opportunities to position the country in global supply chains for EVs, and could provide a template for other low-carbon energy technologies. The number of public actors involved illustrates the government's push to develop the EV industry. Relative to other countries, China's government bodies and SOEs (including with provincial competition) are significantly more involved in clean energy VC. However, there are concerns that the wide availability of cheap finance, especially through state-backed VC and "guidance funds", could lead to over-valuations, preventing smaller private actors from taking part and increasing risks of bust.

Selection of notable public sector support to electric mobility start-ups in China

Company	Selected public support and investments (incl. SOEs)
Xiaopeng (Xpeng) Motors Guangzhou, 2014	• Local: Guangzhou Rural Commercial Bank • National: China International Capital Corporation, Agricultural Bank of China, Bank of China, China Construction Bank, China CITIC Bank • International: Mubadala (Abu Dhabi), Qatar Investment Authority
Leap Motor Hangzhou, 2015	• Local: Shanghai Electric Group (power industry), Industrial Securities Co. (Fujian province), Hefei City
Byton Nanjing, 2016	• National: Tsinghua University Holdings, FAW Group (car company)
WM Motor Shanghai, 2016	• National: China Structural Reform Fund, State Development and Investment Corporation, SAIC Motor Corporation (car company), China Minmetals Corporation (mining company), Tsinghua Holdings via Tsinghua Unigroup, Industrial and Commercial Bank of China, China Construction Bank • Regional: Yangtze River Industry Fund (Hubei), Guangzhou Finance Holdings Group • Local: Shanghai Pudong Development Bank
Singulato Shanghai, 2016	• Local: Tongling Municipal City Investment Fund, Suzhou government
CHJ Automotive Beijing, 2015	• National: Shougang Group Fund (steel company)
Youxia Motors Shanghai, 2014	• Local: Qianhai Equity Exchange (supervised by local government) • Regional: Huzhou Wuxing South Taihu Lake Construction Investment • National: China Environmental Protection Industry Corporation
Enovate Motors (ex DearCC) Shanghai, 2015	• Local: Shanghai Electric Group (power industry), and undisclosed local government industry funds • National: State Grid (industry), and undisclosed state-owned banks
Hezhong Automobile Tongxiang, 2014	• Local: Beijing Synohitec (hydrogen company), Zhejiang Yangtze Delta Region Institute of Tsinghua University (Jiaxing) • National: Undisclosed government industry fund

Source: IEA analysis based on Cleantech Group i3 database.

Talents and human capital

Metrics relating to China's education and training, and availability of R&D personnel have significantly improved in the last two decades. For example, official data show that between 2005 and 2019, the proportion of 20- to 34-year-old Chinese graduating in scientific and engineering fields at college level or above has more than doubled, and the number of full-time R&D personnel per 10 000 inhabitants more than tripled.

Although this goes beyond the scope of energy, the number of R&D personnel in China is greater than in any other country and continues to increase. While the per capita number of R&D personnel remains weaker than in other major innovating countries, the gap is narrowing. In 2019, over 75% of the country's total R&D personnel were employed in enterprises, against about 20% in research institutes and academia. About 45% of R&D personnel are researchers, of which nearly 80% work on experimental development (generally concentrated in enterprises) against 12% in applied research and 8% in basic research (generally in research institutes or academia).

In 2021, President Xi shared China's plans to become a "global talent highland" as the country today faces fierce "talent and education competition". Expectations for the 14th FYP include stronger policy support to foster human capital development; develop innovative talents; train graduates, researchers, engineers and technicians; and reform existing talent evaluation mechanisms. Specific guidelines are included in a dedicated chapter in the 14th FYP to "Stimulate talent's innovation and vitality". These are a continuation of guiding principles from the previous period. In 2019, the NDRC issued policy guidelines for Building a Market-Oriented Green Technological Innovation System, in collaboration with MOST and the Ministry of Education. These aimed to develop "green technology innovation talents", and improved hiring, employment and career opportunities for R&D personnel and innovators.

China has put in place a variety of talent management plans at the national level. In the early 2000s, the government put forward the National Talent Building Plan (2002-2005), a first-of-its-kind programme to foster domestic talents and increase focus on human resources. In 2010, after years of expert consultations, it approved the more ambitious National Medium- and Long-Term Talent Development Plan (2010-2020). The plan intended to attract, train and retain talents in industry segments including equipment manufacturing, ICT, biotechnology, new materials, environmental protection, energy resources and transportation. It involved ramping up domestic training capacity as well as attracting Chinese nationals trained abroad and foreign individuals. The same year, the government issued a white paper on the country's human resources situation, which noted improvements in recent years but identified a remaining "lack of high-level innovative talents" domestically. The notice notably emphasised the importance of strengthening education systems as well as encouraging international exchanges and co-operation.

As part of its overarching strategy, China put in place specific mechanisms to attract foreign talents. The Thousand Talents Programme involved identifying and attracting graduates, experts, professors, innovators and entrepreneurs in high-tech areas and other high-profile talents to come work in China through incentives and financial support (e.g. easier visa procedures, medical care, social insurance, tax deductions). The government set eligibility conditions to ensure these would help achieve national science and technology priorities. In its 2019 notice of the National High-End Foreign Expert Recruitment Plan, MOST identified "industrial technology innovation" and "green development" as key areas. Provincial and local government are also encouraged to take part.

In 2012, together with more than ten other ministries, MOST launched the National Special Support Plan for High-Level Talents, also known as the Ten Thousand Talents Plan, which aims to select 10 000 talents in the fields of natural sciences, engineering, technology, and philosophy and social sciences over ten years, and to provide special support including funding or incentives. The plan fleshed out three levels of talents, including one for 2 000 younger talents aged below 35, and another for 100 talents "at the forefront of world science and technology".

In practice, various agencies, ministries, universities and local government contribute to implementing these high-level plans. For example, the Chinese Academy of Sciences has put in place various fellowship initiatives for international scientific exchanges and research co-operation, such as the President's International Fellowship Initiative, including with other emerging market countries. Research teams and applicants can fill in submissions that are reviewed by government officials. The Ministry of Education, the Ministry of Human Resources and Social Security, and universities implement the Support Programme for Innovative Postdoctoral Researchers. The top five universities receiving most support over the 13th FYP period (2016-2020) were Tsinghua University, Peking University, Shanghai Jiaotong University, University of Science and Technology of China, and Fudan University.

At the subnational level, regions and cities implement national plans by guiding and supporting local candidates. New programmes tailored to local needs may also be in place. In 2017, for example, President Xi shared a new vision for Shanxi province, one of China's largest coal provinces, to become a core actor of the country's energy revolution and a pilot zone for the energy transition. In November 2019, the Shanxi Provincial Department of Human Resources and Social Security issued an Urgently Needed Talents Catalogue in the Energy Sector to help achieve this vision, opening over 250 positions for highly innovative talents to take on responsibilities in the province's energy activities. The plan focused on 16 key technology areas including: solar and wind, bioenergy, internet and smart energy, safer and more efficient coal mining, coal-to-chemicals production, high-end manufacturing equipment, new energy vehicles, and aluminium processing. Among the open positions, 35% were earmarked for coal-related activities such as mining, chemicals production and coal-fired power generation upgrading. There were also mentions of international co-operation, notably under the Belt and Road Initiative.

Shanghai has put in place the Shanghai Pujiang Talent Plan for innovators under the age of 50 and teams willing to work in the city, with incentives to relocate. Financial support may go up to CNY 300 000 per individual or CNY 500 000 per team. The plan is divided into four categories: R&D, enterprise innovation and entrepreneurship, social sciences, and “special urgent needs” based on local government priorities. The city also runs basic research projects under its Science and Technology Innovation Action Plan, with support for academics.

Within SOEs, talents are identified by senior management and given opportunities to rotate among multiple departments, get familiar with the broader organisation and its various functions, and receive guidance from leadership. SOEs also regularly open calls to hire talents globally. For example, in 2020 Sinopec Group launched a high-level talent recruitment programme focusing on oil and gas and petrochemicals. Individuals who recommended such talents to the company would also be financially rewarded. Talents typically benefit from internal support in terms of career development and funding for R&D activities in strategic fields.

In certain sectors of strategic interest, China has put in place dedicated talent development plans. In the nuclear sector, for example, the NEA, the Ministry of Education and Tsinghua University launched in 2017 the International Nuclear Power Talent Training Agreement, with state-owned China National Nuclear Corporation, State Power Investment Corporation and China General Nuclear Power Group. The initiative aims to train talents to prepare for China’s nuclear expansion as part of the “going out” strategy focusing on countries under the Belt and Road Initiative. The launch event was attended by over 100 representatives, including from the following countries: Cambodia, the Czech Republic, Egypt, Indonesia, Iran, Kazakhstan, Laos, Pakistan, Poland, South Africa, Sudan, Tunisia, Turkey, Ukraine and the United Kingdom. The first cohort of fellows graduated in 2019.

