4. UHV and solar PV in China

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Clean energy innovation policymaking should actively engage diverse stakeholders to foster broad consensus and support for clean energy innovation activities. Aligning clean energy innovation with national strategies at the macro level can effectively garner political support for clean energy policymaking and break policy impasses. Where state-owned enterprises play a large role in energy technologies, governments can incentivise them to take on more clean energy innovation, leveraging their financial capacities and abilities to forge political and social consensus. In China, state-owned enterprises play a pivotal role in advocating clean energy technologies in policymaking and fostering clean energy innovation. Private actors face challenges in influencing clean energy policymaking and innovation in China, necessitating additional support from governments. Top-down intervention can help to break political deadlock and advance clean energy policymaking once there is a clear national vision.

Country context

China is the world's second-largest economy. At around USD 18 trillion in 2023 (market exchange rate basis), its GDP is around two-thirds that of the United States. However, on a purchasing power parity (PPP) basis, which takes into account the price of goods in each country, its GDP is 20% higher than that of the United States. Annual GDP growth averaged an impressive 10% between 1980 and 2010, driven by investment in industrial and infrastructure expansion as well as exports, much of which was powered by coal and accompanied by limited environmental protections. Between 2010 and 2022 the rate slowed to 6.9% on average and is expected to be around 5% in 2024. The government's 14th Five-Year Plan for the country, which runs from 2021 to 2025, charts a shift towards higher environmental protection and more high-tech output.

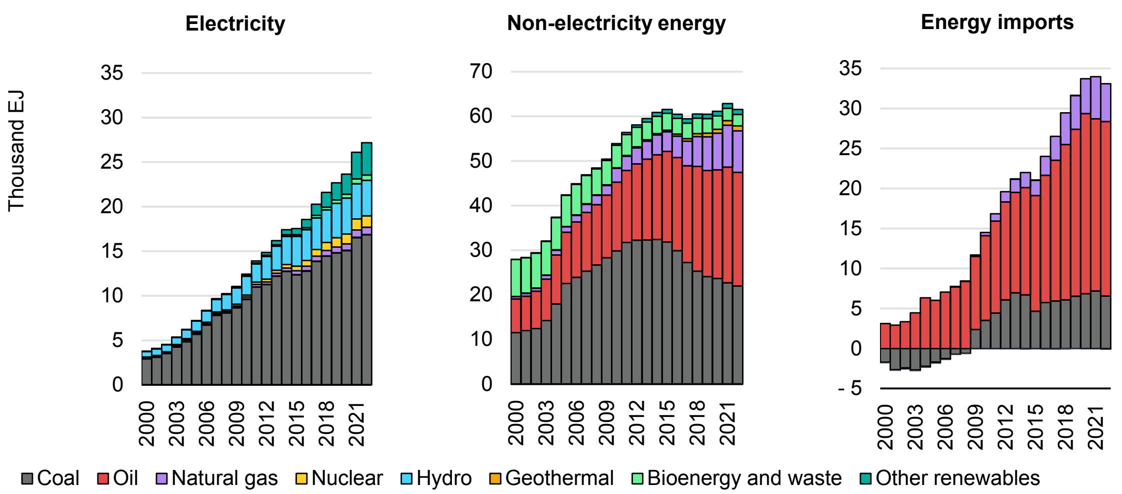
The government aims to reposition China from being a middle-income country to the high-income country by 2035. Its GDP per capita in 2022 was 2.9 times the minimum threshold for a lower-middle income country, and just 7% below the minimum threshold for a high-income country. However, it is one-sixth of the level of the United States (which has a car ownership rate five times higher) and one-third that of the European Union. In China's case, these national averages belie stark differences between regions and population groups, with the urban population enjoying per-capita disposable income that is 2.5 times that of rural residents. Through its “common prosperity” initiative and initiatives like the Solar Energy for Poverty Alleviation Programme, the government aims to narrow this gap.

Energy sector context

China’s energy demand is the highest in the world, and it leads global consumption of several individual energy sources, including coal (56% of global demand), wind (35%), solar PV (32%) and hydropower (30%). It is the second-largest user of oil and nuclear after the United States, and the third-largest user of natural gas after the United States and Russia. Unlike GDP, which grew strongly in the latter decades of the twentieth century and through to 2010, China’s final energy consumption grew most strongly between 2000 and 2010 – at an average annual rate of 8% – a period characterised by particularly energy-intensive development. Since 2010 this rate has slowed to 2.5% on average as GDP growth has dipped.

The high share of coal in meeting China’s final energy demand, at 44% in 2022, contributes to the country’s high CO_2 emissions, which have more than tripled since 2000. In 2006 China became the country with the highest CO_2 emissions from fuel combustion, being 40% higher than those of the United States in 2021. In 2020 President Xi Jinping committed China to reaching peak CO_2 emissions before 2030 and achieving carbon neutrality before 2060. China has an interim target to increase the share of non-fossil primary energy to 25% by 2030, from around 13% today.

Figure 4.1 Energy sources for electricity and other uses, and level of imports, China, 2000-2022



IEA and IITD. CC BY 4.0.

Notes: Electricity and non-electricity energy are shown on a final consumption basis. Imports are shown net of exports. “Other” refers to imported or exported electricity.
Source: IEA (2024), World Energy Balances.

One of the factors that has spurred China's pursuit of nuclear power, renewables and electric vehicles in recent years is its reliance on imported oil and natural gas (Figure 4.1). Net imports account for 75% of China's oil demand and 40% of its natural gas demand.

