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Clean energy innovation in China: Fact and fiction, and implications for the future

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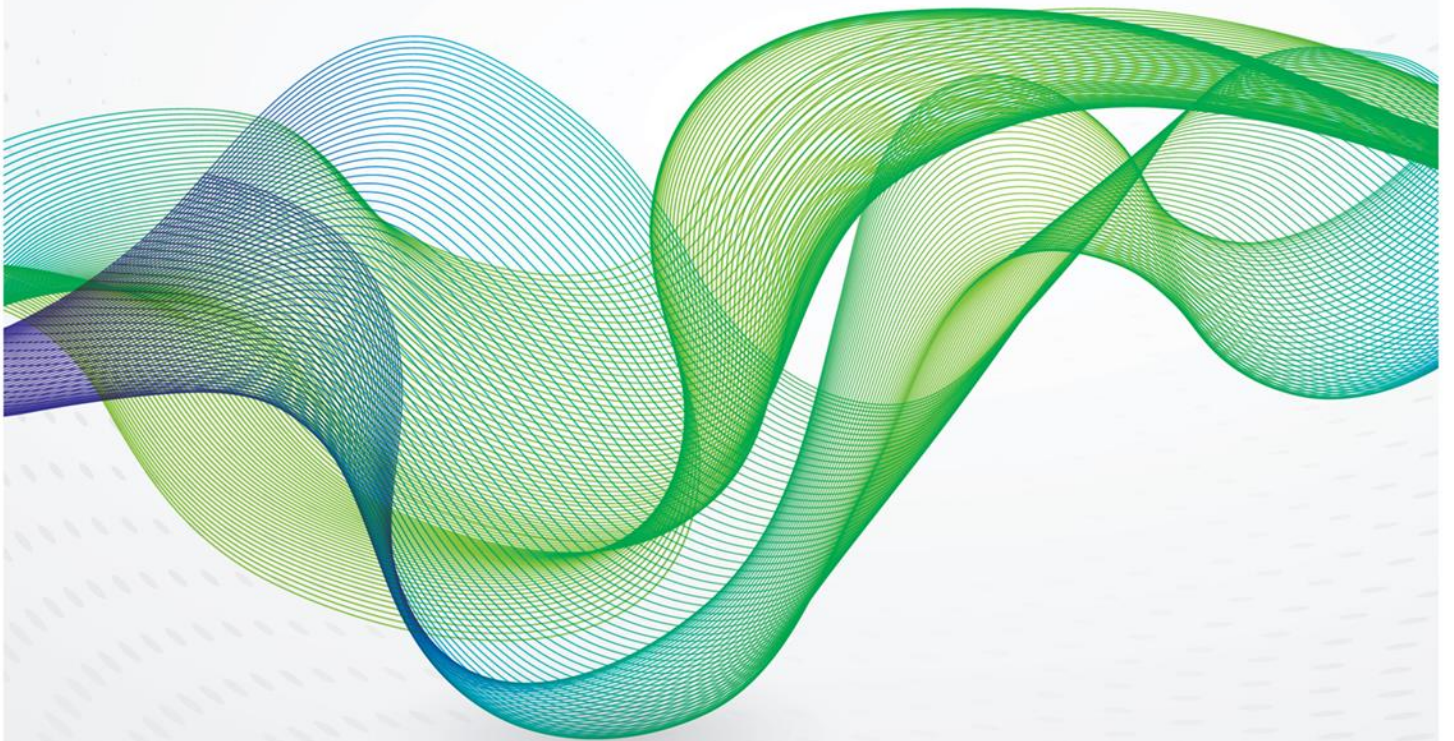
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July 2024

Clean energy innovation in China: fact and fiction, and implications for the future