In 2018, Xi’an Jiaotong University and Hong Kong Polytechnic University established the Silk Road Institute of Engineering – under the framework of the Silk Road University Alliance – to foster regional co-operation and contribute to talents development. In 2019, the institute launched the Belt and Road Advanced Professional Development Programme in Power and Energy, in collaboration with state-owned State Grid Technology Institute and Hong Kong Electric. The three-year programme focuses on senior managers, executives and researchers and offers two-week trainings with expert training and field trips in various regions. Typical focus areas include ultra-high-voltage transmission, smart grids and city infrastructure. So far, the programme has gathered participants from over ten countries along the Silk Road and beyond, including Brazil, Kazakhstan, Malaysia, Nepal, the Philippines, Russian Federation, Tanzania and Thailand.

Knowledge management and networks

Introduction

This section tracks recent innovation output metrics for China's research institutes and universities (e.g. academic publications, patents), and provides insights relating to China's strategies to develop and acquire knowledge, and foster collaboration among innovation actors domestically and internationally.

Key takeaways

- China's research institutes and universities rank among the most prolific globally in academic publishing in physical sciences and engineering as well as for new energy technologies. The number of highly cited publications is increasing, suggesting quality improvements and broader visibility.
- In addition to its large domestic R&D programmes, China's innovation strategy involves acquiring and importing knowledge such as through joint ventures with foreign multinationals and the acquisition of firms, R&D and technology centres.
- To strengthen its role as a knowledge creator, China has also put emphasis on indigenous technology innovation, improved IP regimes and set incentives to file patents. However, there remain disputes about IP malpractice with trading partners, as well as concerns that "strategic patenting" driven by incentives undermine the average quality of patents.
- In the last decades, China's national knowledge ecosystem has transitioned from a state-directed model towards more collaborative interactions among state, academia and industry. However, science-industry links still lag behind.
- Engagement with the international community and multilateral platforms for energy innovation – such as the IEA Technology Collaboration Programmes and Mission Innovation – has increased in the last 30 years, with efforts to improve trust and make partnerships sustainable. However, high-level engagement does not immediately translate into active collaboration.

Chinese research institutes and universities on the global stage

Public research institutions and universities have historically played a prominent role in knowledge creation in China, and although the role of enterprises has strengthened in the last decade, this is still the case today. Chinese institutions such as the Chinese Academy of Sciences and high-profile universities have also significantly increased their presence on the international stage, such as through scientific publications and patents.

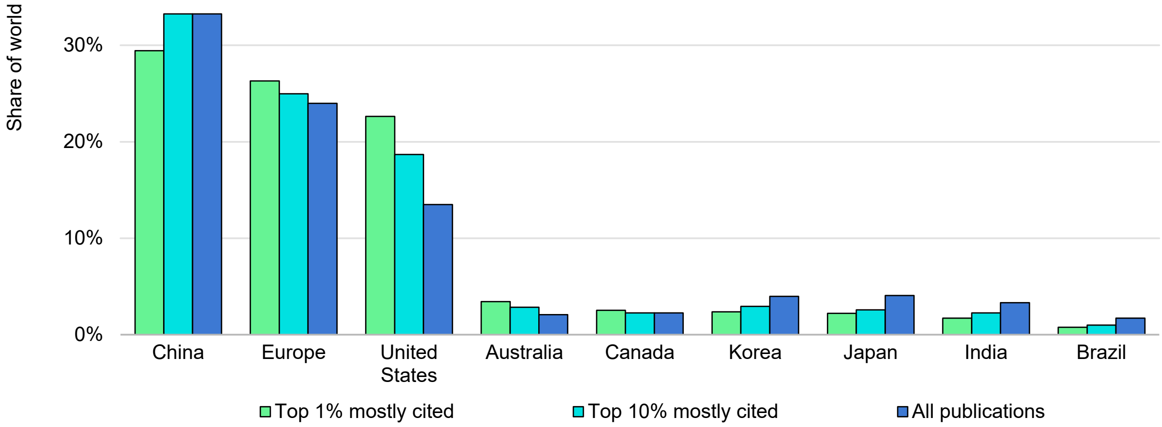
In 2021, China topped Nature Index rankings, which count high-quality research outputs in 82 natural sciences journals selected on reputation. The Chinese Academy of Sciences scored much higher than other government institutions, with a number of research outputs aggregating to more than the French National Centre for Scientific Research, the National Institutes of Health and Lawrence Berkeley National Laboratory in the United States, and the Spanish National Research Council combined. In chemistry, seven Chinese institutions figure in the top ten; four in earth and environmental sciences; and two in physical sciences. Data also show that Chinese institutions display fastest annual growth rates.

In 2019, three of the top five universities for patent applications under the Patent Cooperation Treaty – the international process for filing patents – were based in China (Tsinghua University, Shenzhen University and the South China University of Technology), the other two being in the United States (University of California and Massachusetts Institute of Technology). In the top 50, 20 were located in the United States and 14 in China.

While energy-specific data are not systematically available and published for academic publications, data for physical sciences and engineering show that Chinese universities have been publishing in peer-reviewed journals more than any other country in recent years. IEA analysis suggests that over the 2016-2019 period, China accounted for a third of the world's publications in such fields, more than Europe (24%), the United States (13%), Japan and Korea (each 4%).

In 2021, the Chinese Academy of Sciences published an analysis of opportunities and challenges for new energy technology research, in collaboration with Springer Nature, based on energy-specific bibliometric analysis and patents. The study primarily examines solar, wind, biomass, geothermal, nuclear, hydrogen, energy storage and energy internet technologies. It shows that China accounted for over 25% of global publications in these areas over the 2015-2019 period, up to 45% for energy storage, 30% for hydrogen, and 25% for solar. In the selected fields, the compound annual growth rate over the period was 7.7%, up to 13.1% for energy storage, 10.0% for geothermal and 9.5% for hydrogen – and there are signs that growth rates are increasing.

Share of global publishing in physical sciences and engineering in selected countries or regions over the 2016-2019 period



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Notes: Mostly cited academic publications in physical sciences and engineering in their respective field and year. Europe includes European Union member countries as well as the United Kingdom, Norway and Switzerland.
Source: IEA analysis based on Leiden Ranking data.

If Chinese universities are the world's most prolific institutions for scientific publications, many still lag behind in terms of citations – often used as a proxy for impact. Overall, China accounts for a smaller share of the world's mostly cited publications in physical sciences and engineering. Specifically, Chinese universities published 29% of the world's top 1% most frequently cited publications (in a given field and year), which is less than their 33% share of all publications. In contrast, Europe (26%) and the United States (23%) accounted for a greater share of mostly cited publications than of all publications, suggesting greater quality or visibility. Tsinghua University topped global rankings by publishing more papers in physical sciences and engineering than Harvard University, Stanford University and the Massachusetts Institute of Technology combined over the 2016-2019 period. Yet only 1.7% of these publications ranked among the world's top 1% mostly cited in their field and year, far behind American peers (4.4% for Harvard, 3.9% for Stanford and 3.7% for MIT).

Similarly, the energy-specific analysis by the Chinese Academy of Sciences and Springer Nature shows that China's average citation per paper lags behind that of the United States, Germany and Japan, and concludes that the "overall impact of research output needs to be further improved". Yet Chinese papers fare better than the global average in terms of citations in each of the main energy technology areas examined in the study, led by solar, hydrogen and bioenergy. In certain areas, they even account for a notable share of the top 1% mostly cited publications, such as for solar fuel (4.5%), hydrogen production (3.1%), battery storage (2.3%), solar PV (2.2%) and fuel cells (1.3%). The study concludes that these technologies have promising prospects in China.

Quality has been steadily improving in the last decade, suggesting that Chinese academics are having greater impact and their work is benefiting from more visibility. Over the 2006-2009 period, China accounted for only 8% of the world's top 1% mostly cited publications of physical sciences and engineering in their field and year, and only 0.6% of Chinese publications made it to such status. Over the 2016-2019 period, China accounted for 29% of the world's mostly cited publications, and 1.0% of Chinese publications made it to such status.

Collaborative learning through joint ventures and R&D centres abroad

As part of its socio-economic development push, China has been actively pursuing strategies to acquire IP and concepts from abroad to accelerate equipment upgrading and foster domestic technology development. These include setting up collaborative partnerships with international peers, embedding information sharing and IP transfers in industry joint ventures agreements, and acquiring foreign companies and R&D centres.

