

# Innovation for carbon neutrality

Excerpt from An Energy Sector Roadmap to Carbon Neutrality in China

International Energy Agency

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# Abstract

In September 2020, President Xi Jinping announced that the People's Republic of China will "aim to have  $CO_2$  emissions peak before 2030 and achieve carbon neutrality before 2060". Amid the growing wave of governments around the world setting targets for reaching net zero emissions, no pledge is as significant as China's. The country is the world's largest energy consumer and carbon emitter, accounting for one-third of global  $CO_2$  emissions. The pace of China's emissions reductions will be an important factor in global efforts to limit global warming to 1.5 °C.

This report, *An Energy Sector Roadmap to Carbon Neutrality in China*, responds to the Chinese government's invitation to the International Energy Agency to cooperate on long-term strategies by setting out pathways for reaching carbon neutrality in China's energy sector. It shows that achieving carbon neutrality fits with China's broader development goals, such as increasing prosperity and shifting towards innovation-driven growth. The first pathway in this *Roadmap* – the Announced Pledges Scenario – reflects the enhanced targets China announced in 2020. The report also explores the implications of a faster transition – the Accelerated Transition Scenario – and the socio-economic benefits it would bring beyond those associated with reducing the impact of climate change.

This *Roadmap* examines the technology challenges and opportunities that this new phase of the clean energy transition will bring for China's development, with a focus on long-term needs. The technology innovations required in the Chinese context are a key in-depth focus area. The report concludes with a series of policy considerations to inform China's energy debate.

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# Chapter 6: Innovation for carbon neutrality

#### Highlights

- The People's Republic of China (hereafter, "China") has joined the top table of energy-innovating countries. Public spending on low-carbon energy research and development (R&D) has risen by 70% between 2015 and 2019 and now represents 15% of the global total. China accounts for nearly 15% of patent activity in renewables and 10% in electric vehicles (EVs). In the last three years its start-ups have attracted 35% of global early-stage energy venture capital, compared with 5% in 2010-2014. China's contributions to solar photovoltaics (PV) cost reductions, in particular, have changed the way the world thinks about energy innovation.
- A major push for clean energy innovation will be required for China to achieve its carbon neutrality targets. About 40% of the CO<sub>2</sub> emissions reductions in 2060 in the Announced Pledges Scenario (APS) come from technologies that are at prototype or demonstration stage today. This share is highest in heavy industry and long-distance transport. To ensure that critical emerging technologies are available by the 2030s, major innovation efforts are needed in the 2020s.
- The 14th Five-Year Plan (FYP) aims to shift the focus of technology development to carbon neutrality and pursue new policy approaches, building on a unique foundation. China's energy innovation system exhibits five key policy features that are rarely found together elsewhere: the ability to mobilise funding towards strategic national missions; devolved responsibility to state-owned enterprises (SOEs); empowering provincial and municipal governments to experiment and compete; reaping the benefits of a vast domestic market that spreads risks and sustains competition; and learning from international co-operation, especially between firms. Together, they form a framework that is highly centralised in goal setting and relatively decentralised in goal attainment.
- Low-carbon energy technologies, including carbon capture, utilisation and storage (CCUS), hydrogen, biofuels and electrification value chains, are highly diverse. The various features of China's innovation system will need to be harnessed appropriately for each technology. Large-scale technologies like CCUS and biorefining are suited to the main Chinese policy incentives, as are some elements of network infrastructure, while for low-carbon consumer products, China's manufacturing strengths provide a strong foundation. Building trust through strong intellectual property governance, fair access to markets and depoliticised supply chains would reduce the risk of undermining international collaboration and co-operation on clean energy innovation.

### **Clean energy innovation in China**

This chapter summarises the case for China to intensify clean energy innovation, drawing on various examples and policy statements to indicate a way forward. It reviews the status of energy innovation policy making in China at the inception of the 14th FYP (2021-2025) and explores five unique features of the Chinese energy innovation landscape that the government could harness to accelerate the development of the key technologies needed for carbon neutrality.

#### Innovation is needed to meet climate goals

The Chinese government recognises that reaching carbon neutrality by 2060 will not be achievable without a major acceleration in clean energy innovation. Such innovation, which is expected to be a major driver of economic growth in the coming decades, stands at the confluence of three major strategic national objectives:

- **Technological leadership:** to become "the top innovation-oriented country by 2035" and "the world's major science centre and a highland of innovation" (Xi, 2021a; Xi, 2021b).
- Innovation-driven growth: to build a "new momentum" for high quality economic development, with scientific and technological achievements as the "main battlefield of the economy and society" (Wang, 2021).
- **Tackle environmental challenges:** to achieve the vision of an "ecological civilisation", including a peak in CO<sub>2</sub> emissions before 2030, carbon neutrality before 2060, and tackling air, water and land pollution.

Reaching net zero emissions will require the widespread use after 2030 of technologies that are still at the prototype or demonstration stage today. In the APS technologies that are available on the market today provide the bulk of the  $CO_2$  emissions reductions required in 2030 relative to 2020 but, in 2060, 40% of the reductions come from technologies that are under development today. The share of emissions reductions in 2060 that come from technologies currently at demonstration or prototype stage is the highest in heavy industry and long-distance transport, whose decarbonisation rely on electrification, hydrogen, CCUS and advanced biofuels.



IEA, 2021.



More than 90% of the  $CO_2$  emissions reductions by 2030 are from technologies readily available today whereas about half of the reductions in 2060 relative to 2030 come from technologies that are currently only at the prototype or demonstration phase

To ensure that critical technologies for carbon neutrality are available in China and the rest of the world by the 2030s, major innovation efforts are needed in the current decade. As one of the world's largest energy markets and an emerging leader in clean energy innovation, China will be central to the global challenge. It is expected to be home to many first-of-a-kind energy projects and products, especially in heavy industry. China has become a major exporter of clean energy technology in recent decades. With its R&D resources and world-scale companies, China has the potential to innovate advanced low-carbon technologies for adoption and adaptation in other countries, especially in emerging market and developing economies. Announcements in support of the 14th FYP (2021-2025) recognise the importance of international co-operation alongside other policy mechanisms as highlighted in this chapter.

#### Clean energy innovation in the five-year plans

China's overarching ambitions for energy and climate technology innovation are encapsulated in its FYPs and supported by high level strategies including "Made in China 2025" and "China Standards 2035", which seek to ensure that Chinese companies participate throughout strategic value chains and have a voice in international rulemaking (Chipman Koty, 2020). The 14th FYP emphasises energy technology innovation to support decarbonisation efforts more than in previous plans (Li, 2021; Xinhua News, 2021a). It also continues the shift towards technology areas compatible with carbon neutrality started in the 11th FYP (2006-2010). Together, these plans shape how China promotes clean energy innovation and innovation in related areas such as critical minerals, in which China has already demonstrated strategic interests (IEA, 2021a).

# Table 6.1Technology development and key energy innovation priorities outlined in<br/>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, electric vehicles 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 and smart digital systems.

Notes: CCUS = carbon capture, utilisation and storage. Key focus areas for innovation 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 (FYPs), the table focuses on additions relative to previous FYPs.

Sources: NDRC (2016); NDRC and NEA (2016a and 2016b); NEA (2016); State Council (2016a and 2016b).

Documents in support of the 14th FYP (2021-2025) published since it was released in 2020 set out expectations for energy innovation. The Energy Development in the New Era White Paper establishes high level guidelines for strengthening the "driving force of technology innovation" and developing emerging strategic industries in light of China's new carbon neutrality targets (State Council, 2020). The paper calls for major science and technology (S&T) projects in oil and gas, third- and fourth-generation nuclear power, new energy vehicles, smart grids, coal mining and use, renewables, hydrogen and fuel cells, and energy storage. It targets building over 80 national energy R&D centres and laboratories in collaboration with scientific research institutes, universities and enterprises. While the plan aims to prioritise the development of non-fossil energy, it still foresees a major role for technology for more efficient use of fossil fuels.