China achieved universal electricity access before 2000 and, unlike many emerging market and developing economies, this issue is not among its energy policy priorities.

Innovation context

Technology innovation is a central pillar of China's economic development strategy and this is emphasised at the highest levels by the change in strategic focus from "Made in China" to "Innovation in China". Its spending on R&D, at USD 433 billion in 2021, represents 2.4% of GDP and is second only to the United States in absolute terms. However, 2.4% remains below the OECD average of 2.7% and the level of 5% reached by Israel[1] and Korea. Nonetheless, the higher spending on R&D in recent years has driven up China's patenting activity and it now accounts for 47% of global patent applications, having overtaken the United States as the largest source of applications in 2011.[2] Since 2012 China has risen from 34th to 12th place in one international ranking of innovation performance, and produced the most-cited scientific research papers in 2021.

Clean energy innovation is one of China's top national priorities, alongside other strategic areas including artificial intelligence, semiconductors, quantum computing and synthetic biology. The government of China spends more on energy-related R&D than any other country. It seeks to compete with other countries to produce the most cutting-edge energy-related equipment in a range of areas, including advanced batteries, electrolysers for hydrogen and electric vehicles. Its manufacturers are already exporting high-quality lithium-ion batteries and solar PV modules designed in China. Critically, China's contribution to lowering the global price of these items lies partly in technology innovation related to manufacturing processes and not just input costs. By one estimate, China produced more research outputs in clean energy between 2001 and 2020 than any other country.

Choices about technology development in China are often characterised as being the result of decisions taken and applied in a top-down manner, but this

[1] The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

[2] While the impressive quantity of filings is undeniable, many analysts conclude that the quality of China's patents is not as high as those of other regions.

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:

- Mobilising large budgets for strategic national missions.
- Devolving responsibility for innovation to state-owned enterprises.
- 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.
- Negotiating international partnerships to accelerate domestic learning, especially between firms.

The case of UHV technology in China

Since UHV transmission technologies were first proposed in China in 2004, it has successfully managed to catch up with the global innovation frontier and achieve leadership status in terms of deployment. The term UHV is applied to any power transmission line, whether alternating current (AC) or direct current (DC), that can operate above 800 000 volts for AC or DC. For long-distance transmission, higher voltages are more efficient and can carry several multiples more electricity compared with equivalent cables at 500 000 volts. While there are some examples of the technology being used experimentally over relatively short distances in Japan and longer examples in the former Soviet Union in the 1980s, no country other than China has deployed significant lengths of UHV lines. However, the path to successful operation was not a smooth one and UHV remains a contested technology in China.

When UHV was proposed in December 2004 it was not in line with the national vision for the economy and energy, mainly for two reasons. Firstly, as UHV technology was costly, central government was reluctant to invest in the UHV technology innovation using national finance. Secondly, there was a lack of practical international experience of UHV technology to learn from, with developed countries' research on the technology remaining at the laboratory stage and not put into practical application. At that time the maximum voltage of power transmission lines that the country could build independently was no higher than 750 000 volts.

This misalignment changed early in the next decade. China experienced some of its worst pollution and air quality from coal combustion near major cities, leading the State Council to issue an Action Plan for Air Pollution Prevention and Control in September 2013. This plan made combating air pollution a top priority for central government and was followed by a strategy of "electricity as substitute", which referred to replacing inefficient coal and oil power plants near population centres with remote power generation in distant provinces and long-distance power transmission. This initiative gained support from central government, and UHV was included as part of the technology options.

Between 2005 and 2018 UHV was highlighted in a series of national strategies, moving it from an innovation or sectoral topic to the centre of national industrial policy:

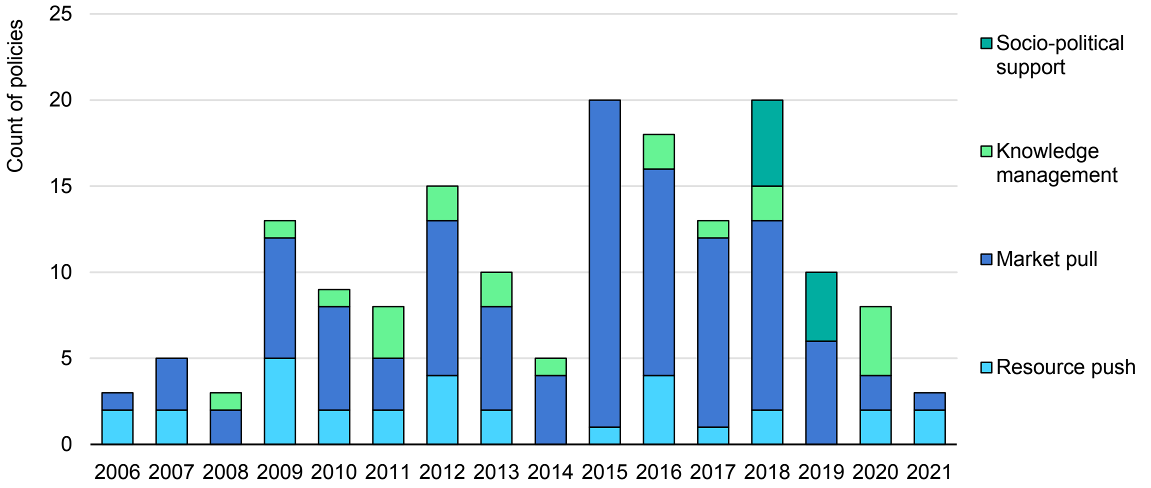
- The 2005 National Programme for Medium- and Long-term Scientific and Technological Development
- The 2011 12th Five-Year Plan for National Economic and Social Development
- The 2014 Work Plan for Strengthening Air Pollution Prevention and Control in the Energy Sector
- The 2018 Communiqué of the 2018 Central Economic Work Conference.