Over time, knowledge transfers and collaborative learning-by-doing can spill over into China's innovation system, contribute to enhancing domestic innovation, and lead local inventors and firms to develop home-grown concepts and technologies. For example, in nuclear power, China successfully built reactors based on two foreign designs imported from France and the United States under technology transfer agreements before developing an indigenous one for domestic use and exports. After importing high-speed train models, China developed its own, and it is ready for exports. Solar, wind and hydropower are examples of renewable energy technologies for which China has improved indigenous innovation capabilities in the last two decades, whereas it historically relied on North-South technology transfer and co-operation schemes.

Joint ventures between a Chinese and foreign actor are a means to transfer and co-develop knowledge and technology. In practice, foreign multinationals seeking to enter China's market, such as for local expansion or export-oriented manufacturing, are to enter into partnership with Chinese firms with the view to help these build capacity, based on the Joint Venture Law promulgated in 1979 as part of the country's modernisation programme.

The NDRC notably publishes and updates a Catalogue of Industries for Guiding Foreign Investment, which is a guiding document listing the industry segments for which investment is encouraged, or conversely restricted or prohibited. Foreign investment projects on the list of encouraged industries can benefit from preferential treatment including land, taxation and other administrative regulations. Some measures may be specific to certain regions and provinces. Restrictive measures have steadily decreased over time – from 180 in the 2011 edition to 93 in 2015 and 63 in 2017 – and in 2020, the catalogue included 1 235 entries across all sectors of the economy, against 1 108 entries in 2019. Exploration and development of oil and natural gas was limited to equity or co-operative joint ventures until 2019, when it was opened to wholly foreign-owned enterprises. New energy vehicles, hydrogen production, storage and transportation, and carbon capture were also added that year.

While many energy segments have progressively become part of the list of encouraged industries, foreign actors still regularly set up joint ventures to enter the Chinese market, especially in instances where domestic players benefit from near-monopoly positions. In 2013, for example, Siemens formed a joint venture with Shanghai Electric to produce offshore wind turbines in Jiangsu province, although the industry was already open to investments by wholly foreign-owned enterprises. In 2018, a licensing agreement enabled Shanghai Electric to manufacture, sell and install Siemens Gamesa’s 8 MW high-tech turbines. In 2020, Volkswagen increased its stakes in a joint venture with car and truckmaker Jianghuai Automobile (JAC) to control 75% of the venture, which was established in 2017, following the relaxation of rules relating to foreign investments in Chinese firms. Volkswagen’s other notable ventures are with SAIC Motor (in which it holds 50% of equity) and with FAW (40%), which date back to the 1980s and enabled Volkswagen to become the most successful foreign carmaker in China. In 2021, Volkswagen announced intentions to increase its stakes in Chinese ventures again, notably to reap greater profits as part of its EV development strategy.

The large size of China’s domestic market has allowed the country to set incentives for multinationals to manufacture technologies in China (e.g. cheap manufacturing costs) and embed IP and technology transfer clauses within joint venture agreements – which is not usually the purpose of such partnerships. Through joint ventures, significant knowledge transfers have occurred over time. Some of the country’s domestic labs and research facilities have in fact been set up by foreign actors. General Motors, for example, started forming joint ventures with Chinese firms in 1997, such as with automotive major SAIC Motor today. In 2009, General Motors set up a China Science Lab in Shanghai to carry out local innovation activities. In 2019, the lab received its second R&D 100 Award since its creation, for new capacitor-assisted battery technology. As part of its joint venture with JAC, Volkswagen opened an R&D centre in Hefei in 2020 with aims to develop local technology innovation capabilities.

In parallel, Chinese companies have been actively investing in energy companies and R&D centres abroad, such as in the United States and Europe. Building or acquiring innovation capabilities abroad enables China to generate new knowledge by tapping into a broader pool of talents and innovators, foster personnel mobility, transfer concepts and technologies back to China, and expand into overseas markets. For example, wind turbine manufacturer Envision Energy located its Global Innovation Centre in Denmark in 2010 and filed all international patent applications by the Danish entity. In 2019, battery manufacturer CATL invested about USD 2 billion in its Germany-based R&D and production centre.

Reforms to intellectual property regimes

Addressing concerns of "strategic patenting"

Alongside increasing spending on energy R&D, building industry champions, and investing in universities and research institutes, China has implemented targeted IP policies to promote the creation and protection of new indigenous knowledge. Stronger IP regimes and rule of law, as well as more accessible and effective procedures through IP offices, have contributed to support Chinese inventors and reward their efforts to innovate. The increase in energy patenting activity of the last decades, and particularly over the 2000-2010 period, illustrates China's push to build stocks of IP.

However, analysts observe that China's surge in patenting activity results not only from improvements in indigenous R&D activities, but also from levers that are unrelated to innovation. Non-innovation motives for acquiring patents include preferential tax treatments and other socio-economic incentives via amendments to the patent law, as well as requirements to meet FYP objectives relating to the number of patents per 10 000 inhabitants. "Strategic patenting" might have played an important role in China's patenting activity and decreased the average quality of patents. Firms that were not actively patenting in the past, which accounted for most of the growth in the last decades, had a greater propensity to pursue non-innovation-related patenting.

While the quantity of patents filed by Chinese inventors has significantly increased, including international applications that are typically of higher quality, research shows that China's patents are less likely to be cited, which is another proxy for quality, impact and visibility.

In CCUS, comparative analysis between China and the United States showed that although patent counts were similar in 2015, significant disparities in terms of quality remained, and CCUS technologies were more mature in the United States than in China. The 14th FYP brings increased focus on CCUS as Chinese policy makers seek to bridge a "large gap with the international community" in the area and strengthen support for R&D and demonstration. In wind power, while China has become a key player in producing and deploying wind energy technologies, Chinese patents are less likely to be cited than those of foreign counterparts.

In recent years, studies have noted that the overall impact of Chinese patents is becoming stronger, albeit unevenly across the country, noting regional disparities in terms of patent quality. Provinces such as Shanghai, Hebei, Beijing, Sichuan and Shanxi lead the way relative to other regions, based on metrics covering technological, legal and commercial aspects of patenting.

Despite very high numbers of patent applications and goals in the National Patent Development Strategy (2011-2020) to increase patent transaction amounts, China generates less revenue from IP rights than other innovating countries. China spent over USD 180 billion to purchase foreign IP rights between 2008 and 2017 across the economy, whereas Chinese IP only generated about USD 10 billion, most of which occurred in 2017 alone. Meanwhile, the United States generated nearly USD 130 billion in IP revenues in 2017, and Japan USD 40 billion.

The Chinese government has identified some of these challenges as part of its efforts to improve both the quantity and quality of new knowledge. Efforts to improve the governance of patent offices and strengthen their capacity, expand evaluation mechanisms, as well as to adjust incentives to mitigate non-innovation strategic patenting, may contribute to enhancing the overall quality of Chinese patents and new domestic knowledge more generally.

The 14th FYP brings additional focus on improving the quality of China's home-grown IP, technological self-reliance and strengthening IP regimes. In 2021, the government issued the Guidelines for Building a Powerful Country with Intellectual Property Rights (2021-2035) and the 14th FYP for the Protection and Utilisation of Intellectual Property Rights (2021-2025), which raise the ambition relative to existing plans to achieve the vision of a more innovative China. The government also announced a phase-out of patent application subsidies by 2025.

Aligning IP protection with international practice

China has put forward a number of reforms to its IP and patents regulations since 1984, when they were first introduced shortly after joining the World Intellectual Property Organization (WIPO). In 2001, after China joined the World Trade Organization, efforts were made to align domestic IP practices with international standards. In 2008, China fleshed out an Outline of National Intellectual Property Strategy, which elevated IP into the national strategy to support the country's objective to become more innovative. The strategy set the goal of reaching a comparatively high level of "creation, utilisation, protection and administration" of IP rights by 2020. Implementation plans were put forward in the National Patent Development Strategy (2011-2020), with intermediary goals for 2015 (e.g. volumes of patent applications, patent transaction amounts, speed of administration). Additional policy plans included the Action Plan for Further Implementation of the National Intellectual Property (2014-2020) and the Intellectual Property Judicial Protection Programme (2016-2020).