The Ministry of Science and Technology is developing a "carbon peak and carbon neutral technological innovation action plan", which will be complemented in 2021 with a detailed carbon-neutral technology development roadmap and a list of new R&D and demonstration programmes (ACCA21, 2021 and 2020; MOST, 2021a).

There are signs that they will align much more closely with the technology needs of the APS than the initiatives associated with previous FYPs. However, there are also indications that fossil fuels, including coal, will continue in parallel in 2021-2025 but will be scaled back.

China's economy-wide push to be in the vanguard of technology innovation involves the introduction of new policy approaches, including efforts to stimulate competition among technology developers and strengthen innovation cultures in research institutions and the corporate sector. Under the 14th FYP (2021-2025), China is expected to:

- Increase R&D spending by over 7% every year (more than the gross domestic product (GDP) growth target for 2021) to surpass the US and European R&D budgets, and raise the share of basic research in total public R&D to 8% (up from about 6% in 2019).
- Concentrate resources on strategic emerging energy areas, including CCUS, hydrogen, industrial decarbonisation, digital and smart energy, and advanced biofuels for transport.
- Grant more autonomy to researchers and increase competition among them by broadening access to publicly funded programmes for young scientists and using performance-based open competition mechanisms, such as the new "bounty system" and "disruptive technology innovation competitions" (MOST, 2021b).
- Set up climate neutrality innovation centres to foster collaboration between research institutes, enterprises and universities, including China's first carbon neutral innovation centre in Sichuan, announced in April 2021 (Li and Chen, 2021), and a CCUS innovation centre.
- Encourage enterprises to increase R&D spending and capture a larger share of global supply chains for clean energy technologies, including through 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 (MOST, 2021c).
- Enhance governance by aligning intellectual property protection with international best practice, modernising S&T institutions, improving evaluation and monitoring mechanisms for R&D, and promoting international collaboration in energy R&D and demonstration.

#### Box 6.1 Bounty system

In support of its renewed focus on innovation in the 14th FYP (2021-2025), China's State Council announced in May 2021 the adoption of a new bounty system to "give young and capable scientists more opportunities, facilitate the commercialisation of their research results and help them clear technological obstacles to meet the country's socio-economic needs" (State Council, 2021; Xinhua, 2021b). The system has been pilot tested locally since 2016, mostly for non-energy technologies and will now be rolled out nationwide (Zhihao, 2021a and 2021b). Several fields relevant to clean energy have been identified. For example, special projects under this scheme have been put forward in critical and rare earth minerals (with funding of USD 3 million [CNY 20 million]), new energy vehicles (USD 8 million [CNY 60 million]), energy storage and smart grids (USD 5 million [CNY 33 million]) and hydrogen technologies (USD 8 million [CNY 55 million]) (Yezi, 2021).

The details have not yet been published, but the expected for applying and receiving a bounty is:

- The government publishes a list of specific research obstacles (submitted by public institutions or private companies).
- Any capable research teams can apply to clear those obstacles irrespective of their educational qualifications or the job positions of their leading scientists, with priority given to younger applicants.
- Selected research teams will receive government funding and policy support.
- Recipients will be evaluated rigorously for quality and timeliness.

The bounty system represents a break with previous funding programmes, which were often limited to SOEs or government research intuitions and followed the same direction as their existing research.

#### China's role in global energy technology development

China has made major contributions to energy technology development since 2000. As a hub for manufacturing innovations, innovation in China has had an impressive impact on the clean energy sector, notably in helping to reduce the costs of solar PV by over 90% since 2005 and automotive lithium batteries by 90% since 2010. The experience with solar PV, batteries and light-emitting diodes (LEDs), has arguably changed energy technology expectations more generally, raising confidence that innovation will lower the economic and political barriers to tackling climate change. More recently, China's contributions to product and equipment improvements have grown as its foundational science capabilities have improved, particularly in ultra-supercritical coal (UCS) combustion, coal conversion, ultra-high voltage transmission and nuclear power. China is now at the forefront of further advances in solar PV, battery, electric vehicle (EV), hydrogen and digital technologies as researchers and technology developers worldwide seek energy solutions that can follow similarly steep learning curves based on modularity and large-scale manufacturing.

China accounted for one-quarter of global public spending on energy R&D and 15% of spending on low-carbon energy R&D in 2020.<sup>1</sup> Public energy R&D spending increased under the 13th FYP (2016-2020) from about USD 6.8 billion (CNY 47.2 billion) in 2015 to USD 8.3 billion (CNY 57.3 billion) in 2019, making China the world's largest energy R&D spender in absolute terms ahead of the United States in that year and the third-largest per unit of GDP after Norway and Finland. Following pledges made in 2015 under Mission Innovation, China's lowenergy R&D spending increased 70% from USD 2.4 billion carbon (CNY 16.8 billion) to USD 4.1 billion (CNY 28.1 billion) over the same period, compared with a rise in GDP of about 30%, raising the low-carbon share of total energy R&D from 35% to nearly 50%.





Notes: Left graph: R&D = research and development. Spending includes government and "state-owned enterprises budget estimates. Middle graph: venture capital represents seed, series A and B, grants, growth equity, private investment in public equity, buyout and late-stage private equity, and coin/token offering venture capital deals in clean energy start-ups. Right graph: EVs = electric vehicles; HVAC = heating, ventilation and air conditioning; PV = photovoltaics. Patent counts in climate-change mitigation technologies relating to energy filed in at least two geographical offices. Three-year moving averages are used.

Sources: IEA analysis (2021) based on data from: IEA (2021b); Cleantech Group (2021); OECD (2020).

# China accounts for about 15% of global public spending on low-carbon energy R&D and a rising share of start-up and patenting activity

<sup>&</sup>lt;sup>1</sup> While data on inputs to innovation, such as R&D spending and finance for entrepreneurs, and outputs from innovation, such as patents, are imperfect proxies for innovation quality and long-term outcomes, they illustrate the rising level of effort and importance given to clean energy innovation in China.

The increase in China's clean energy funding has been accompanied by a shift in the focus of energy innovation from publicly led R&D and demonstration projects to addressing other elements of its innovation system (IEA, 2020a). This includes more decentralised responsibility for both R&D and deployment of new technologies, as well as more attention to flows of knowledge between researchers and industry.

China's share of international patenting activity for clean energy technologies has grown markedly over the last two decades. In 2018, Chinese inventors accounted for 32% of global patenting for lighting, 23% for heating and cooling, 25% for solar PV, 10% for wind, 12% for other renewables, 13% for batteries and 8% for EV and charging technologies. In addition, venture capital activity started to skyrocket in China around 2015, with a focus on electric mobility and a number of very big early-stage deals (above USD 150 million [around CNY 1 billion]); there were few Chinese start-ups in the energy sector just ten years ago. In 2019, energy in total attracted about as much venture capital investment as semiconductors or medicine and health (MOST, 2021d). Over 2018-2020, China accounted for about 35% of global early-stage financing for clean energy start-ups.

## China's approach to energy innovation

Choices about technology development in China are often characterised as the result of decisions taken and applied in a top-down manner, but this oversimplifies the unique systems in place that encourage rapid innovation. These systems have several features that are largely unmatched in their nature or scale worldwide. This section focuses on five features, assessing their impact on innovation and contrasting them with approaches in other countries:

- Mobilising funding for strategic national missions.
- Devolving responsibility for innovation to SOEs.
- Empowering provincial and municipal governments to experiment and compete.
- Reaping the benefits of the country's vast domestic market to spread risks and sustain competition.
- Facilitating international co-operation to accelerate learning, especially between firms.