Alignment of the UHV innovation agenda with national and international visions for the energy sector were further strengthened towards the end of the 2010s as long-distance efficient power transmission became closely identified with renewable energy. The ability to bring electricity from diverse regions with solar and wind resources to power distant urban areas is central to most stakeholders' visions of how China will realise its 2060 carbon neutrality goal. In September 2020, when the Chinese carbon neutrality goal was articulated, UHV was emphasised as an important channel for delivering clean energy power generation.

UHV policy development through consultation and debate

China's central government issued 163 UHV-related policy documents between 2006 and 2021, covering different elements of innovation policy. Policies in the resource push and market pull categories were most frequently used, with less focus on knowledge management and socio-political support (Figure 4.2). From the outset, the successful scaling up of UHV – a technology that had not previously been effectively used commercially anywhere in the world – was far from certain and the policy approach had to evolve as more was learned about the technology and its fit with policy objectives.

Figure 4.2 Policy instruments used to support UHV technology by year of implementation, 2006-2021



Source: Government Document Center of the School of Public Policy and Management of Tsinghua University.

From 2004 to 2010 the focus was on funding basic research, demonstrations and pilots. This began in 2004 when State Grid Corporation of China (SGCC) – the largest state-owned power grid operator – independently conducted early UHV technology R&D to support its advocacy of the technology to the National Development and Reform Commission (NDRC), which is responsible for the macro-level direction of China's energy policy and must approve any major projects. SGCC allocated R&D funds specifically for UHV research, mandating its subordinate research institute, the China Electric Power Research Institute, to undertake the technological research. It also assembled a group of international experts to assess the status of the technology.

The period after 2004 was marked by several distinct debates about whether UHV technology should be developed and to what extent UHV power lines should be promoted. These debates were largely transparent and involved multiple stakeholders, including but not limited to a powerful state-owned enterprise as the lead advocate for UHV. Critics raised concerns about technical security, economic cost and effectiveness. These opponents were mainly retired officials and experts, some of whom were very senior power industry experts and had extensive experience of working in government sectors. This made it easier for them to gain access to central government leadership and gave their discourse significant influence. They jointly wrote a report on the problems relating to, and their recommendations for, developing UHV power grids and sent it to Premier Wen Jiabao.

In response to the report, Premier Wen Jiabao instructed the NDRC to carefully examine the feasibility of the UHV project. The NDRC brought together more than

200 experts from China's top think tanks to discuss UHV in June 2005. SGCC's research team presented a report at this meeting that aimed to cover almost all foreseeable technical concerns. The strong opposing views of some well-known power sector experts, researchers and senior government officials that were voiced at the meeting were recorded, including an expert from the former Ministry of Electricity (now National Energy Administration, NEA) and an expert form the Investment Association of China. Without a consensus at the meeting, demonstrations of the technology were approved with the support of delegates from Shanxi province, a coal-rich part of China. However, as central government was reluctant to provide finance from the central budget, these demonstration projects were funded by SGCC. They comprised a 1 million volt AC line from Shanxi Province to Hubei Province and the first DC line of around 800 000 volts from Sichuan Province and Yunnan Province to Shanghai.

The debate did not fully subside, however. In 2010, 23 power industry experts requested in a letter to Premier Wen Jiabao that the State Council stop UHV technology development and delist it from the 12th Five-Year Plan. While the Premier asked for a response from the NEA and SGCC, UHV projects continued. The critics then turned to Former Premier Zhu Rongi. whose protests that the approval of UHV projects did not meet procedural requirements managed to delay implementation until October 2013. Then, in April 2014 China Central Television (CCTV), the national broadcaster, devoted an episode of "Dialogue" on its financial channel to a nationally broadcast show entitled "Debating UHV". This episode brought much more attention to UHV as opposing sides presented several critiques of the UHV decision-making process, which related to: the administrative procedure for project approval; safety and security; cost; the considerable influence of SGCC as a monopoly; and whether UHV could realistically mitigate the air pollution problem.

In the end, the successful demonstration projects did much to convince the opposition and facilitate the politics of the policymaking process. In May 2014 the NDRC, the NEA and the Ministry of Environmental Protection jointly issued the Work Plan for Strengthening Air Pollution Prevention and Control in the Energy Sector, which proposed to increase the scale of UHV power transmission. Later, the NEA included nine UHV projects in priority locations for long-distance transmission corridors to help relocate coal combustion and reduce local air pollution impacts. From this point, the policy instruments evolved quickly to incentive investment via market pull. Concessional loans, simplified administrative approvals and financial subsidies for deployment were all offered.

UHV policy and project implementation through iteration

The implementation of UHV on a large scale was not monolithically imposed by central planning. Rather, it involved a wide variety of government institutions, and in a way that adapted to local contexts and societal concerns.