These plans have enabled China to make progress in aligning domestic IP systems with international good practice. Starting in the 1980s, multinationals have typically leveraged China's patent system to acquire a strategic competitive advantage in local markets, as they would in any country. However, China's use of joint ventures and conditional market access has led to some tensions with trading partners due to allegations of IP malpractice including theft or forced technology transfer, resulting in disputes such as under the World Trade Organization between 2018 and 2021. In 2019, China's central government put forward a reform of the law on foreign investments to improve IP management in joint ventures and mitigate forced technology transfers. Specifically, the new law prohibits theft of IP or trade secrets from foreign partners, and prevents government officials from using administrative measures to force such transfers. Nevertheless, in the 2021 edition of its annual review of IP protection around the world, the United States Trade Representative kept China on the "Priority Watch List" alongside Argentina, Chile, India, Indonesia, Russian Federation, Saudi Arabia, Ukraine and Venezuela. While noting improvements in recent years following government efforts to strengthen IP protection, EU stakeholders in 2021 similarly reported that: "forced technology transfer practices continue to be a systemic problem in China".

In 2020, President Xi reiterated commitment to strengthening IP regimes to transition from "a major IP importer to a major IP creator". He also mentioned the importance of international IP collaboration, such as through the WIPO, with the European Patent Office, Japan, Korea and the United States, as well as Belt and Road countries and African partners.

Developments in China's intellectual property environment since 1980

Mechanism	Description
Amendments to patent laws and intellectual property regimes	• **1980-1984:** In 1980, China joined the WIPO, recognising the value of intellectual assets, and promulgated its first Patent Law in 1984. • **1992-1993:** China broadened the range of patentable subjects, extended the protection period from 15 to 20 years (from 5 to 10 years for utility models), strengthened novelty requirements, limited the granting of compulsory licences, and granted individuals the right to own patents. • **2001:** As part of its application to the World Trade Organization, China aligned IP rights with international standards under the Agreement on Trade-Related Aspects of Intellectual Property Rights. The reform also established equal treatment of SOEs and private firms for obtaining patent rights. • **2009:** China introduced the "absolute novelty" standard to improve patent quality. Prior to this pivotal reform, the Chinese Patent Office limited novelty search to domestic prior art, instead of global prior art. Enforcement was also strengthened. • **2014-2015:** China addressed concerns related to patent infringement (e.g. difficulty to collect evidence, burdensome and costly procedures, low level of enforcement and awarded damage). Three specialised courts were created in Beijing, Shanghai and Guangzhou. Between 2012 and 2016, average awarded damage subsequently increased from about USD 11 000 to USD 65 000. • **2019:** The European Patent Office and Chinese IP office strengthened their strategic partnership and launched a collaborative pilot project to facilitate protection in Europe for Chinese applicants. This would provide additional options for China's international patenting strategies. • **2020-2021:** New amendments to China's patents law are confirmed in 2020, to be effective starting 1 June 2021. The changes aim to further strengthen law enforcement of IP rights, increase infringement penalties, streamline dispute procedures and ease costs of litigation. Based on the circumstances, courts may seek compensations ranging from about USD 4 500 to USD 750 000 – up from USD 1 500 to USD 150 000 previously.
Policy incentives and non-innovation related motives to file patent applications	• **Patent application subsidy.** Local government may reward applications and/or grants for a patent of invention. Shanghai, for example, offered up to about USD 8 000 (CNY 50 000) for foreign patent grants and USD 500 (CNY 2 500) for a Chinese patent. Increasing the compensation to cover patent application fees in 2005 encouraged patenting activity regardless of underlying innovation activity, especially when patenting costs were not a concern, as suggested in the case of the city of Zhangjiagang. In 2021, the government announced that looking forward, "localities shall not provide financial support for patent applications in any form such as subsidies, rewards, etc.", and that all such support schemes should phase out by 2025. • **Preferential tax treatment.** High and new technology enterprises benefit from a reduced corporate income tax rate of 15% (down from 25%), as well as companies owning IP rights developed by "outstanding investors and workers". In 2019, NDRC guidelines further improved income and tax policy conditions for green technology inventors and created a fast track for green technology intellectual property review. • **Other socio-economic incentives**, such as urban household registration, easier admission to a higher-ranked school, etc.

Domestic and international collaboration through knowledge networks

Collaboration between innovation actors is an important aspect of successful energy innovation systems. Smooth flows of knowledge are needed among researchers, policy makers and market actors for new ideas to reach consumers. Government co-ordination is necessary for effective priority setting and resource allocation. Engaging with international networks is also critical to support domestic efforts. Without effective international collaboration, global energy transitions to net zero emissions could be delayed by decades. Since 2000, co-operation and knowledge exchange have improved both within the country and between China and international partners.

Domestic collaboration for research and innovation is getting stronger

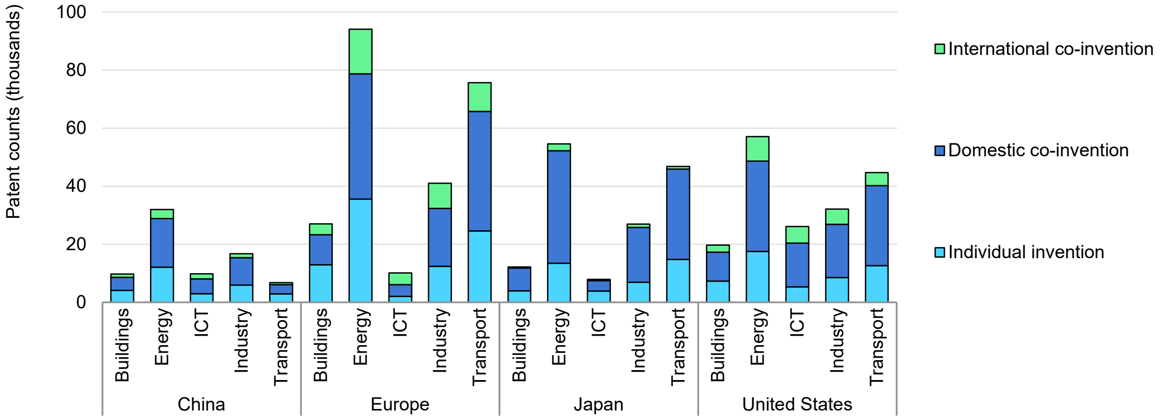
Co-publishing and co-patenting rates are strong, especially between public institutions

Domestically, collaboration is visible between Chinese research organisations, as illustrated by their high propensity to co-publish scientific papers or co-patent.

The share of co-inventions in total inventions for climate change mitigation technologies increased from 50% in the early 1990s to over 75% in the late 2010s, with nearly 85% of these collaborations taking place within China. This trend is similar to that of Europe as a whole (about 50% to 70%), Germany (50% to 70%) and the United States (55% to 75%), and faster than that of France (65% to 70%) and the United Kingdom (50% to 60%). Countries such as India (70% to 90%) and Japan (70% since 1990) feature consistently high co-invention rates.

Furthermore, IEA analysis of data covering physical sciences and engineering papers shows that over 70% of publications by Chinese universities over the 2016-2019 period were published in collaboration with another institution. Of these, only about 20% were co-published with institutions located nearby (under 100 km). This suggests that there are regular long-distance exchanges of knowledge and collaborative projects across cities and regions within the country, and not only between institutions in the same city.

Co-patenting activity in climate change mitigation technologies relevant to energy fields in a selection of countries or regions (cumulative, 1990-2019)



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Notes: Energy refers to the generation, transmission and distribution of energy. “Europe” includes European Union member countries, Norway, Switzerland and the United Kingdom.
Source: IEA analysis based on OECD data on innovation in environment-related technologies.

However, public-private collaboration lags behind

Government-led universities and public research institutions have historically been the primary actors of China’s energy R&D, and captured most funding while businesses were not always able to participate fully. Since the 1980s, China has progressively sought to promote knowledge flows between public research institutions and enterprises – primarily SOEs – and encourage business innovation to foster economic development.

Until the 2000s, many science-industry links remained short-term co-operations or fully outsourced R&D, as illustrated in the case of solar PV development. To achieve more balanced science-government-industry relationships and diversify the range of actors involved in energy innovation, the government started setting up national energy R&D laboratories directly in enterprises, making public R&D funding more accessible, and further promoting science-industry co-operation.

For example, in 2006, the government issued the National Medium- and Long-Term Programme for Science and Technology Development (2006-2020), which encouraged enterprises to “become the mainstay of technological innovation”. The programme included a chapter on the “Reform of science and technology system and construction of national innovation system”, including the goal to establish “an effective mechanism to promote various forms of co-operation between scientific research institutes, enterprises and universities, and promote the flow of knowledge”. The plan mentioned personnel mobility, science and technology resource sharing, joint research, technology contracts and licensing, technology transfers between enterprises and between enterprises and universities and research institutes, and technology clusters or “science parks”.