The energy technologies that China has prioritised in the past decade, including nuclear power, high voltage transmission, coal conversion, batteries, EVs and hydrogen, have all benefitted from these five factors to some extent.

The combination of these features creates a framework that is highly centralised in goal setting and relatively decentralised in goal attainment, providing considerable flexibility for policy makers and companies to experiment quickly and on a large scale (Xu, 2020). While working within the boundaries of the objectives established by the national government, SOEs, private companies, universities and provincial and municipal governments are given considerable scope to define targets, take risks and follow technological paths that would be unfamiliar to most other countries. This is facilitated in particular by the sheer size of the national and provincial economies, which can accommodate several projects at the same time. It is also driven by a history of needing to deliver projects with lower budgets than in other countries, such as the United States.

The innovation system that has emerged benefits from the rapid learning from multiple efforts at different levels of government oversight with a higher tolerance of failure than elsewhere in the world. In digital technologies in particular, China's market size and speed of adoption of new products are bringing high expectations of disruptive change, but have not yet brought the country to the international frontier of certain complex energy technologies. That is the official goal for the next five years.

#### Mobilising funding for strategic national missions

China's FYPs provide a common vision of technology priorities over the medium term and can ensure stable funding for R&D projects that result from the high-level guidance. Certain energy technology objectives have been elevated to the status of national missions with strategic socio-economic importance. They include USC coal and nuclear power generation, as well as oilfield drilling and coal conversion, all of which have received high-level support and large-scale funding in recent FYPs, driven by concerns about energy security and, to a lesser extent, environmental protection.

The development of USC coal power plants, initiated under the 11th FYP (2006-2010), is a good example of China's ability to co-ordinate researchers, developers and investors in meeting a technology goal. The 11th FYP targeted a 20% reduction in energy consumption per unit of GDP and 10% lower sulphur dioxide emissions (Chang et al., 2016). Alongside the closure of small, inefficient coal plants, R&D in advanced combustion was stepped up rapidly, involving tests on older plants. This accelerated during the 12th FYP (2011-2015), leading to the world's largest supercritical circulating fluidised bed boiler and the first 1 GW USC air-cooling unit. By 2016, a combined 66 GW of these USC units were operational in China, with one of them holding the world energy-conversion efficiency record

at 48% (Wiatros-Motyka, 2016). In the case of coal conversion technology, particularly for chemicals production given the sector's dependence on oil and gas imports, resources were similarly mobilised quickly to develop scientific expertise and invest in demonstration plants followed by commercial facilities.

# Box 6.2 Coal conversion: example of large-scale, centrally co-ordinated technology innovation

The Chinese government has sought to develop technologies to convert coal to chemicals and other products since the 1970s, accelerating support in the early 2000s (Xu, Liu and Li, 2020; Wei, Wang and Ding, 2019; Zhao and Gallagher, 2007). The National Medium and Long-term Science and Technology Development Plan (2006-2020) promoted coal-to-chemicals, coal-to-liquids and coal-to-gas as means to reduce reliance on imported energy to produce the goods driving China's economic growth (State Council, 2006). By the end of the 13th FYP in 2020, China was home to most of the world's large-scale coal-to-chemicals plants (about 35 out of 40 in 2016) and some of the world's most advanced-coal conversion technologies, including gasification, indirect coal-to-liquids and methanol-to-olefins. Coal-to-methanol-to-olefins, in particular, is a technology development specific to China, achieved by aligning the funding and incentives of stakeholders across the innovation value chain.

Key actions in developing coal conversion technologies include:

- The Ministry of Science and Technology and other key actors such as the National Energy Administration and the Institute of Coal Chemistry at the Chinese Academy of Sciences included coal conversion among the major S&T projects in 2001 (the 863 programme at the time, a national programme started in 1982) and allocated dedicated annual R&D funding.
- The government set long-term funding horizons and targets to signal that they would sustain efforts over more than a decade. The 2006-2020 plan was followed by the Action Plan for Clean and Efficient Utilization of Coal (2015-2020), the 13th FYP for Demonstration of Coal Deep Processing Industry and the Energy Technology Revolution Innovative Action Plan (2016-2030).
- SOEs, including Shenhua Group, were elevated to become national coal technology champions. Shenhua established a demonstration site in 2004 and now operates the world's largest coal-to-chemicals plant. In 2008, China Development Bank issued a ten-year loan of USD 350 million (CNY 2.4 billion at the time) to set up the 0.6 million tonne capacity Baotou coal-to-olefins demonstration project in Inner Mongolia.

- The government co-ordinated new R&D and test facilities for researchers to focus on specific technology challenges, some of which brought together university and private sector experts. For example, Synfuels China, a 2006 spin-off from the Chinese Academy of Sciences, set up three large innovation centres specialising in Fischer-Tropsch synthesis.
- Provincial governments in coal mining regions were encouraged to co-invest in and extend low cost finance to new facilities and R&D centres, leading to a proliferation of new projects.
- Equipment purchases, licence agreements and joint ventures were all used to test and learn from the products of European and US institutes and companies. Shenhua's first coal-to-liquids plant used imported technology, but by 2016 it had developed its own, as well as a modified methanol-to-olefins technology.



#### R&D spending on coal mining and chemicals production in China

IEA, 2021.

Notes: Main enterprises, refer to companies with revenue from principal activities over CNY 20 million (equivalent to USD 2.9 million in 2019). In official documents they are referred to as "industrial enterprises above the designated size".

Sources: IEA analysis based on data drawn from China's Statistical Yearbooks (NBS, 2020a), China's Statistical Yearbooks on Science and Technology (NBS, 2020b) and annual reports of Shenhua Group (Shenhua Group, 2020).

Despite the technical progress made with coal conversion under this multifaceted and co-ordinated approach, the programme ran into challenges (Minchener, 2011). Notably, the incentives for provincial governments to invest in infrastructure were stronger than expected, especially when coal prices were low. This led to a wave of large-scale projects despite a request for caution in 2006 from the National Development and Reform Commission (Jia, 2008). The central government eventually intervened to suspend new projects as international oil prices fell from their 2008 peak. By 2010, it was also apparent that water extraction from the Yellow River risked exacerbating water scarcity in Inner Mongolia, and several coal-to-chemicals plants were found to be in breach of environmental regulations. In 2012, Shenhua indefinitely delayed its flagship integrated CCUS project intended to show that lignite conversion could have low emissions.

The government has found it much harder to limit coal conversion investments in recent years than it did to initiate the innovation programme. In April 2021, following China's carbon neutrality pledge, the president announced that the government would strictly control coal-fired power generation projects and strictly limit the increase in coal consumption over the 14th FYP period (2021-2025), phasing it down in the 15th FYP period (2026-2030). In July 2021, China suspended the construction of the Yulin coal chemical project by state-owned Shaanxi Coal and Chemical Industry Group Co. over energy consumption concerns, which was expected to start operations in 2025 and become the world's largest of its kind with a total investment of USD 20 billion (more than CNY 120 billion). Since 2010, coal-to-liquids and coal-to-olefins operations in China have added around 750 Mt of  $CO_2$  emissions compared with those that would have arisen had production been based on oil.