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Contents

Contents	ii
Figures and Tables	ii
Summary	1
1. Introduction: Four main factors driving China's clean energy innovation	3
2. China's clean energy industries have benefited from strong and sustained policy support 4	
2.1 Solar and wind supported by feed-in tariffs, targets, and mandates	4
2.2 Stationary batteries promoted recently for renewable integration	6
2.3 Electric vehicle policy began early, but accelerated only when industry achieved success ...	6
2.4 R&D funding and supporting policies steadily ramped up	7
2.5 Clean energy policy continuity aided industrial transition, with occasional abrupt shifts	8
3. China's industry clusters, the unsung heroes that helped achieve scale and contributed to innovation.....	9
3.1 Manufacturing-intensive clean-energy technologies favour close supply chain links	10
3.2 China's policies have supported supply chain integration	12
3.3 Many patterns of supply chain clustering and interaction	13
3.4 Clusters and competition contribute to the pace of innovation.....	14
3.5 Proximity to a large demand base further supports innovation	15
4. China's innovation benefited from global links and technology transfer	16
4.1 Technology transfers were a first step in wind and solar innovation in China	17
4.2 Batteries and EVs benefitted from licensing, joint ventures and localisation rules	18
4.3 Rising Chinese dominance evident in batteries and EVs.....	19
5. Talent, human capital and entrepreneurs were instrumental to clean energy's rise.....	19
5.1 The extraordinary rise in China's skilled worker base	20
5.2 Attracting science and technology talent helped seed new industries	20
5.3 Risk-taking entrepreneurs played a key role	21
6. Looking ahead: Is China's lead in cleantech innovation unassailable?	22
Acknowledgments	28

Figures and Tables

Figure 1: Chinese annual additions of solar PV (left) and wind (right)	5
Figure 2: Timeline of China's wind and solar feed-in tariff policies	5
Figure 3: R&D spending as a share of GDP in China (2010-2021), and comparison to other countries/regions in 2021	8
Figure 4: Total production costs for mono PERC c-Si solar components by input, 2022	9
Figure 5: US-China solar trade balance in 2011 – Solar imports from China to the US, versus estimated exports from the US to China	11
Figure 6: Revenue share of top 10 solar equipment-making companies by country	11
Figure 7: Map of mid-2010s solar PV manufacturing cluster in Yangtze River Delta	12
Figure 8: Number of battery companies by province, location of top battery and EV firms, 2021	13
Table 1: Historic top tech transfer and global innovation factors by sector: wind, PV, batteries, EVs..	16
Figure 10: China's clean energy patent filings	19
Figure 11: PhD graduates in STEM fields, historic and forecast to 2025	20
Figure 12: China battery investments abroad	25



Summary

With the Biden administration in the US introducing tariffs on Chinese clean energy and electric vehicle (EV) goods and components, and the European Union (EU) also imposing duties on electric vehicles because of Chinese state support for these industries, the narrative around China's dominance in clean energy manufacturing is fixated on the uneven playing field afforded by said state's largesse. Such narratives are simplistic and underplay the complex combination of factors that have led to China's rise in cleantech as a dominant producer. True, subsidies and targets have been central to China's clean energy success, but Western governments – who are now also engaging in policies supportive of clean energy industries – ignore the evolution of China's policy design and its breadth. Governments, companies, and observers also overlook the importance of entrepreneurship in China, and, perhaps most critically, the importance of vertically-integrated industrial clusters.

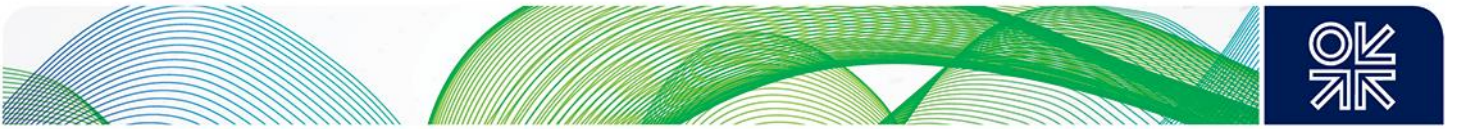
Policy support in China has been significant in helping these industries, but it extends far beyond subsidies or targets, and includes signals for investment, R&D spending, and support for the development of integrated industrial clusters. Yet it is overly simplistic and misleading to reduce China's advantage solely as arising from these supportive measures, or to assert that China is incapable of innovation. To be sure, technology transfer has taken place, often encouraged by explicit policies requiring the localization of manufacturing or technology transfer, but it has also occurred through the co-design and co-evolution of technologies through supply-chain interactions. Entrepreneurship and human capital have also been critical. While policy and subsidies encouraged entrepreneurs, risk-taking and business innovation fed back into the design of such policy, rather than just following the government's lead. This ecosystem of policy support and entrepreneurial drive has evolved into deep supply-chain interactions and a co-evolution of technology between manufacturers (such as producers of solar photo-voltaic [PV] panels or batteries, equipment providers for components, and manufacturing tools), and customers (such as automakers).