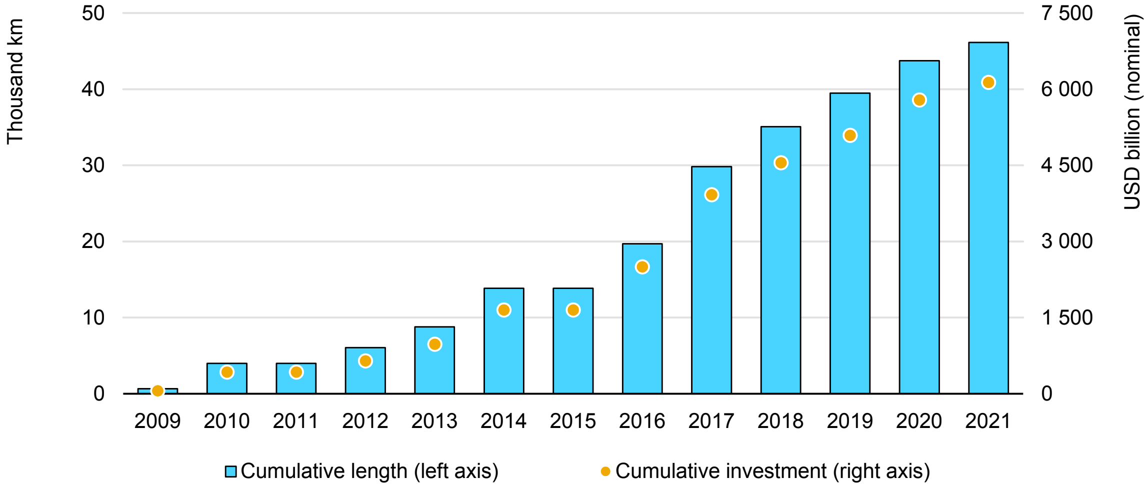
The policy framework designed at the highest level by the State Council and NDRC specified roles for different ministries, departments and local governments. The NEA is responsible for auditing the route of UHV power lines as part of its oversight of energy planning, development, management and regulation. The Ministry of Science and Technology (MOST) is responsible for planning the R&D and development of UHV technology and its applications. Local governments assist and support SGCC's provincial subsidiaries by handling local approval for land acquisition, finance and engineering. The NDRC co-ordinates interaction between ministries, departments and local governments along the UHV power line routes. When the UHV power lines are completed, the NDRC and NEA both have responsibilities for monitoring project acceptance and undertaking evaluation by government institutions and external experts.

Various actors in the implementation of UHV policy had to adapt their approaches due to the evolving knowledge base and public perception of UHV technology in the period after 2014. For example, central government introduced more supervision and regulatory instruments, including the supervision of engineering, safety, quality, the market and costs. From 2014 this included a strong focus on environmental supervision, with mandatory environmental impact assessments for all UHV construction projects. SGCC had to react to several setbacks, including a request for it to suspend its USD 77 billion UHV investment plan in 2011 after its first demonstration projects initially underperformed. Among its responses, it pledged to help insurance companies, large-scale industrial funds and state-owned investment platforms in the regions covered by UHV projects to participate, thereby creating financial benefits for local communities. These measures played an important role in fostering socio-political support for the new technology and reducing potential barriers to further scale-up.

The value of combining state-owned enterprise innovation with checks and balances

By the end of 2021 China's cumulative operational UHV transmission distance exceeded 45 000 km (Figure 4.3). UHV-related patent applications to the national intellectual property office reached 7 206 in 2021, and these came from an array of companies and research institutions beyond SGCC. With China being the only country active in UHV deployment, a whole industry of equipment suppliers and experts has arisen alongside. State-owned enterprises such as China Xidian, NARI Technology and Pinggao Electric, and private enterprises such as TBEA and Beijing Sifang Automation, all generate revenue in this new area. The innovation process of UHV transmission is, however, not entirely closed; international partners (such as ABB) also participate and contribute to its success.

Figure 4.3 Installation of UHV lines and corresponding investment, 2009-2021



Source: guangfu.bjx.com.cn (2023), Inventory – 2023 UHV Project Approval, Construction and Commissioning.

The advocacy of a large, well-capitalised state-owned enterprise is central to the narrative of UHV in China. SGCC and its subsidiaries supply 26 provinces that together cover more than 88% of China's land area, making it one of the most important players in China's energy planning. In 2022 SGCC budgeted a record USD 75 billion for 2023, and spent around USD 22 billion on UHV initiatives alone in the second half of 2022 and the start of 2023. It is difficult to conceive of the rapid build-out of UHV in China without SGCC's ability to fund technology R&D, exploit its links with universities and research institutes, plan UHV lines, finance projects and mandate its provincial companies to conduct engineering and construction.

However, the story of UHV in China shows the importance of independent and critical institutions alongside SGCC. The influence of government and other experts on the trajectory of technology development demonstrate that state-owned enterprises like SGCC do not operate in isolation and are influenced by critical debate as much as they influence it themselves. The result was a slower pace of development, testing of the company's hypotheses and claims, and greater enforcement of environmental principles.

The case of solar PV in China

China's solar PV industry is a manufacturing and installation powerhouse and much has been written about how cells, panels and modules first came to be manufactured in China and then scaled up to world-leading levels. The country has become a pioneer of innovative designs and production techniques that continue to contribute to declining global prices. This section outlines Chinese central government solar PV policy and the factors that spurred technology innovation. It draws a contrast with the UHV case because of the central role played by private companies rather than state-owned enterprises.