In the case of both USC and coal conversion, the government used incentives such as national R&D project funding, tax breaks, rewards for patents and preferential access to capital. In addition, coal-producing provinces were encouraged to invest in these new technologies to help them reach their GDP targets. Under the 14th FYP (2021-2025), this policy approach, involving selecting priority energy technologies and steering research and investment towards them will continue, as will R&D into coal. However, the early signals are that the range of technologies is likely to be broader and that the government will strengthen formal mid-term reviews and monitoring mechanisms for R&D programmes. Without these changes, the risk of over-investment and new vested interests that make it hard to change course, which troubled the coal conversion programme, will persist. Some other countries and regions also have multi-year planning horizons for energy research, but few prioritise strategic technology areas so strongly. The European Union, for example has a longer planning period, with each multi-annual budget spanning seven years. Many governments keep energy and climate technology priorities broader than China's major S&T projects, with more scope for adjustment and technology-neutral competitive processes. Japan is an example of a country that takes a narrower approach to prioritisation, with eight specific technology areas identified for the 2016-2030 period in its National Energy and Environment Strategy for Technological Innovation towards 2050 (IEA, 2016). It also has a dedicated institution - the New Energy and Industrial Technology Development Organization – for co-ordinating public-private consortia for large-scale demonstration projects. As China's expansion of industrial capacity slows in the coming years, it may be less able to depend on provincial investment incentives for demonstrating new priority technologies, and may need to make use of such co-ordination mechanisms as well as performance-based project selection.

#### **Devolving responsibility to SOEs**

SOEs dominate the Chinese energy sector and play a major role in energy investment and innovation, both nationally and globally. The five largest stateowned power generation companies own nearly half of the country's power plant assets, while the State Grid Corporation of China (SGCC) and the smaller stateowned China Southern Power Grid Company have monopolies on grid operations. SOEs have a higher share of ownership of power generation capacity in China than in most other major economies. SOEs are given explicit responsibility for developing certain technologies and almost single-handedly provide the initial market as buyers of new technologies in some sectors, including heavy industry, fossil fuel supply and power generation, where they have spearheaded huge investments in renewables.



#### Figure 6.3 SOE ownership share of power generation capacity in G20 countries

IEA, 2021.

Note: The definition of SOE used here includes any minority ownership of a company by a central or sub-national government as a well as 100% SOEs. Source: OECD (2018).

# SOEs have a higher share of ownership of power generation capacity in China than in most major economies

National R&D and major S&T projects are the primary instrument used by the central government since the 13th FYP (2016-2020) to advance energy innovation via SOEs. The government funds the national R&D projects according to the

technology priorities of the FYP with most funding going to SOEs, who also contribute their own resources to the projects. Major S&T projects are large-scale, multi-year R&D or demonstration projects in priority sectors run by a list of selected SOEs. Nuclear fission power generation has been a focus of major S&T projects and their predecessors under the so-called 863 Programme – a state technology programme that ran from 1986 to 2016. To test and validate different approaches, three SOEs have been given mandates to develop different technologies in parallel.

The national and provincial governments also direct the SOEs to take on other leadership roles in energy innovation. For example, they are required to develop internal technology roadmaps and talent development plans to hire skilled individuals and train staff, and set up R&D projects and laboratories in line with the FYPs. In the 14th FYP (2021-2025), they are required to actively promote the application of new energy saving, low-carbon and environmentally friendly technologies (SASAC, 2021). In 2021, companies including SGCC – a global leader in ultra-high voltage transmission technology and smart grid deployment – and some of the world's largest steel producers began formulating technology development plans compatible with carbon neutrality.

#### Box 6.3 Nuclear technology development by SOEs

Nuclear power has been an energy technology priority in China for many decades. Since 2000, there has been a stronger focus on homegrown concepts for largescale advanced pressurised water reactors, including through major S&T projects proposed by the National Medium- and Long-Term Science and Technology Development and Planning Guidelines (2006-2020) and the Medium- and Long-Term Nuclear Energy Development Plan (2005-2020) (State Council, 2006).

China has three SOEs active in nuclear power generation. Historically, each has adopted a different approach to technology development and innovation, with the government encouraging competition to develop new designs for national adoption and export (Yi-chong, 2010). China National Nuclear Corporation (CNNC) has a mandate to design and operate its own reactor design, building on its military technology expertise. China General Nuclear Power Group (CGN) operates power plants licensed from France's Framatome and has a mandate to adapt and learn from these to produce a new design. State Power Investment Corporation (SPIC) has a similar approach to CGN but focuses on designs from US suppliers.

The government has struggled to combine the resources and knowledge of the three SOEs in an efficient manner in recent years amid divisive views within the

nuclear community about how best to serve China's nuclear technology ambitions. In 2013, China adopted a more hybrid approach to accelerate the development of current (generation III) technologies, bringing CNNC and CGN closer (Hui, 2014). A formal merger has been resisted, but the two SOEs set up a joint venture SOE – Hualong Nuclear Power Technology Company – to develop the Hualong One reactor design based on a combination of CNNC's ACP1000 and CGN's ACPR1000+ designs, which have been developed separately.

Chinese regulators granted the Hualong One design a license in 2014. They were satisfied that its developers owned the intellectual property rights and that core parts were designed and produced domestically. However, full standardisation was not achieved and two slightly different Hualong One versions coexist. The first plant began operating at Fuqing in January 2021 and the first overseas unit in Pakistan in May 2021, with eight others under construction. CNNC stated that it would start construction of Hualong Two by 2024, a potentially cheaper, improved version of Hualong One (Xu, 2021). In July 2021, CNNC started construction of the world's first commercial small modular reactor project, a 125 MW unit based on the domestic Linglong One ACP100 design, and is building the world's first prototype (2 MW) of a commercial thorium reactor (Stanway, 2021). In parallel, SPIC has developed another homegrown third-generation design, CAP1400, drawing on experience with imported Westinghouse AP1000 designs.

It is not yet clear how China's hybrid approach involving indigenous innovation and the incorporation of foreign concepts might be applied to Generation IV technology, reprocessing or other large-scale energy technologies. While it is a successful example of achieving national energy technology goals, lessons could be learned for managing the competing interests of SOEs that each have different sponsors within government. Tensions have arisen in 2021 over co-operation agreements between China and European countries for operating or building nuclear plants with CGN, underscoring the vital importance of good relations with customer countries in the field of nuclear technology exports.

Despite the recent increased involvement of private Chinese companies in energy innovation, especially in solar PV and wind power, SOEs will probably continue to play a central role. SOEs have extensive links to decision makers and research communities, their large balance sheets enable them to finance large-scale demonstration projects and they benefit from preferential access to capital (Zhang, 2020). However, their role will vary by technology. In some resource-intensive areas like nuclear power, chemicals, iron and steel, cement and oil refining, they have the expertise and large-scale industrial laboratories to develop and demonstrate new technologies, often in co-operation with universities. In power generation and supply, governments can direct them to provide commercial test

beds for emerging renewables, hydrogen, storage and CO<sub>2</sub> capture technologies. For end-user goods like vehicles, SOEs do not always dominate markets but can have preferential access to knowledge via international joint ventures (two leading SOEs, FAW Group and SAIC, are manufacturing partners of Volkswagen, China's leading car seller). SOEs also have the resources to invest heavily in start-ups: they accounted for 15% of all venture capital investments in 2019, about as much as government-led funds (MOST, 2021d). For example, SAIC Motor led a USD 1.5 billion (CNY 9.7 billion) funding round in 2020 among other state-backed actors to back WM Motor – one of several China-based competitors of the EV manufacturer Tesla.

Relying heavily on SOEs for clean energy innovation, which is unusual among the major economies, carries risks. Their market dominance and internal technology preferences, based on prior experiences or know-how, can create high barriers to entry for other companies or innovators with promising technologies. These barriers can be reinforced by economic incentives that encourage SOEs to meet government targets in ways that preserve the value of existing assets. Additionally, while Chinese SOEs are unusually quick to adjust to changes in governmental policy priorities, there are always risks associated with the inertia and influence of large, dominant companies with close ties to policy makers (Genin, Tan and Song, 2020; Tõnurist and Karo, 2016; Luo et al., 2016, Zhou, Gao and Zhao, 2016). Moreover, energy SOEs typically have an incremental engineering-oriented approach to technology and are less likely to pursue completely new innovative technologies.