China's strength therefore lies beyond subsidies or policy support. With policymakers in many countries turning towards industrial policy aimed at manufacturing, exemplified by the Inflation Reduction Act (IRA) in the US, it is important to consider the variety of factors that have helped China excel in these fields. This study represents a first step towards understanding the drivers of China's dominance in clean energy innovation. It also seeks to evaluate the potential for China to retain and build upon its innovation leadership in the fields it now dominates.

This paper groups the factors responsible for China's dominance of the clean energy industry, and subsequent innovation, into four categories: (1) consistent policy support at various levels of central and local government; (2) a focus on encouraging and facilitating technology transfer, implemented as a matter of policy and corporate strategy; (3) advantages in manufacturing scale-up and process-level innovation, facilitated by efforts to develop integrated technology and manufacturing clusters; and (4) human capital, including both technical expertise and entrepreneurial risk-taking.

For countries and companies looking to engage and/or compete with China, it is important to recognize that competing in wind, solar PV, batteries, and EVs requires process-level innovation,¹ which in turn requires mastery of, and ongoing interaction with, the entire supply chain. While basic R&D spending and top-notch universities will remain important, the benefits of such research may not always flow into the hands of domestic players. China's EV, battery, and solar firms are able to innovate and scale up output quickly in part because of the important role of vertical integration and manufacturing clusters. Vertical integration and clustering appears to benefit the type of innovation – namely, in manufacturing and related processes – that yields a competitive advantage in these fields.

Related to this, human capital and entrepreneurship have also been important, and their development in China has been both linked to and facilitated by an industrial base in clean energy technology fields. This runs against the historic perception that developing experienced human capital and entrepreneurs is a strength found only in advanced economies², or that China's advantage relies on attracting prominent firms that rely on low-cost, imported components.



Lastly, much will depend on whether advanced economies can underpin investment with longer-term policies than have been possible to date. Meanwhile, China's own supportive clean-energy policies could face increasing internal pressures, as incumbent industry resistance grows towards the structural changes needed to integrate clean energy.



1. Introduction: Four main factors driving China's clean energy innovation

Over the past two decades, China has not only become the world leader in the manufacturing and deployment of wind, solar PV, batteries, and EVs, but the country is also recognized as at the forefront of research and innovation in these fields.³ Other countries and regions are increasingly introducing policies that aim to re-shore or diversify some elements of the clean energy supply chain, including both in manufacturing and in research and innovation. Examples include the aforementioned Inflation Reduction Act in the US, which limits certain clean energy subsidies to items manufactured in the US or free-trade agreement partners, and targets others to build out manufacturing capacity in the US; and the EU's Green Industrial Plan, which requires 40 per cent of clean energy technologies to come from Europe.⁴ However, as these policy ideas have come to the fore, so have a number of often overly simplistic narratives about how China became dominant in these fields. In recent years, the history of China's rapid industrial development has often been told in the context of government policy, official targets, five-year plans, and long-term strategies.⁵ Similarly, for technology transfer, China is often viewed as a manufacturing giant that has benefitted from one-way tech transfer, or even outright theft, and its role in global innovation networks and technology co-evolution is often omitted or discounted.⁶ Aside from being inaccurate, such narratives can hold back efforts to advance the clean energy transition or successfully re-shore and remain competitive in important clean energy industries.