When solar PV technology first became an industrial activity in China, it came from outside the state planning system and was misaligned with the national vision of the future Chinese energy system. For example, MOST delayed its manufacturing demonstration project scheduled for 1998 due to an uncertain domestic market and weak support for solar PV in China. It eventually came online five years later, in 2003, and was operated by the private company Yingli Solar, which went on to become a global leader in solar module production. By that time, another small manufacturing line had been started in 2002 by Suntech Power, which also went on to become one of the world's largest PV manufacturers before its bankruptcy in 2013. Suntech Power was founded in 2001 by a Chinese student of solar technology returning from Australia and its factory was backed by private equity financing. At this time, there was no expectation among senior decision makers that solar PV would become either a significant source of electricity or revenue for China. It was considered too expensive for Chinese consumers and utilities. The technology for these facilities was purchased or brought in from overseas. The output mostly found its way to Europe and other export markets, where market pull policies were stronger.

In the early 2000s solar PV was an R&D topic at MOST and funded via the so-called 863 and 973 Programmes, but few efforts were made to develop Chinese innovation capacity in the technology. Furthermore, the key linkages between policy makers, including MOST, the NEA and NDRC, and the main state-owned electricity enterprises, were underdeveloped for solar PV. Core technology and policy developments were concentrated in Europe, Japan and North America.

It was not until 2010 that the State Council identified solar PV as a strategic emerging industry. It included solar PV in the national vision for economy and energy because of an appreciation that it could generate numerous jobs and also be one of the ways to reduce reliance on coal. In 2009 an important document, "Several Opinions of NDRC and Other Nine Departments on Curbing Overcapacity and Redundant Construction in Some Industries to Guide Industries' Healthy Development" had been published to hasten the construction permits for polysilicon production plants, a core material for the solar PV industry.

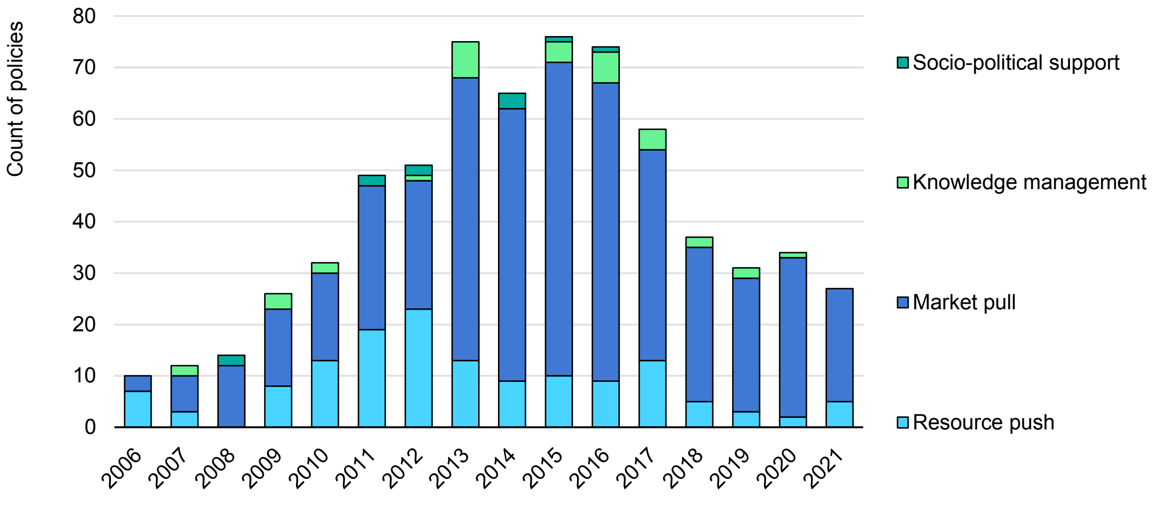
The evolution of policy choices as the market grows

To demonstrate the evolution of policy as the sector scaled up, we have identified 671 central-level policy documents targeting solar PV between 2006 and 2021 (Figure 4,4). In numerical terms, these ramped up rapidly after 2009, and mostly covered domestic deployment rather than manufacturing. Notably, the period from

2009 to 2013 contained the most resource push policies that supported R&D. These included demonstrations and pilots financed from the national budget, including the Solar Rooftop Programme, to which the Ministry of Finance (MOF) and the Ministry of Housing and Urban-Rural Development allocated USD 190 million for 111 projects with a total capacity of 91 MW nationwide. Technology innovation was also encouraged via knowledge management instruments that included awards to recognise excellence and disseminate high-potential advances.[3]

To start building demand for solar PV technologies, a sequence of policies was implemented between 2009 and 2013. These included the MOF and NEA Golden Sun Demonstration Project, which covered 50% of the costs of solar PV power plants (70% in remote areas), and the NEA solar PV concession projects, which funded 16 solar PV projects via competitive bidding. It was not until 2011 that China's first national power production subsidy for solar PV was introduced via a feed-in-tariff,[4] as it took some time to reach consensus around budget implications and institutional perspectives. For example, the NEA expressed concern that individual technologies should not be protected from competition as that would reduce their incentives to innovate. The policy was introduced after a series of internal dialogues.

Figure 4.4 Policy instruments used to support solar PV technology by year of implementation, 2006-2021



Source: Government Document Center of the School of Public Policy and Management of Tsinghua University.