Other governments have found various ways to engage large corporate energy players in the development of cutting-edge technologies. In the case of regulated network operators, several countries have followed the lead of the Netherlands (2015) and the United Kingdom (2016) in instituting so-called regulatory sandboxes to allow innovators to trial new products and services without needing to comply with all existing regulation (ISGAN, 2019). In the United States, the National Renewable Energy Laboratory (NREL) runs two programmes – IN2 and GCxN – involving a private entity funding government laboratory staff to identify entrepreneurs with relevant, high impact technologies and support their testing, validation and incubation. The funders get to learn quickly about new technologies that were not on their radar, but do not have exclusive access to them. In 2014, NREL helped establish a network of energy start-up incubators and accelerators, which are now operated by electric utilities who have equal access to the ideas that emerge and can co-operate to create demand for those closest to commercialisation (NREL, 2015).

Ensuring that SOEs have incentives to continually improve technological performance and compete fairly with each other and newcomers will help achieve clean energy goals. Staff promotion is increasingly linked to environmental and innovation performance at Chinese SOEs, some of which are actively introducing cultures that foster innovation, such as through the National Institute of Clean and Low-Carbon Energy (NICE) at China Energy Investment Corporation.

#### **Empowering provincial and municipal governments**

Provincial and municipal governments have been key players in the development of certain energy technologies in recent years. There are 17 Chinese provinces with economies that are each larger than that of the Philippines. Provinces and municipalities have strong incentives to attract investment in and become manufacturing hubs for new technologies. Large solar PV and battery manufacturers such as CATL, LDK, Suntec, Trina and Yingli have set up R&D centres in cities (Ningde, Xinyu, Wuxi, Changzhou and Baoding) that supported the establishment of their manufacturing bases. The central government encourages sub-national governments to experiment with market creation and different approaches to creating local champions, for example in EVs.

In 2009, the "Ten Cities, Thousand Vehicles" programme, which ran until 2012, established a group of municipalities that were encouraged to support EV production and purchases. Ten pilot cities were selected to deploy 1 000 vehicles in each location, with each city being free to decide on how to achieve that. The Ten Cities became home to the pioneers of EV deployment in China, such as BYD in Shenzhen, using different combinations of purchase incentives, loans, tax rebates, access to land, permits, export credits and direct government procurement. The cities also set up specialised innovation clusters and demonstration zones and spurred related investments and improvements in battery manufacturing. By 2012, seven cities reached the target and another 15 had been added to the programme. Subsidies of up to 60% of vehicle costs were common. Shenzhen mandated electrification of its 16 000 strong bus fleet by 2018, subsidising up to half the bus purchase price, installing charging facilities at 180 bus depots and working with manufacturers to reduce risks for customers, for example by providing battery warranties and leases.

Since 2015, local government autonomy to provide subsidies has been gradually curtailed and the central government released new policy support schemes with stricter technology standards. As subsidy conditions have become more stringent, national, provincial and municipal support schemes have shifted to having tighter thresholds for subsidies that encourage performance improvement, including for

vehicle range, energy consumption, battery standards and safety requirements (Muniz, Belzowski and Zhu, 2019).

Building on the country's experience with EVs, the devolution of policy experimentation to sub-national governments to stimulate new markets for nascent clean energy technologies is likely to continue. One advantage is that local policy makers are closer to the needs, preferences and resources of local businesses and consumers, and can create support for public spending that promotes tangible jobs and environmental benefits. The most suitable technologies may be those for which an individual region can use public procurement and infrastructure investment to gain a competitive edge, and look to sell a superior technology to consumers across China and overseas. The rapid growth of hydrogen R&D and demonstration programmes since 2017 has so far largely followed this model, building in particular on the "Ten Cities, Thousand Vehicles" programme.

#### Box 6.4 Hydrogen technology development at the sub-national level

Hydrogen technologies have long been a focus of China's energy innovation. They were included in the Medium- to Long-Term Science and Technology Development Plan (2006-2020) and the government has been providing subsidies to hydrogen fuel cell electric vehicles (FCEVs) since 2009 (Ministry of Finance, 2020; State Council, 2006). Between 2006 and 2010, Shanghai and Beijing funded FCEV demonstration programmes and SAIC Motor, an SOE, developed its own fuel cell systems with Tongji University. However, while these early programmes helped build some expertise in hydrogen-based mobility, overall activity has remained limited to date.

In 2020, the Chinese government amended its fiscal support measures for "new energy vehicles" to include FCEV demonstrations, R&D in key core technologies and support for building a complete FCEV industry chain over the 14th FYP period (2021-2025). It has also launched a programme to nurture FCEVs modelled after the "Ten Cities, Thousand Vehicles" EV initiative. It encourages provinces to set up demonstration zones in cities, provide funding for the establishment of fuel cell industries and co-ordinate efforts in agglomerations that cross provincial borders, such as Jingjinji Metropolitan Region, Yangtze River Delta and Greater Bay Area. By the end of 2020, 22 provinces and cities had issued a total of 105 policy documents to support hydrogen development, up from almost none before 2017 (OGRI, 2020). Guangdong, Jiangsu and Shandong have been most active to date.

Several of the provincial strategies cover the entire value chain, including hydrogen production and storage, refuelling and vehicles, as well as fuel cells.

The central government has recently changed its policy of encouraging subnational governments to subsidise FCEV purchases to rewarding technology innovation and deployment. Bonuses will be provided to producers that achieve performance goals for specific technologies, including electrolyser membrane, electrode assemblies, proton-exchange membranes, carbon paper, catalysis, bipolar plates and compressors. To obtain a bonus, the technology must be used in over 500 vehicles, each driven for more than 20 000 kilometres and performance must be verified by a third-party.

The focus of the hydrogen plans being developed by regions and cities varies. For example, Shandong already had some hydrogen-related technology capacity before 2020, with Weichai, an SOE that makes engines, becoming a 20% shareholder in Ballard fuel cells in 2018, and the private sector Dongyue Group producing fuel cell membranes. The province now aims to set up an industrial cluster for fuel cells in Weifeng and one for related materials in Zibo, plus others for FCEVs in Liaocheng and hydrogen supply in Jining. It plans to transform Qingdao into the "Eastern Hydrogen Island" and Jinan into the "Chinese Hydrogen Valley". In contrast, Ningxia and Shanxi provinces, which are major coal producers, are focused on developing new value streams for hydrogen, especially from coal.

While the central government is seeking more co-ordination of provincial subsidies and limits on their use to avoid boom-and-bust cycles, funding from sub-national governments remains larger than that from the central government in many cases. These governments often own important local businesses have strong connections to industry. These factors, combined with inter-provincial competition, could drive rapid scale up of the hydrogen sector and innovation to produce better and cheaper components and hydrogen supplies. However, it remains unclear whether performance-based rewards will guide researchers towards the same narrow set of technical solutions or whether competition for export market share will prioritise costs over longer term technology leadership and knowledge sharing between provinces. As policies are currently directed mostly towards manufacturers, some provinces might need additional R&D funding and skills to be able to develop cutting-edge technologies.

Hydrogen and other clean energy technologies supported by provincial and municipal governments can also benefit from the National High-Tech Zones – a programme launched in 1988 and significantly expanded since 2010. The State Council approves these zones, which benefit from infrastructure investment, access to a broad pool of skilled workers and financial incentives such as tax breaks. The 169 existing zones have established networks of researchers,

laboratories, companies, incubators and technology transfer institutions (MOST, 2021e). The Ministry of Science and Technology has stated that the programme will be modified to support the new carbon neutrality targets, including the introduction of evaluation metrics relating to low-carbon energy (MOST, 2021f).