Successive FYPs since the 2000s all included aspects relating to science-industry co-operation. In recent years, for example, the NDRC issued policy guidelines for Building a Market-Oriented Green Technological Innovation System (2019), in collaboration with the NEA, MOST and the Ministry of Education. The notice included plans to support ”leading enterprises to integrate universities, scientific research institutes, industrial parks and other forces to establish a green technology innovation consortium”. The 14th FYP’s chapter on “Enhancing the enterprise's technological innovation capability” (2021-2025) also aims to “promote open co-operation in science and technology”, including internationally.

Policy attempts to improve domestic collaboration have met mixed success. While enterprises have certainly taken a more prominent role in energy innovation today than they did in the 2000s, research suggests more can be done. In 2021, the Chinese Academy of Sciences and Springer Nature identified that “the industry-academia-research integration in new energy technologies still needs to be strengthened”. Specifically, fewer patents in new energy technologies appear to cite relevant publications in China relative to other innovative countries in the benchmark – the United States, Germany, France and Japan. The technology transfer rate from publication to patent remains relatively high in energy storage (lithium batteries), biomass and solar (organic solar cells).

While collaboration between public research institutes including academia has improved, IEA analysis of co-publishing rates suggests that science-industry links still lag behind to some extent. About 5.0% of Chinese publications in physical sciences and engineering involved university-industry collaboration in recent years, which is more than other economies such as Mexico (1.8%), India (1.8%), South Africa (3.0%), Thailand (3.3%) and Brazil (3.4%), and similar to or higher than more developed economies such as Isreal (3.7%) and Australia (4.8%), but less than the world average (6.1%). In contrast, typical rates are higher in Europe (7.6%) and the United States (7.5%), and a few countries have established strong ties, such as the Netherlands (9.2%), Japan (9.8%), Denmark (10.9%), Sweden (12.9%), Finland (13.1%), Austria (13.8%), Ireland (14.9%), and Estonia (17.1%).

Government funding – whether national or regional – for innovation activities has had an impact on the likelihood of collaboration between innovation actors in China. In the case of solar PV, researchers from universities and public research institutions who receive public funding have been more likely to collaborate with each other domestically as well as internationally, than peers who do not receive funding. However, public funding may not have encouraged science-industry collaboration in the general case, possibly due to a lack of requirements or more independence of researchers in public institutions compared with those in enterprises. The exception was for researchers based in Beijing and Shanghai, who engaged more in science-industry collaboration, especially with reputable affiliations. Putting in place incentives for stronger collaboration could help industry better absorb new knowledge and bring these to markets. There are also disparities between provinces, with science-industry collaboration within South China being relatively stronger than in other regions.

Open-access publishing remains limited

Promoting an open access to academic findings (e.g. by making open-source publishing compulsory upon reception of public grants and pre-assigning budget, as with EU research grants) can foster knowledge exchange between innovation actors and help stimulate overall activity.

IEA analysis suggests that 25% of Chinese publications in physical sciences and engineering over the 2016-2019 period were made open access, which is slightly more than India (22%) and less than Korea (31%), but much less than Brazil (47%), Japan (48%), the United States (64%) and Europe (66%). This may result from the higher costs associated with open access publishing, and difficulties in securing dedicated funding unless budgeted in advance.

Co-operation with international partners is core to China’s energy innovation strategy

Increasing engagement with international partners

China has significantly accelerated its engagement with the international community as part of its innovation strategy. China’s participation in multilateral platforms is strong and increasing, including in the IEA Technology Collaboration Programmes (TCPs), Mission Innovation (MI) and the Clean Energy Ministerial (CEM), and the government has also established numerous bilateral partnerships.

This trend is expected to continue in the 14th FYP period, as Chinese decision makers seek to actively integrate into the global innovation network, establish innovation dialogues with key partners and “conduct joint research with over 50 countries and regions”. There are incentives for enterprises and research institutes to “go global” and seek co-operation with international partners, as set out in NDRC’s guidelines for Building a Market-Oriented Green Technological Innovation System in 2019.

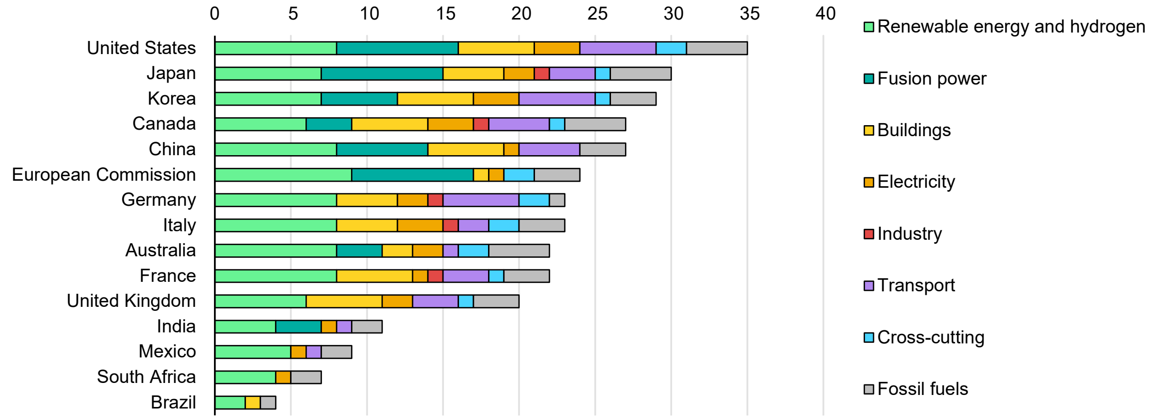
International co-operation programmes for energy innovation are mostly co-ordinated by MOST and CAS, under the leadership of the NDRC and NEA. For example, MOST published in 2021 guidelines for eight new collaborative activities as part of the National Key R&D Project on "International Co-operation in Science and Technology Innovation between Governments", including with Croatia, Denmark, Israel, Japan, Malaysia, Malta, Norway and. the European Union. Collaboration areas cover a broad range of energy fields, including fossil fuels (e.g. coal, oil and gas), CCUS, renewables, power and smart grid technologies, hydrogen, power-to-X, aviation, shipping, and transportation. MOST also devolves some responsibility to provinces and cities, which can seek strategic co-operation opportunities with foreign partners – such as Qingdao in 2017 on topics relating to biology, new materials, energy saving and emissions reduction with partners such as Austria, France, Japan, the United States, and the European Union.

CAS has established co-operation with a number of foreign research institutions and international organisations around the globe – such as through the International Partnership Programme and the Science and Technology Collaboration Action of the Belt and the Road – and plays an active role in the international talents programme.

As of October 2021, China was a member of 27 out of 37 possible TCPs, including eight out of nine in the renewable energy and hydrogen category. This corresponds to the fourth-highest participation in TCPs, behind the United States (35), Japan (30), Korea (29) and Canada (27), ahead of the European Commission (24), and far ahead of other emerging economies such as India (11), Mexico (9), South Africa (7) and Brazil (4). China plays a proactive role in MI, in which it has been co-leading two innovation challenges since 2015 on smart grids and sustainable biofuels, and has launched with Italy and the United Kingdom a new Mission in 2021, Green Powered Future. China is also involved in CEM, technology initiatives under United Nations bodies, and regional energy innovation partnerships such as under the Asia-Pacific Economic Cooperation and the Association of Southeast Asian Nations.

China has also set up bilateral partnerships, such as with the European Union to enhance technical co-operation, the United Kingdom to promote industrial development and academic co-operation in CCUS in a centre in Guangdong, France on nuclear power, and the United States in a joint Clean Energy Research Center. It has also established South-South partnerships for knowledge sharing through new channels of technology transfers. This includes an increasing presence in Belt and Road countries, as promoted in the Belt and Road Science, Technology and Innovation Cooperation Action Plan, which included a Talented Young Scientist Programme aiming to help over 5 000 foreign scientists to work in China and set up 50 joint laboratories.

Membership in IEA Technology Collaboration Programmes, by technology focus area



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Note: Membership as of October 2021.
Sources: Adapted from Expanding the global reach of the TCPs and Tracking clean energy innovation.

Collaboration on clean energy between China and the United States

In 2009, the United States-China Clean Energy Research Center (CERC) was launched to develop clean energy technologies and carry out demonstration projects. It leads five initiatives, which started in 2011 (Advanced Coal Technology, Buildings Energy Efficiency and Clean Vehicles), 2016 (on energy and water) and 2017 (on medium- and heavy-duty truck efficiency).