Since around 2010 solar PV has received an increasing level of socio-political support in China, with the technology being highlighted in an increasing number

[3] The government organised a range of awards, including patent awards, science and technology awards, engineering design awards, university scientific research awards and basic research awards. Some of these came with financial rewards.
[4] Prior to this, renewables support since 2006 had been allocated mostly to wind energy.

of national strategies (Table 4.1). These publications are widely used in China to signal political support and build consensus around a path of action. In these documents it is possible to see solar PV move from being a technical curiosity to a topic that is mentioned by non-energy government departments in relation to national innovation competitiveness, jobs and the rural economy. The 12th Five-Year Plan for Solar Power Development set a goal of 21 GW of installed solar power capacity by the end of 2015, a level that was around four times higher than installed capacity in China and equivalent to 25% of all global installations at the time of its publication. In the end, the target was exceeded and installations reached 43 GW. In the 2015 Work Plan on the Implementation of PV-based Poverty Alleviation Project, promotion of solar PV is described in relation to the development of local agriculture, jobs and social benefits. Likewise, by 2015 the NEA's Solar PV Leader Plan took into account enhanced targets for moving the country to less polluting forms of energy and encouraging innovation to improve the quality of domestically manufactured solar PV. While this increased alignment with the national policy vision for the economy, manufacturing of solar PV was not an explicit policy goal – as it has been in other countries – but rather an implicitly expected outcome given China's manufacturing strengths.

Consequently, at the central level the focus on promoting the deployment of solar PV was not matched by an equivalent focus on supporting investment in manufacturing capacity. The production of solar PV equipment was largely left to the private sector and support from provincial governments. This support, for example via access to cheap capital and land, can be substantial but might not be targeted at specific industries. In total, direct and indirect support to firms to pursue a variety of industrial policy goals in China has been estimated to have been equivalent to 1.7% of GDP in 2017-2019.

Table 4.1. Selected socio-political support documents of China's central government related to solar PV

Year	Document
2012	12th Five-Year Plan for Solar Power Development
2014	Work Plan on the Implementation of PV for Poverty Alleviation Project
2015	State Council Leading Group Office of Poverty Alleviation and Development (OPAD) Listed Solar PV for Poverty Alleviation as One of Ten Major Projects for Targeted Poverty Alleviation
2015	Solar PV Leader Plan
2016	13th Five-Year Plan for Solar Power Development
2018	Notice on Matters Related to Photovoltaic Power Generation in 2018

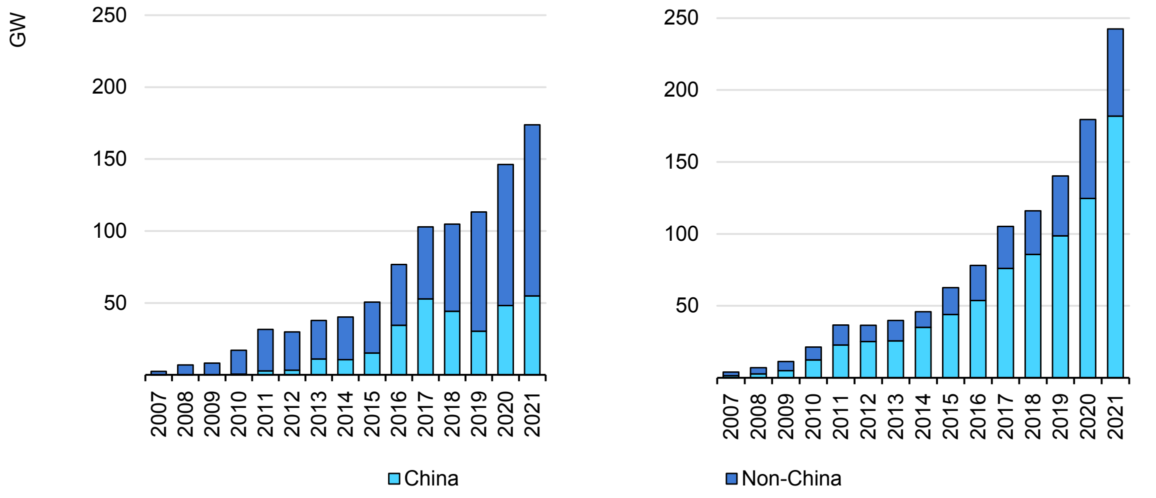
Sources: NEA (2012), Solar Power Development Twelfth Five-Year Plan; NEA and OPAD (2014), Notice On The Work Plan Of Photovoltaic Poverty Alleviation Project; OPAD (2015), China Promotes the Implementation of the Top Ten Projects of Targeted Poverty Alleviation; NEA (2015), Opinions on Promoting the Application of Advanced Photovoltaic Technology Products and Industrial Upgrading; NEA (2016), Solar Energy Development 13th Five-Year Plan; NEA (2018), Notice on Matters Related to Photovoltaic Power Generation in 2018.

In the period from 2013 to 2018 market pull and socio-political support policies dominated. Annual solar PV deployment targets were issued by the NEA each year for utility-scale and small-scale projects. Support policies for uptake in specific sectors multiplied, and included agriculture, water conservation, civil aviation, poverty alleviation in rural and western regions, and use in public institutions and enterprises. Market development was aided by the establishment of standards, quality control and monitoring, including for equipment, land use, corporate bonds and environmental impacts. It was during this period that market pull policies expanded to also encourage technological leadership and industrial investment in module production.

However, subsidy measures came to an end on 31 May 2018 when the NDRC, MOF and NEA jointly issued the Notice on Matters Related to Photovoltaic Power Generation in 2018 (the so-called "5.31 new policy"). Among the factors behind this decision were the challenges that rapid expansion of solar PV was causing for electricity grid integration and for public budgets. Another reason was the increasing belief that solar PV technologies were approaching grid parity. Due to constraints on grid infrastructure and market structure (whereby many coal plants were given priority access to the network), the rate of solar PV curtailment rose in northwest China by between 20% and 32% in 2015 to 2017. This significantly increased the cost per unit of solar electricity consumed, and MOF's Renewable Energy Development Funding could not keep up with the subsidy bill from the flourishing installations. By the end of 2017 the cumulative budget shortfall was almost USD 15 billion despite a tenfold increase in the levies imposed on electricity consumers to help fund the cost.