Reliance on sub-national led innovation is not without risks. The development of EVs saw some cities or provinces strongly back local champions that ultimately went bankrupt. At the other extreme, this approach can incentivise sub-national governments to do the minimum to attract political recognition and investment approvals, leading to superficial pilot projects that foster minimal innovative activity and distract from the efforts of technology leaders. In addition, the *ex-ante* selection of regions to host demonstrations and innovation clusters might exclude some potential innovators in other parts of the country and lead to an over concentration of resources for innovation in certain areas, such as corporate R&D funds currently concentrated in eastern regions (MOST, 2021g).

The European Union has a different approach to co-ordinating test beds in different regions. In 2008 it established a unique legal entity – the Fuel Cells and Hydrogen Joint Undertaking – to accelerate the market introduction of hydrogen energy technologies and develop an industrial base. It has a multi-year budget, which was EUR 1.3 billion (USD 1.6 billion) for 2014-2020, to which the European Commission contributes half, and manages calls for projects in co-ordination with the Commission, an industry grouping and a research institute. It has supported over 250 projects and shares the technology learnings among participating EU countries and municipalities.

#### Reaping the benefits of a vast domestic market

The sheer scale of China's domestic population and the large market that has resulted from decades of rapid economic growth benefits energy innovation in several ways:

- Multiple competitors can each attract substantial amounts of capital in the early stages of market expansion for a particular technology.
- A company only needs to capture a small market share to justify building a worldscale factory.
- There is scope for market differentiation, including a large market for low-cost products and services.
- The market is large enough to have its own standards and regulations that allow local firms to focus on a single set of requirements and raise barriers to entry for overseas competitors.

• Risks can be spread widely and under-performing technologies are quickly superseded by newer generations. In a market for many millions of units per year, a company can launch an upgraded generation of products frequently, advancing the innovation frontier.

The benefits of having a large domestic market are substantial for energy technologies sold to other companies, such as wind turbines and ultra-high voltage transmission, and even greater for end-use consumer technologies. China has been one of the most dynamic markets for production and innovation in a range of energy-related consumer products, including heat pumps, energy efficient appliances, air conditioning, smart meters, digital connected devices, EVs and other devices containing lithium-ion batteries. EVs are a notable example of how policy in China can create a huge new market almost from scratch and create some of the world's most valuable companies that are able to outcompete established multinationals. China is keen to apply this market creation approach to hydrogen and FCEVs too, though these technologies differ from batteries and EVs in two critical ways: they require a co-ordinated approach to pipeline and refuelling infrastructure, and, as fuel cells are still a relatively immature technology, more focus on fundamental innovation R&D compared with that required, for example, by batteries and PV at the times when China adopted them.

#### Box 6.5 Turbo-charging China's EV technologies by boosting demand

China's EV industry emerged in response to strong government support related to concerns about import dependency and urban air pollution in the face of booming demand for personal mobility. The sale of new cars increased more than fivefold between 2005 and 2015 as the population grew and people became wealthier. The 11th FYP (2006-2010) aimed to "accelerate the development of automobile engines... and components with independent intellectual property" (NPC, 2006). The "Ten Cities, Thousand Vehicles" programme was launched in 2009. The Energy Saving and New Energy Vehicle Industry Development Plan (2012-2020) elevated "pure electric drive as the main strategic orientation for the development of new energy vehicles" and set performance targets for technology development in EV technologies (NPC, 2006; NEA, 2012). As a result, China overtook Europe in 2015 as the world's largest market for electric cars. Today, it is home to 98% of the world's electric buses (IEA, 2021c and 2020b). Chinese companies now account for significant parts of the global EV value chain from lithium extraction and processing, battery and EV manufacturing and charging to recycling. Many of

these companies did not exist in 2015, or were focused on other sectors, but now possess world-class technologies.

China's success in developing its EV industry was driven by its large internal market and a broad consensus on the strategic importance of supporting this new industry. Yet the creation of a large domestic EV market did not on its own spark innovation. In the early days, several protectionist measures designed to nurture Chinese companies – such as high purchase subsidies with local sourcing requirements and favouring smaller EVs with limited range – held back technological progress and resulted in a gold rush for EVs, with over 200 companies producing on average less than 3 000 cars per year in 2015, which created a bubble, fragmented the market and triggered subsidy fraud in many cases. Based on the experience of the regional pilots, the central government subsequently linked incentives to continual performance improvements and established quotas and fuel economy standards for all automakers (Muniz, Belzowski and Zhu, 2019).

Over the past five years, Chinese car companies have collaborated with research institutions and established large R&D facilities that have led to major technological advances in the field of EVs. With sales of 1.2 million electric cars in 2020, the domestic market is large enough to support hundreds of manufacturers of cars and batteries, catering for different levels of performance and luxury. BYD, a Shenzhen-based battery company, received over USD 400 million (over CNY 2.5 billion) in public subsidies for manufacturing EVs between 2010 and 2015 (Heller, 2017), despite having no automotive experience prior to the 2000s. It is now one of the world's largest EV and battery companies, second only to Tesla in cumulative global EV sales. Its innovative Blade Battery, which is set to go on sale in Europe in 2021, offers world-leading safety performance. Since 2015, Chinese investors, including digital companies such as Alibaba, have mobilised the world's biggest venture capital investments for EV start-ups including WM Motor, Xpeng and NIO.

A large and growing domestic market for consumer products is not a sufficient condition for innovation. China has benefitted from a corporate culture that prioritises speed to market and market share above meeting the highest quality standards. The result is a high level of comfort with risk and commercialising new products in advance of full regulatory clarity. Product managers within companies also have considerable freedom to establish new production lines (Yip and McKern, 2017). In contrast with some popularly held impressions of Chinese manufacturing, it has many similarities with a "permission-free" innovation or a "move fast and break things" model, i.e. the scope of activity is only limited by what is explicitly outlawed, rather than one that waits for the consent of regulators and

society before investing. However, in coming years innovating firms may need to adapt to evolving market trends, including higher levels of disposable income and a rapidly ageing society. Higher expectations of product quality and environmental protection could result and pose a risk to China's dynamism.

The governments of some other countries that do not have such large and growing markets use public procurement to facilitate investment in demonstration projects or manufacturing plants for new clean energy equipment. For example, the Netherlands uses a system for public building works that discounts bids based on the  $CO_2$  performance of the tenderer, giving suppliers of low-carbon cement a financial advantage (Hasanbeigi, Becqué and Springer, 2019). As in China, many countries use grants and concessional loans. However, it can take a high degree of international co-operation to bring several countries together to create a large enough early market for new technologies. Within the European Union, state-aid rules affect how much financial assistance that countries or the European Investment Bank can provide to companies, with larger shares of co-financing allowed for smaller companies and innovations that benefit the environment. In North America, British Columbia, California, Oregon and Washington have formed the Pacific Coast Collaborative to create one regional market for low-carbon fuels, notably by unifying their low-carbon fuel standards that can support bioenergy, hydrogen and CCUS.

#### **Facilitating international co-operation**

International co-operation is an important means by which China seeks to achieve global leadership in energy technology and a crucial pillar of accelerating global energy innovation. The sharing of knowledge via formal agreements, trade and informal personnel exchanges is vital if the quality of research and its ability to reach markets and drive down costs are to be maximised. China's large internal market helps secure domestic manufacturing and knowledge sharing with overseas companies that want to invest in China, especially given much slower economic growth in the advanced economies. For example, from 2007 until 2017 when sales of new passenger cars in China peaked, the market grew by 15% per year on average, compared with less than 2% in the rest of the world. By 2017, China represented more than one-quarter of the global market, compared with 10% in 2007.