For example, the Changing District Pilot Project, which focused on building energy efficiency technologies, mobilised 72 partners – 13 research institutes and 59 industry actors – in a Buildings Energy Efficiency Consortium under the leadership of the Lawrence Berkeley National Laboratory, which included MOST, MOHURD and Tsinghua University, among others. The United States Department of Energy committed USD 25 million in public funding over the 2011-2020 period, matched by MOST. Additional funding and in-kind contributions from industry actors were provided. Overall, China's investments exceeded that of the United States, reaching nearly USD 10 million in 2015 (out of a total of USD 17.5 million).

The first phase (2011-2013) primarily focused on reports, papers and incremental improvements in single components. The second phase (2013-2015) opened the opportunity for demonstration projects and independent IP, and the third (2016 onwards) for joint IP. Tangible technological progress has been made throughout these collaborative activities. For example, novel materials and technologies for improved insulation in buildings were developed, tested and commercialised through the CERC, and were awarded a Gold Edison Award in 2016.

Some of the key potential risks identified by partners included reduced funding over time, project delays, shifting policy priorities, slow bilateral R&D collaboration, and lack of adequate demonstration sites. Furthermore, analysts observe that little of the new IP came from collaborative activities between participants relative to in-country activity under the programme, despite a dedicated Technology Management Plan to mitigate concerns on each side. Learnings from this experiment may be valuable in designing future collaborative activities with Chinese research institutions.

Delivering tangible benefits from international collaboration

While there is strong engagement from the Chinese government in international energy innovation partnerships and associated political fora, fewer collaborations are observed between Chinese researchers and international peers in terms of filing for co-patented inventions or co-publishing scientific papers.

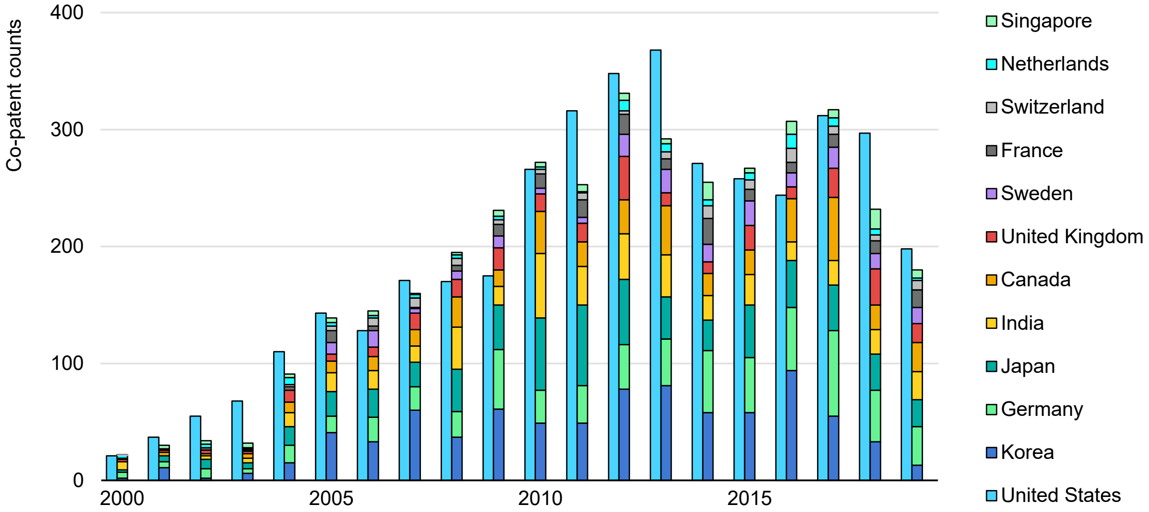
China's share of co-inventions in total inventions for climate change mitigation technologies surpassed 70% in the 2010s, but on average only 25% of these collaborations involves international partners. Most co-operations remain domestic partnerships. Co-operation strategies at home can foster knowledge flows among innovation actors and increase chances of breakthrough, and collaborating with foreign partners can help adapt foreign concepts to local needs and build domestic innovation capabilities.

China's main collaborating partners include the United States – which accounts for the majority of international co-patenting in energy-relevant climate change mitigation technologies – and other regional economies such as Japan and Korea, followed by European countries. With the United States, most collaborations since 1990 in the selected sample are related to energy generation, transmission and distribution (35%), followed by ICT (25%), industry (16%), buildings (13%), and transport (9%). Notable collaboration with India is observed since the mid-2000s, with a primary focus on ICT (over 40%), followed by energy generation, transmission and distribution (31%), and to a lesser extent industry (13%), and buildings and transport (11% together).

Joint analysis on low-carbon energy technologies by the IEA and European Patent Office shows that international co-patenting rates are lower in China than in the United States and Europe, but higher than in Korea and Japan. The share of co-invention increased in the United States from 9.3% over the 2000-2004 period to 12.7% over 2015-2019, in Germany from 9.6% to 13.1%, in the United Kingdom from 20.6% to 22.3%, and it remained stable in France at 13.0%. However, it fell from 12.9% to 7.2% in China, suggesting more "self-sufficient national innovation systems, but also potential missed opportunities for shared learning". Overall, China is involved in few of the world's top country-country collaborating pairs across energy sectors and technology areas. In Japan and Korea, international co-patenting rates are stable below 2% (Japan) and 3% (Korea) in the last decade.

Similarly, Chinese universities tend to co-publish less with international research institutions than other countries. Over the 2016-2019 period, only 26% of Chinese publications in physical sciences and engineering involved international collaboration, which is similar to India (27%) but among the world's lowest rates. In contrast, global international co-publishing rates average 50% and reach 38% in Korea, 42% in Japan, 45% in Thailand, 46% in Brazil, 47% in Mexico, 59% in the United States, 60% in Malaysia, 62% in Canada, 63% in Israel, 66% in South Africa, 68% on average in Europe and 71% in Australia.

China's main collaborating partners in terms of co-patenting in climate change mitigation technologies relevant to energy fields (2000-2019)



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Notes: Includes climate change mitigation technologies in the fields of CCUS, ICT, buildings, industry, energy production and distribution, and transport. Bilateral country pair collaborations based on inventor country of residence.

Source: IEA analysis based on OECD data on innovation in environment-related technologies.

Market-pull forces for innovation

Introduction

Market demand for energy products and services can create incentives for innovators to develop new, better and cheaper technologies, and trigger feedback loops from users back to innovators – all of which contribute to "pulling" innovation from markets. This section summarises China's key market-pull strengths for technology innovation, examines the specific role of and risks associated with industrial policy, and illustrates cases where demand-driven innovation can happen outside the traditional system of centrally managed R&D programmes.

Key takeaways

- China has unique market and economic features that can be effective market-pull levers for innovation, such as a large domestic market size, central decision-making and subnational implementation, availability of cheap capital for industry development, and whole-of-industry strategies to set up integrated majors.
- Market-creation and industrial policy are core elements of China's development strategy, and enabled a quick development of manufacturing to serve foreign and domestic markets. Through learning-by-doing, joint ventures and knowledge partnerships and in combination with resource-push support, market creation contributed to improve technology innovation capacity as industry developed. However, relying on centrally managed, large-scale industrial policy can hinder technology innovation in some instances, and key issues will need to be addressed to meet China's climate goals.
- In the 20th century, China's innovation system was shaped by a tension between rapidly growing market demand for energy technologies and low support and resources available for R&D. This fostered a culture of innovation stimulated by local demand and support, with some success such as in the case of solar water heaters, but limited long-term impact.

China's key market-pull strengths for technology innovation

Markets play an important role in fostering or hindering technology innovation, and there are various ways in which market forces "pull" ideas along the innovation process. For example, if the expected market value of new technologies, products or services is large enough to make the R&D risks worthwhile, it creates incentives for innovators to innovate. Commercial scale-up also leads to learning-by-doing and feeds innovators with new ideas for improvements and products.

Market-pull levers are often a function of rules and incentives established by legislation. In 2019, the NDRC published policy guidelines on Building a Market-Oriented Green Technological Innovation System, which illustrates Chinese efforts to strengthen the role of markets in fostering innovation. The notice aims to "give full play to the decisive role of the market in … technological route selection and the allocation of innovative resources". It promotes the use of market-oriented instruments such as business-led innovation, public procurement and technology standards for green technologies, and market-led green finance.

In China, market and economic structures are different from other major innovating countries. Combined with resource-push policy support, some of its specific features can be key market-pull strengths to accelerate innovation.