As the price of solar PV generation dropped towards the fixed price paid to coal-fired power generators – a threshold it passed in 2021 – deployment continued apace (Figure 4.5). Every step of its market expansion has been accompanied by a corresponding growth in its solar PV manufacturing output, which has continuously been larger than any other country for polysilicon, wafers, cells and modules since at least 2010. Among the top 20 solar PV manufacturing companies in 2022, 17 were Chinese and many of these have operations around the world.

Figure 4.5 Global solar PV installations (left) and module production (right), 2007-2021



Source: IEA (2021), PVPS trends reports.

Achieving this level of output and dominance at the same time as continual dramatic cost reductions would not have been feasible without technology innovation. Economies of scale played a significant role, but advances in cell design and assembly techniques were also fundamental in lowering costs. While early output was based on overseas technology, Chinese researchers have become a significant source of international patents in solar PV. While their rate of patenting lags that of Europe, Japan, the United States and Korea in most areas, they account for more than 10% of the total in areas including power conversion and organic PV cells. 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. Jinko Solar and Longi reported record efficiencies above 25% for variants of n-type and p-type monocrystalline cells in mid-2021. In 2023 Longi achieved records of 27.1% and 33.9% combined efficiency for silicon heterostructures (HIT) and hybrid tandems. Nanjing University reported a record efficiency of 29.1% for perovskite tandem cells in 2022 and the University of Science and Technology of China reported 26.1% for perovskite cells in 2023. These results demonstrate how Chinese corporate and university laboratories have followed government laboratories and universities in shifting their R&D focus to next-generation solar PV designs. However, most of the PV efficiency records set in recent years have been by German, Japanese, Korean and US firms.

Notable features of the solar PV case

By comparing the different routes by which China achieved global leadership in solar PV and UHV, notable features of the solar PV case emerge. They include the participation of more private companies, a more diverse set of accountable ministries, the importance of international co-operation, and the challenges of regulating mass-manufactured products. These are each discussed in turn:

1. The influence of private companies and market competition.

China's solar PV manufacturing industry initially became established outside the central planning system, with private companies setting up factories to manufacture imported technology designs. These companies had government backing, but it was from provincial and municipal administrations and their banks. Suntech Power, for example, raised USD 2.9 billion in Jiangsu province in 2010. Several important dynamics resulted from this situation:

- At the outset, the companies were reliant on markets outside China and experienced boom-and-bust cycles due to external policy changes. There were a number of high-profile bankruptcies, including Suntech Power.
- With support from different provinces and no involvement of national state-owned enterprises, competition between these firms was intense. This was especially the case during periods when the global market cooled down, but in this commodity business the margins have been persistently thin and competitive. This incentivised innovation to stay competitive without needing dedicated government R&D policy.
- Once central government stepped in to support and promote solar PV in response to various national and international trends, the main private players were already established. Policy support from central government provided market stability, but entrenched the competition between private firms and provinces. To stay competitive, industrial clusters emerged around the main manufacturing companies with a relatively open exchange of knowledge and expertise between universities, component suppliers and the finance community. This spurred more effective innovation.

2. Policy experimentation was facilitated by the involvement of multiple ministries.

As a sector straddling energy, manufacturing, environmental and rural development policy, there was considerable diversity among the government departments with a stake in solar PV. For example, ten departments including the NDRC and the Ministry of Industry and Information Technology co-issued a 2009 opinion on how to address overcapacity in polysilicon production resulting from changes in overseas policies. These departments had different opinions on issues such as whether solar PV support should prioritise utility-scale or small-scale projects, or whether state support should be via administrative approval or competitive processes. The outcome of the lack of consensus was more diversity of policy. The Solar Rooftop Programme of the Ministry of Housing and Urban-Rural Development targeted small-scale projects, the Golden Sun Demonstration Projects of MOST and the NEA targeted utility-scale grid-connected projects using the administrative approval approach, and the solar PV concession projects launched by the NEA targeted utility-scale grid-connected projects using the competitive bidding approach. This level of policy experimentation was magnified by interventions at the provincial and municipal levels, which included various combinations of production subsidies, demand subsidies and innovation support measures.[5] It has been shown that production subsidies were frequently combined with innovation support at the subnational level between 2006 and 2022, and these policies were most successful at stimulating patenting and capacity expansions.

3. International partnerships can be key to knowledge exchange and launching a new sector.

In the early days of solar PV in China, rapid technology learning was facilitated by joint ventures and licensing of intellectual property. 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. The value of access to China's large domestic market gave Chinese companies a negotiating edge, but non-Chinese were generally keen to enter such partnerships to improve the competitiveness of their manufacturing activities, which would benefit from access to cheaper finance and labour in China. Some Chinese companies also acquired foreign competitors and progressively absorbed their R&D activities. For example, Hanergy Group acquired Alta Devices, a US company, in 2013.

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. According to the patent data, a relatively high share (13%) of all co-inventions between innovators from at least two different countries involved Chinese entities in 2000-2009. Compared with a state-owned behemoth such as SGCC, the flexibility and freedom to engage in such a variety of international partnerships is likely to have made it easier for private companies in an internationally growing segment such as solar PV. However, these interactions appear to have slowed after 2015, with growth in patents by Chinese-only innovators and no growth in co-inventions.