Solar PV exemplifies how China managed to enter a new technology area via joint ventures and licensing. Initially, this was not part of the central government's solar PV strategy. Rather, local governments helped Chinese companies set up manufacturing facilities based on licenced intellectual property or, in the case of

Suntech, on that developed abroad and part-owned by a Chinese citizen. This provided an entry point for several firms to scale up to become world-scale manufacturers and then undertake manufacturing innovation and, more recently, fundamental innovation in PV technology. Nuclear power and transport vehicle technologies are other examples of how the Chinese government and companies have used joint ventures with overseas companies to learn quickly about new technology areas and facilitate technology transfers.

In the case of EVs and batteries, the process was inspired by the experience with solar PV, as well as other technologies such as smartphones. Chinese authorities targeted manufacturing as the entry point from which to build the capacity to innovate, creating such strong local networks of component and sub-system suppliers that they attracted companies and orders from around the world. The firms generally are not the original designers of the products, but by working with the best components, interacting regularly and competing to meet the needs of international innovators they have innovated new approaches, functionalities and even new products that integrate locally available components, especially digital systems.

China's central government has also encouraged companies to tap into state-ofthe-art of energy technology by investing abroad, particularly since the 10th FYP (2001-2005) with the "Go Global" strategy. This has included the acquisition by SOEs and private companies of high-tech companies abroad, including specialists such as Alta Devices (acquired by Hanergy in 2013) and large engineering conglomerates such as Volvo cars (acquired in 2010 by Geely, which had only started making cars eight years earlier). As is normal in these cases, the purchasing company integrated the R&D activities of the new subsidiary into its own operations, often with government support (Osborne, 2015). Chinese SOEs have also invested in infrastructure, companies and R&D centres abroad to tap into a broader pool of skilled labour.

Another type of international co-operation adopted by China is bilateral and multilateral agreements with other governments. China funds joint energy R&D activities on common challenges with several countries around the world. The US-China Clean Energy Research Center, which has been operational since 2016, is a notable example. It brings together researchers from both countries to work on five main technology areas: advanced coal, energy efficiency in buildings, clean vehicles, medium-duty and heavy-duty truck efficiency, and energy and water. One product of the centre is a sprayable sealant technology for energy efficiency in buildings (US DOE, 2017). Other bilateral partnerships include the UK-China (Guangdong) CCUS Centre and a China-France Agreement to co-

operate on nuclear power technology (GDCCUS, 2021; WNN, 2018).<sup>2</sup> In addition to such bilateral mechanisms, China is a member of Mission Innovation – a global initiative of 22 countries and the European Commission to catalyse action and investment in R&D and demonstration in clean energy and a co-lead of its smart grids, biofuels and power sector programmes. China also participates in 27 of the 38 IEA Technology Collaboration Programmes – the fourth largest.

There is no doubt that China has the resources to continue each of these types of co-operation and to help other emerging economies move up the technology ladder. China's Belt and Road Initiative – a global infrastructure development strategy adopted by the government in 2013 to enhance physical ties to overseas markets – is just one opportunity to work with international partners to help other countries access the best international technology in the future, just as China benefitted from such access in the past. Experiences from HydroChina's involvement in wind power development in Ethiopia indicate how such programmes can incorporate local innovation capacity building (Chen, 2018). There are also examples of support by multilateral development banks to local innovation ecosystems, such as World Bank funding for entrepreneurs in Morocco and the International Finance Corporation's Catalyst Fund and Startup Catalyst programmes (World Bank, 2017).

In contrast to the continuing expansion of China's international co-operation on energy technology generally, patent activity suggests that its international collaboration on R&D has recently been in decline. The number of clean energy inventions co-patented by a Chinese inventor and someone from outside China has declined in absolute terms since 2013. The United States remains China's main patenting partner in clean energy, but China has a lower share of international co-patents among all its clean energy patents than the United States. Building trust through strong intellectual property governance, fair access to markets and depoliticised supply chains would reduce the risk of undermining international collaboration and co-operation on clean energy innovation.

<sup>&</sup>lt;sup>2</sup> Other examples of formal bilateral agreements, in addition to those in which China participates, include the research component of the US-India Partnership to Advance Clean Energy (PACE-R), which has operated a joint R&D centre since 2010, and the Joint UK-India Clean Energy Centre launched in 2017. In a more targeted approach, Japan has engaged partners in Australia, Brunei, Saudi Arabia and Norway for the development of hydrogen projects.



#### Figure 6.4 China's role in international clean energy technology co-patenting

IEA, 2021.

Notes: An international patent family represents a single invention for which patent applications have been filed at a regional patent office or in at least two jurisdictions worldwide. Source: IEA and EPO (2021).

Over the last two decades, inventors in China have been involved in a declining number of clean energy patents with international partners, which represents a lesser role than in some other major economies

# Box 6.6 China's transformation from a solar PV technology importer to innovator

China has funded solar PV R&D since the 1950s, but it was not until the early 2000s that innovation efforts took off. 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, other Chinese firms built on this model of attracting world-leading companies to manufacture in China, gaining access to technology and global value chains (Zhang and Gallagher, 2016). 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. Some Chinese companies also acquired foreign competitors and progressively absorbed their R&D activities (Urban, Geall and Wang, 2016). 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. In addition, 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 academic and professional experience abroad, with a focus on Chinese nationals working abroad (de la Tour, Glachant and Ménière, 2011).

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 the domestic deployment of solar PV in the 12th FYP (2011-2015). Competition for market share, often between companies backed by different municipalities, helped to drive impressive manufacturing innovations in China. 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 around industrial clusters with relatively open exchange of knowledge and expertise (Ball et al., 2017).

Chinese policy makers have indicated an ambition to remain the leading manufacturer of solar PV and the leading developer of new PV technologies. Chinese government laboratories and universities have already shifted their focus to next-generation PV designs, with corporate labs increasingly moving in the same direction. In 2016, Trina Solar set the world efficiency record of 19.9% for a laboratory version of a multi-crystalline solar module, though it has since been beaten (NREL, 2021). Microquanta Semiconductor earned the record of 17.3% for a perovskite submodule in 2018 and MiaSolé Hi-Tech, purchased in 2013 by Hanergy, holds a record of 17.4% for a copper-indium-gallium-selenide (CIGS) thin film module and claimed further records of 18.6% for a flexible module in 2019 and 27% for a hybrid perovskite-CIGS cell in 2021. Jinko Solar and Longi reported record efficiencies above 25% for variants of n-type and p-type monocrystalline cells in mid-2021. The gap between the performance of Chinese firms and overseas competitors has shrunk rapidly. However, most of the PV efficiency records set in the last three years have been by German, Japanese, Korean and US firms.

### **Opportunities to accelerate innovation**

The main features of China's energy innovation system give it unparalleled capacity to adopt, improve and bring new technologies to market quickly. Government policy is central to all these factors. The policy tools currently used vary according to the type of technology and sector. They include funding for

large first-of-a-kind projects, strategic guidance of SOEs, establishing deployment targets for selected regions, regulating equipment performance, banning certain technology options and international co-operation. They provide a good foundation for Chinese policy to foster the technologies needed to meet its energy and climate goals, taking account of the specific attributes of each technology.