Among these core specificities and key strengths:

- **Huge domestic market size and strong demand growth prospects** for energy technologies and services in line with the country's socio-economic development, which opens significant business opportunities for energy entrepreneurs and innovators, including foreign multinationals.
- **Central politico-economic decision-making and priority setting**, which enables the government to quickly set incentives and regulations to steer industry actors – starting with SOEs – towards national priority goals and ramp up manufacturing capacity as new technology opportunities arise.
- **Availability of cheap capital for strategic industries,** such as to establish and finance new companies, set up new manufacturing facilities and deploy emerging technologies at scale.
- **Whole-of-industry strategy to develop integrated supply chains,** from raw material to manufactured goods and recycling, and for as many technology sub-components as possible, which decreases overall production costs and mitigates risks for investments in new technologies that rely on existing supply chains.
- **Strong socio-political support to build global industry champions**, which opens significant business opportunities for innovators developing clean energy technologies and concepts with high potential in foreign markets.

- **High involvement of subnational levels of government in market creation,** which enables implementation of national strategies through targeted incentives and regulations based on local strengths and contexts, and quick set-up of new high-tech demonstration zones and manufacturing facilities in collaboration with local industry, finance, research and academic actors.
- **Clear national vision and market signals with visibility at several time horizons,** which contribute to increasing market confidence and lowering risk of investments in new technology areas that can support national priorities. There are typically three clearly fleshed out horizons: 1) long-term development aspirations and energy and carbon neutrality goals in the 21st century and beyond; 2) medium-term economic and technological action plans that can cover periods of 15 years or more; and 3) near-term policy schemes that are dynamically evaluated and updated through the FYP decision-making process.

The notable role of industrial policy in China

Manufacture, export, create domestic markets, innovate

China's strong reliance on market creation and industrial policies to secure high global shares of manufacturing sectors and maintain economic growth are features that mark it out compared with other countries.

Key policy objectives underpinning China's industrial policy include technology upgrading and developing domestic innovation capabilities – all of which are cited in support of long-term structural growth per guidelines set out in the successive FYPs. Policies such as Made in China 2025 and China Standards 2035 illustrate the country's industrial strategy to become a front runner in new technology areas and reduce reliance on technology imports, just as the 12th FYP and its predecessors aimed to reduce reliance on fuel imports.

Industrial policy has helped shape China's technology innovation in numerous ways, including the following:

- **Industrial policy helps build manufacturing capability in strategic sectors**, and using FYPs has enabled China to adjust national priorities dynamically and quickly invest in key energy and industrial segments when opportunities arose.
- **Low-cost capital, cheap inputs, subsidies and other support schemes** have contributed to bringing down the cost of goods manufactured in China relative to international standards.
- **Strong incentives to produce technical components and set up manufacturing in China** successfully attracted foreign industry actors, in part drawn by the prospects of lower production costs and more lenient labour policy than in their country of origin.
- **Lower prices as well as large-scale policy push to boost exports and stimulate domestic demand expanded markets for Chinese goods** and

strengthened Chinese enterprises, especially SOEs. Several Chinese enterprises grew quickly to become global majors competing with foreign front runners. This stimulated new support in other regions such as in the United States and Europe, including anti-dumping policy.

- **Foreign direct investments materialised through joint venture agreements** between foreign and local industry actors to fulfil requirements to enter the Chinese market, and these typically embed knowledge sharing and technology transfer clauses to build local capacity.
- **Learning-by-doing and extensive knowledge and technology transfers occurred** as domestic manufacturing capabilities improved and Chinese enterprises developed, although the focus remained on manufacturing and process innovation as well as pursuing economies of scale to bring costs down.
- **Chinese industry majors increased spending on innovation as they generated increasing revenues**, especially from exports, and progressively shifted their focus from manufacturing foreign technologies only to developing home-grown concepts.
- **As other regions of the world strengthen policy support for low-carbon technologies, China faces new incentives to invest** in technology development, innovation and manufacturing. Competition between Chinese suppliers to keep pushing down costs and increasing reliability fosters innovation.

In the case of solar PV, industrial policy through export-oriented and domestic market-creation support schemes and other demand-pull levers were essential to build a strong industry and become a global manufacturer. Combined with resource-push support for innovation, including increasing R&D investments along supply chains in various components, China’s solar PV ecosystem progressively shifted from manufacturing to novel technology innovation.

China has become an important energy technology manufacturer and is progressively emerging as an innovator through similar industry-led patterns, in technology areas beyond solar PV, such as:

- EVs and associated technologies, including batteries and charging.
- Renewables, such as wind turbines, hydropower and solar thermal.
- Power grid equipment including for smart grids.
- Nuclear power designs and associated technologies.
- Buildings technologies such as lighting, heating and cooling systems.
- Biofuels production and bioenergy technologies.
- Coal-based power generation and chemicals production.
- ICTs with applications in energy.

Possible risks of industrial policy for innovators

China’s use of industrial policy for selected strategic industries has enabled it to compete in international technology markets, but there are also some negative consequences as far as innovation is concerned. While there is no clear expectation for China to change course radically in the 14th FYP period, it will need to overcome some of these issues to reach carbon neutrality goals.

First, while central decision-making enables the steering of national efforts towards new technology priorities and long-term goals quickly and effectively, it presents risks of “picking winners”. Relative to technology-neutral policy approaches, this limits the chances of market rationalisation and radical innovation. Within a given technology area, “picking companies” such as by mandating SOEs also hinders competition that could trigger technology improvements, and decrease incentives for major incumbents to innovate beyond targets set out by policy. Research suggests that political connections of Chinese firms can have a negative impact on green technology innovation, and that firms without close ties to public bodies increase investments in innovation to ensure they remain competitive.

Second, industrial policy has pushed companies or sectors such as in heavy industry towards excess capacity in some instances, notably due to a focus on economies of scale for exports and a resulting mismatch between market demand and local production capacity. As international demand and trade shrank in the 2010s after the financial crisis, efforts to expand domestic markets were strengthened to compensate, but excess capacity remains an issue. Oversupply has led to fierce competition in domestic and international markets, required resources to help so-called “zombie enterprises” with low capacity utilisation rates stay afloat, and triggered bankruptcies and restructuring both in China and countries where Chinese companies had captured market share.

Third, it can be a challenge to create incentives to improve technology performance when industrial policy seeks to lower costs to capture international market share or foster local deployment. In fact, this can also result in reducing the global level of performance innovation in some instances. For example, in the case of solar PV, incentives to innovate and explore new and alternative concepts may have decreased internationally because of stark cost reductions of older generation technologies through economies of scale and excess capacity in China, even if innovation related to associated technologies is stimulated by low-cost basic products (e.g. PV integration, smart controls, inverters, tracking, installation). Research on China’s wind power suggests that relying on fixed industrial investments and subsidies can undermine technology innovation but that local government action to stimulate R&D can balance these effects.

Innovation outside the traditional system: The case of solar water heaters in the 1990s

Prior to the 2000s, China's budgets for energy R&D and demonstration were relatively low, and there were few incentives and resources available for radical innovation and basic research (resource push). Yet local demand for affordable, efficient and reliable energy products and services was steadily increasing as the country quickly developed and energy access expanded (market pull). This has fostered a culture of demand-driven innovation and engineering, in which innovators have had incentives to develop technologies to meet pressing and local needs, and adapt and incrementally improve existing technologies or foreign concepts. This could be described as "frugal innovation", a term that has been applied to small-scale and grassroots entrepreneurial activity in resource-constrained settings, particularly in emerging economy contexts.

This type of innovation has led to some successes in China. For example, increasing demand for affordable and efficient thermal comfort systems triggered the emergence of China's solar water heater technologies in the 1990s, which reached mass production from grassroot technology development with little central government support in the early stages. Today, China is by far the largest market worldwide for solar heating and cooling technologies, and a key member of the IEA Solar Heating and Cooling TCP.

While some knowledge in solar water heater technologies had been developed by public research initiatives (e.g. patent for low-cost evacuated tube collectors by the Beijing Solar Energy Research Institute of Tsinghua University in the 1990s), the national government did little to develop the technology once initial products reached markets. An innovation cluster for solar water heaters emerged in Shandong province, a region with abundant solar resources that lacked directly available cheaper alternatives for water heating. The first solar water heater entrepreneurs often came from public research institutes, such as the Energy Research Institute of the Shandong Academy of Sciences. Today, Shandong is home to half of China's top solar water heater companies. Over time, these enterprises have successfully brought the costs of solar water heater technologies down including thanks to incremental innovation and technology improvements.