[5] Production subsidies are those that provide financial support to firms building new manufacturing lines. Demand subsidies are those that provide financial assistance to the users of solar PV for generating electricity or to their customers who purchase electricity. Innovation support measures include R&D funds but also, as in Guilin city in 2011, payments to reward firms if their R&D centres achieved provincial-level certifications.

4. Regulating mass-manufactured technology from multiple producers brings challenges.

In contrast to the centralised and large-project nature of UHV, policy implementation for solar PV was hampered by quality control and monitoring in a fast-moving technological environment. MOF allocated over USD 700 million to the Golden Sun Demonstration Projects in 2009, but some recipients never constructed the promised plants or used substandard equipment, leading to the cancellation of 54 MW of capacity, including projects owned by well-regarded firms such as Wuxi Suntech, AT&S and BP. Another 11 firms were found to have defrauded MOF of USD 35 million in other ways. For the following phases of policy, the quality control and monitoring regulations were tightened.

Findings

The two cases explored in this chapter reveal different types of policies and dynamics that can help emerging market economies to achieve their ambitions for domestic clean energy innovation. China is in many ways a unique case, given its vast domestic market, large national budget and range of socio-economic contexts – from high-tech engineering towns to low-wage industrialising provinces. Nonetheless, several insights stand out from the UHV and solar PV cases. These may be especially relevant to other countries that have a high degree of centralisation of economic and social development planning, dominant state-owned enterprises and devolution of policy implementation to subnational levels.

One emerging finding is that centralised systems still face tensions among powerful departments and stakeholders. Contrary to some external perceptions, it is not sufficient in such a system for a single government department to issue a diktat in the expectation that everyone will toe the line. The processes by which consensus is built and agreement on how to proceed are vitally important in China. This was especially the case for UHV technology. The two cases both show the need to foster consent and actively engage diverse stakeholders through consultation and co-ordination, highlighting the importance of socio-political support for innovation policies.

China's clean energy policymaking process included prominent consensus building activities in both the case of UHV and solar PV. They covered consultation meetings, expert reviews and collective drafting of key strategic documents that involved some of the most senior politicians in the country. The time and effort required by these processes should not be underestimated. In both the UHV and solar PV cases, institutional stakeholders were given space to test technology or policy approaches that could then be appraised by a cross-departmental group. In the UHV case, setbacks had to be navigated, while in the solar PV case it was necessary to negotiate an end to support policies that had shared responsibilities among departments. The UHV case demonstrates the benefits of transparency and inclusivity in terms of consultation for highly visible and high-cost infrastructure projects. In the solar PV case, institutional dialogue was less public, perhaps arising from the challenges of co ordinating and integrating the views of a larger number of smaller private companies in the nascent sector. Overall, however, an iterative process is often necessary to ensure the commitment of all stakeholders to a course of implementation and requires patience.

In both cases, the socio-political support of consensus building gave way to the socio-political support of strategic planning as the technology scaled up. The technologies were increasingly integrated into sectoral and national strategies that were aligned with the national vision, first for energy and then for the wider economy and society. In 2006 UHV technology was included in the influential National Programme for Medium- and Long-Term Scientific and Technological Development (2006-2020), thereby placing it in a special category of technologies of national strategic priority. Likewise, solar PV was classified as a strategic emerging industry. In this way, technology maturity (i.e. policy makers' confidence in its effectiveness and suitability to solve policy problems) was accompanied by a move from the political periphery to the centre of national policy in a stepwise fashion. China could potentially have moved into PV even earlier if it had been better aligned with the national vision.

Another clear finding is that different clean energy technologies benefit from different approaches to innovation policy. The role of SGCC as an advocate and then implementer of UHV technology policy would not have been appropriate for solar PV. Because of its substantial financial capacities, SGCC does not need public R&D funds. What it needs most is the permission to innovate. Solar PV was already established as an effective technology abroad, it had several competing designs and it would be adopted by a variety of different customers if it could be manufactured at sufficient scale and quality in China. China's existing manufacturing excellence in other sectors helped it to move quickly into PV. An approach to solar PV that gave a single company the type of preferential access to central government leadership enjoyed by SGCC would have been unlikely to yield the benefits of technological competition, a plurality of international partnerships and local industrial clustering. However, the private solar PV companies suffered from being outside the policy process and vulnerable to policy changes and funding gaps in a way that SGCC never needed to worry about for UHV. Where state-owned enterprises have significant resources and close connections to the centre, governments can incentivise them to take on more clean energy innovation, leveraging their financial capacities and abilities to forge political and social consensus. Private entities and new entities outside existing regimes may require additional financial and political support to foster innovation. Policy makers should consider providing necessary resources and interventions to facilitate their participation and contribution.

Finally, key individuals and networks are important, especially if they have international connections. It can be observed that in both cases it was critically important for Chinese companies to be familiar with the latest international technological developments, but that this did not happen via a government–government process. The six main ways that Chinese companies established a foothold in the new technology areas would be very familiar to any major international technology developer:

- joint ventures between private companies
- technology licensing from private companies
- engagement of foreign technology suppliers as contractors
- acquisition of foreign companies and integration of their R&D capabilities
- research partnerships with overseas universities
- relocation of human capital from overseas universities and companies to become founders or employees of Chinese firms.

While these six approaches can be considered as specific to the Chinese case of a rapidly growing economy with a large population in the period studied, they indicate ways of thinking about domestic innovation in emerging economies even if other countries were unlikely to find some of the exact policy instruments as easy or effective to implement.