Mass manufacturing of key technologies in the energy system is a relatively recent phenomenon and one in which China has been a leader for solar PV, batteries and LEDs. It has led to a wider range of innovation dynamics for energy equipment than existed in the 20th century, when most technologies were based on larger scale engineering solutions with unit sizes in the MW to GW range. By mapping low-carbon energy technology types according to their general attributes of size and modularity versus the likely barriers to entry in their markets – including the number of new purchases per year, access to regulated infrastructure, monopoly ownership and network effects – we identify four archetypal technology groupings that respond differently to various policy options. These groupings provide insights into how the component technologies of CCUS, hydrogen, bioenergy and electrification – four of the central pillars of the energy transition in China and the rest of the world – can be supported by governments.

Technologies characterised by small unit sizes, replacement cycles of under 20 years and high levels of standardisation, modularity and mass production play a major role in achieving carbon neutrality in China in the APS. These technologies are generally well suited to China's manufacturing strengths. Some of them, including smart controls, appliances and low-carbon vehicles, are characterised by high levels of product differentiation (i.e. they can be branded according to their distant characteristics) and are generally unsuited to vertical value chain integration and horizontal monopoly ownership (IEA and EPO, 2021). They also generally have low barriers to market entry. They can be disruptive in the sectors in which they are deployed, especially if policies incentivise innovation through competition between companies.

# Figure 6.5 Low-carbon energy technology types mapped according to their general attributes of size and modularity versus barriers to market entry



Sources: Adapted from IEA (2020c); Malhotra and Schmidt (2020); Schmidt and Huenteler (2016).

Large-scale technologies like CCUS and biorefining are suited to different policy incentives than network infrastructure or end-use consumer products

The second group of low-carbon technologies deployed in the Announced Pledges Scenario in China, including low-carbon industrial processes, modular nuclear reactors, low-carbon fuels production and CCUS, are more similar to traditional energy sector technologies. They are characterised by large upfront investment, chemical engineering approaches and economies of scale at the plant level, with only a small number of projects commissioned each year. They are not amenable to product differentiation and are often owned by vertically or horizontally integrated monopolies. Innovation in these areas tends to be slower

and does not benefit as much from the accumulation of knowledge and experience that is typical of smaller modular technologies, such as solar PV, wind power and batteries. Nonetheless, China has shown that it can mobilise SOEs and large Chinese companies to reorient their R&D plans and take responsibility for largescale demonstrations of these technology types. A concerted innovation effort, including rapid dissemination of the knowledge and experience that arises from such demonstrations, will be key to their widespread deployment in China, as in the rest of the world.

Between these two extremes lie two other groups of technologies. The first includes enabling technologies, i.e. intermediate or upstream supply-side technologies that are needed to pave the way for the deployment of end-use technologies. Electrolysers, long-duration batteries and certain types of direct air capture are in this category. They are generally modular, mass-produced and designed for industrial customers, so are less amenable to product differentiation. They have the potential for rapid cost declines through manufacturing competition, but could become dominated by a small number of large companies. To achieve rapid improvements in these types of technology, stronger policy incentives to invest in R&D and manufacturing are likely to be required.

Another group of enabling technologies that are targeted to industrial users are those that are generally not modular and are embedded in physical networks. These include thermal and mechanical energy storage technologies (such as pumped storage), district heating and cooling equipment, and smart grid hardware. Network infrastructure is often the responsibility of highly regulated monopolies, creating barriers to entry and limiting the number of potential customers. Public R&D and access to commercial test beds to demonstrate new ideas can be crucial for accelerating improvements in these technologies.

Ease of access to capital differs markedly among the four technology groups. In recent years, China's financial system has proven capable of allocating large sums of risk capital to early-stage technologies with high market growth potential, mostly new consumer-facing products and services such as EVs. For technologies that displace existing industrial processes, the central government has steered public and SOE funds to incumbent technology owners. These technologies usually have longer development times, higher development costs and higher barriers to market entry than venture capitalists will tolerate.

It is possible to identify the features of China's energy innovation system that can be mobilised for the development of the four technology groups and the types of capital they require. While this gives some overall guidance to policy approaches, each technology area has its own technical and market specificities. As discussed, China possesses considerable experience in tailoring policy incentives and innovation support to specific technologies. It can also draw on the wealth of international experience in this field.

Not all emerging technologies will fall within the four stylised groups presented here. For instance, digital technologies have specific innovation dynamics and can readily penetrate new sectors by delivering productivity gains and commercial data. They are poised to transform energy supply and use in unexpected ways in the coming decades, yet are not expected to yield significant CO<sub>2</sub> emissions reductions unless combined with the types of technologies in the four groupings described, as well as energy efficiency measures. The energy intensity of data centres is a particular concern in China, which prompted the introduction of national minimum energy performance standards in 2020.

Low-carbon technology group	Capital required to accelerate innovation	Relevant features of China's energy innovation system	Possible policy approaches in 2021-2025
New products and services for consumers	<ul> <li>Grants and tax breaks for early- stage experimentation.</li> <li>Venture capital and growth equity.</li> <li>Debt for manufacturing plants.</li> <li>Corporate and lab partnerships for market testing.</li> </ul>	<ul> <li>Spreading risk and sustaining competition within a vast internal market.</li> <li>Competing provincial and municipal pilot projects.</li> </ul>	<ul> <li>Sub-national level deployment targets.</li> <li>Performance-linked purchase incentives.</li> <li>Entrepreneurship prizes.</li> <li>Access to public and SOE laboratories for product testing and validation.</li> <li>Encourage partnerships between companies and universities.</li> </ul>
Modular enabling technologies	<ul> <li>Stable public R&amp;D funding.</li> <li>Venture capital and growth equity.</li> <li>Debt or grants for manufacturing plants.</li> <li>Corporate and lab partnerships for market testing.</li> </ul>	<ul> <li>Spreading risk and sustaining competition within a vast internal market.</li> <li>Competing provincial and municipal pilot projects.</li> <li>International co- operation.</li> </ul>	<ul> <li>Industry roadmaps and performance targets.</li> <li>Provincial and municipal pilots and test beds.</li> <li>Public procurement to create demand for final products.</li> <li>Innovation prizes.</li> <li>International R&amp;D projects on fundamental technology.</li> <li>Access to public and SOE laboratories for product testing and validation.</li> </ul>

# Table 6.2Low-carbon energy technology groups relative to possible innovation<br/>policy approaches that build on China's innovation strengths

Low-carbon technology group	Capital required to accelerate innovation	Relevant features of China's energy innovation system	Possible policy approaches in 2021-2025
Enabling network infrastructure	<ul> <li>Stable public R&amp;D funding.</li> <li>Corporate venture capital.</li> <li>Funds for field trials and commercial-scale projects.</li> </ul>	<ul> <li>Funding of strategic national priorities.</li> <li>Devolved responsibility to SOEs.</li> <li>International co- operation.</li> </ul>	<ul> <li>Industry-wide roadmaps and performance targets.</li> <li>Public investment in infrastructure with third-party access conditions.</li> <li>Incentives for inter-firm collaboration on technology.</li> <li>Open access knowledge sharing from network pilots and trials.</li> <li>Investment incentives for infrastructure upgrades, linked to performance targets.</li> <li>Reciprocal engagement in international technology trials.</li> </ul>
Industrial engineering processes	<ul> <li>Public co-funding and tax breaks for long-term R&amp;D and demonstrations.</li> <li>Corporate venture capital.</li> </ul>	<ul> <li>Funding strategic national priorities.</li> <li>Devolved responsibility to SOEs.</li> <li>International co- operation.</li> </ul>	<ul> <li>Industry-wide roadmaps and performance targets.</li> <li>Co-ordinated and differentiated SOE technology strategies and targets.</li> <li>National major S&amp;T projects and open access demonstrators.</li> <li>Public procurement to create demand for final products.</li> <li>Certification to promote international trade in low-carbon products.</li> </ul>

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