Local support – provincial and municipal – helped pull product development along the innovation value chain, motivated by the economic prospects of developing a strong industry to meet market demand. In 2004, for example, the first policy for mandatory installation of solar water heaters in buildings was introduced in Rizhao, a coastal city in Shandong province seeking to transition from a history of heavy industry and exposure to pollution to a nationally recognised cleaner city. Retrofitting was initiated at a large scale: 99% of households in the central district and 30% of rural residences are estimated to be equipped with solar water heaters. In 2007, the provincial government put in place subsidies for solar water heating installations, issued mandatory installation rules, established quality and performance standards, and sought financial support from national institutes.

As the technology gained socio-political support, local initiatives benefited from increasing support and recognition, including internationally, such as in 2009 when Rizhao received a United Nations Habitat Honour Award. In 2009 and 2012, demonstration projects backed by the central government were launched in Shandong as Rizhao and Dezhou were each recognised as National Demonstration City for the Application of Renewable Energy in Buildings. However, national support remained low overall in terms of both resource-push and market-pull schemes, notably relative to technologies such as solar and wind.

Local, demand-driven innovation has been effective at developing home-grown solar water heating and cooling technologies in China. Leading companies have been able to generate significant profits, allocate budgets to technology development and bring costs down thanks to incremental improvements and economies of scale, and China remains the world's largest market for this technology. However, there are some limits to the model. Relative to other energy segments that have benefited from stronger and more centralised support for R&D, innovation capacity in solar water heating and cooling lags behind. Companies have more limited experience with novel R&D and innovation, which could make it more challenging for them to adapt to changing market conditions, compete with new technology concepts and designs, and remain competitive relative to alternatives such as electric and gas heaters in the long term.

Where next for energy innovation in China?

In the last 20 years, China has strengthened its position on the global stage as an energy innovator. Looking forward, clean energy innovation will play a crucial role to achieve China's carbon neutrality objectives.

While there was little to no activity in energy R&D in the country prior to 2000, Chinese actors – public research institutes, universities, SOEs and private firms including start-ups – have accounted for a steadily increasing share of the world's new energy technology developments. Today, China ranks among the world's biggest public spenders on energy R&D, and is second to the United States in terms of low-carbon energy R&D spending. In certain technology areas such as solar PV, recent patenting and performance trends suggest that China may be close to tying up with other leading innovating countries. In electric mobility, China is home to the world's most dynamic start-up ecosystem with concerted support from public and private actors, and increasingly integrated supply chains from raw materials for batteries to EVs and charging infrastructure. China is successfully developing and demonstrating home-grown nuclear power plant designs.

These developments are the result of two decades of increasing policy focus on technology innovation, which underpin China's ambitions to become a producer of knowledge rather than an importer. Energy innovation has become a central part of FYP priorities and high-level strategy documents, particularly since the 2010s, and this policy push has been confirmed for the coming 14th FYP.

The story of how China came to dominate global solar PV manufacturing is well known, but there is less documentation of how this revolution in mass manufacturing of energy supply technologies has changed the global conversation around energy innovation and helped China to move to the frontier of solar PV R&D. In just two decades, China became a global production front runner, achieving significant cost reductions through manufacturing and process innovation and economies of scale, and is now shifting focus towards technology innovation. This was made possible thanks to strong market-pull industrial policy to support the solar PV industry, combined with targeted resource-push and knowledge management schemes to foster domestic technology development. The government's strategy involved, among others: investing along the entire value chain from raw materials to final products, and in both manufacturing capacity and R&D activities; developing integrated companies in a whole-of-industry approach; creating domestic markets and facilitating exports; acquiring IP, R&D centres and competing companies abroad; and pursuing technical co-operation with international partners.

The experience with solar PV is illustrative of several of the emergent key features of China's innovation ecosystem, which have also been evident in the arrival of China as a source of innovation in battery and EV designs and production. These strengths include:

- **Increasing resources for innovation**, such as funding for R&D and demonstration, abundant and cheap VC for tech start-ups, availability of human capital and skilled workforce, and the development of research facilities, innovation centres and enabling infrastructure.
- **More effective and dynamic knowledge management**, illustrated by improvements in research output quantity and quality, better visibility for Chinese research institutions and universities on the global stage, proactive international collaboration strategies to acquire or co-develop IP, amendments to IP regimes to progressively align with international standards, and stronger knowledge networks among government, science and industry.
- **Strong market-pull levers for innovation** through large-scale industrial policy, domestic market creation and export-oriented manufacturing, building on China's unique economic structure and huge domestic market, which enable to quickly build integrated industry champions.
- **Co-ordinated decision-making to steer innovation towards national priorities**, with government processes to quickly align the country's innovation activities and key actors (including industry, academia and finance) with pressing domestic needs and arising strategic opportunities.

Looking forward, China's leadership has identified areas for possible improvement in the country's innovation ecosystem. Government announcements signal that China would focus on promoting original and breakthrough innovation projects; optimising resource allocation based on pressing needs and strategic opportunities; increasing the efficiency and effectiveness of research institutions, and modernising their structure; further including companies in innovation; and strengthening evaluation and monitoring mechanisms.

In the 14th FYP (2021-2025), energy innovation is featured as a core theme to accelerate socio-economic development. In 2021, the government fleshed out plans to achieve long-term carbon neutrality goals with a strong focus on developing new technologies and pursuing strategic opportunities in global supply chains (e.g. low-carbon hydrogen production and use, CCUS, bioenergy, energy storage and advanced batteries, nuclear, and critical minerals). The message from government sources is that China is seeking to secure a position as a global leader in clean energy technology innovation while also maintaining its dominance and competitive edge in manufacturing. However, while it is tempting to believe that solar PV provides a blueprint for energy innovation, there is no clear evidence that it is an appropriate analogue for larger and more complex technologies, for which mass manufacturing plays a smaller role (e.g. nuclear, CCUS and biorefining).

Part of China's innovation strategy has involved tapping into global knowledge networks, engaging with international partners to share information and learn, and setting up bilateral partnerships with other governments and industry actors. This has been illustrated by increasing participation in key energy innovation partnerships such as the IEA TCPs and MI, among other multilateral partnerships for energy innovation, but also by the numerous joint ventures between Chinese industry and foreign actors. On the other hand, there remain concerns about IP malpractice, including among China's key trading partners, which undermine mutual trust and can hinder effective collaboration between institutions. Addressing such concerns can help promote mutually benefitial partnerships and strengthen international collaboration, which will be needed for China to achieve its carbon peaking and neutrality targets. Without effective international collaboration (e.g. on markets, supply chains, standards and R&D), global energy transitions to meet net zero ambitions could be delayed by decades. Co-operation can help improve further China's innovation ecosystem on one hand, and facilitate the diffusion of new energy technology concepts and products designed in China on the other, thereby supporting collective success.

Annex

Abbreviations and acronyms

AC	alternating current
ACCA21	Administrative Centre for China's Agenda 21
CAE	Chinese Academy of Engineering
CAS	Chinese Academy of Sciences
CATL	Contemporary Amperex Technology Co. Limited
CCUS	carbon capture, utilisation and storage
CEM	Clean Energy Ministerial
CERC	Clean Energy Research Center
CNOOC	China National Offshore Oil Corporation
CNPC	China National Petroleum Corporation
CNY	Yuan renminbi
DC	direct current
EV	electric vehicle
FYP	Five-Year Plan
GDP	gross domestic product
HVAC	heating, ventilation and air conditioning
ICT	information and communication technology
IEA	International Energy Agency
IP	intellectual property
IPO	initial public offering
JAC	Jianghuai Automobile
LED	light-emitting diode
MEE	Ministry of Ecological Environment
MI	Mission Innovation
MIIT	Ministry of Industry and Information Technology
MoF	Ministry of Finance
MOHURD	Ministry of Housing and Urban-Rural Development
MOST	Ministry of Science and Technology
NDRC	National Development and Reform Commission
NEA	National Energy Administration
NEC	National Energy Commission
NREL	National Renewable Energy Laboratory
OECD	Organisation for Economic Co-operation and Development
PGAs	professional governing agencies
PV	photovoltaic
R&D	research and development
S&T	science and technology
SASAC	State-owned Assets Supervision and Administration Commission
SMEs	small and medium-sized enterprises
SOE	state-owned enterprise
TCP	Technology Collaboration Programme
USD	United States dollar
VC	venture capital
WIPO	World Intellectual Property Organization

Units of measurement

g CO_2/kWh	grammes of carbon dioxide per kilowatt-hour
GW	gigawatt
GWh	gigawatt-hour
km	kilometre
kt	kilotonne
kV	kilovolt
kW	kilowatt
MJ	megajoule
MW	megawatt
MWh	megawatt-hour
TWh	terawatt-hour

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