This paper seeks to develop a more nuanced understanding of China's innovations in clean energy as well as evaluate the potential for China to retain and build upon its innovation leadership in the fields it now dominates. Building on prior analysis of the country's clean energy innovation institutions,⁷ the paper considers various factors that contributed to its success to date, such as strong and relatively consistent policy support, policies that enabled technology transfer, and global supply-chain integration. Section two examines in particular whether three of China's enabling factors will continue to hold advantages for China in the immediate future, as in the next five to 10 years: the speed in manufacturing scale-up based on integrated supply chains; integration and interaction with transnational research and innovation networks, sometimes known as global innovation systems;⁸ and interlocking cooperation between private entrepreneurs, state-owned companies, and research institutions.

Below is a summary of the main findings:

- Strong and sustained policy support for clean energy has been a critical enabling factor, not only for industry growth, but for innovation. While policymakers have reduced subsidies over time, and there have been boom-and-bust cycles for manufacturing players, the overall direction of policy has continued to emphasize renewable energy and new energy vehicles as a national strategy. The large and growing domestic market should continue to underpin China's strength in these fields, though slowing growth implies its domestic players will need to look abroad for growth.
- Industry scale-up, which has been essential for cost reductions in clean energy technology, was largely facilitated by integrated supply chains within China, often in industrial clusters established through the interaction of policy and market actors. Not only do clusters reduce costs and accelerate technology diffusion, they have directly contributed to the pace of innovation and the introduction of new products. As Chinese firms expand manufacturing abroad and other countries seek to build up their own clean energy manufacturing bases, it is unclear whether policymakers in other regions could adopt similar strategies to catch up. Policies aimed at scale-up may be unsuccessful unless they try to replicate some aspects of China's technology cluster model.
- Technology transfer and global innovation networks have been important to the emergence of all of China's clean energy sectors, and while there has been an element of forced technology transfer, innovation, and learning have been more multidimensional than is often portrayed. In the future, global learning networks could fracture, but China's central or dominant position in key technologies implies this may hurt technology catch-up outside of China as much as it affects Chinese players.



- Human capital and entrepreneurship have also played a strong role in China's innovation in clean energy. While entrepreneurs have spurred product and technology innovation, there are some concerns that tightening constraints on the private sector could eventually affect the pace of innovation in fields where China now dominates – though this is hardly apparent today.

Each of these factors is further elaborated upon in the following sections, showing how they have interacted with one another as policies and technologies evolved over time. In each case, while policy may have played a strong role, other aspects also came into play, often in ways that were unanticipated.

2. China's clean energy industries have benefited from strong and sustained policy support

Government policy has played a central role in China's stunning success in expanding its clean energy industries. While this paper argues that narratives of China's clean energy rise often begin and end with policy and subsidies, and that this isn't the whole story, it is nevertheless a critical part of the story.

China's largest clean energy sectors – namely wind, solar PV, batteries, and new energy vehicles – straddle the line between being state-owned and the market economy. China's central government began targeting manufacturing in each of these clean energy fields for various forms of support, initially starting with pilot projects or narrow efforts to popularize technologies in small niches, such as rural electrification for solar PV, or buses as EVs. As this section will discuss, the government also supported the localization of technology through domestic content requirements and policies to encourage or mandate technology transfer, and eventually promoted the rapid expansion of these technologies through various demand-pull policies such as feed-in tariffs, quotas, or planning targets. Supportive policies have varied by technology, sometimes based on examples adapted from abroad, such as Germany's feed-in tariff for wind and solar, or California's zero-emissions vehicle (ZEV) mandate. In other cases, incentives were either novel or adapted from existing support mechanisms.

A full history or timeline of the development of each of the clean energy fields is beyond the scope of this paper, but given the importance of policy to their development and the emergence of a strong sectoral and national innovation system in each, a synopsis of supportive policies is an important starting point for understanding how innovation will evolve in the near future.

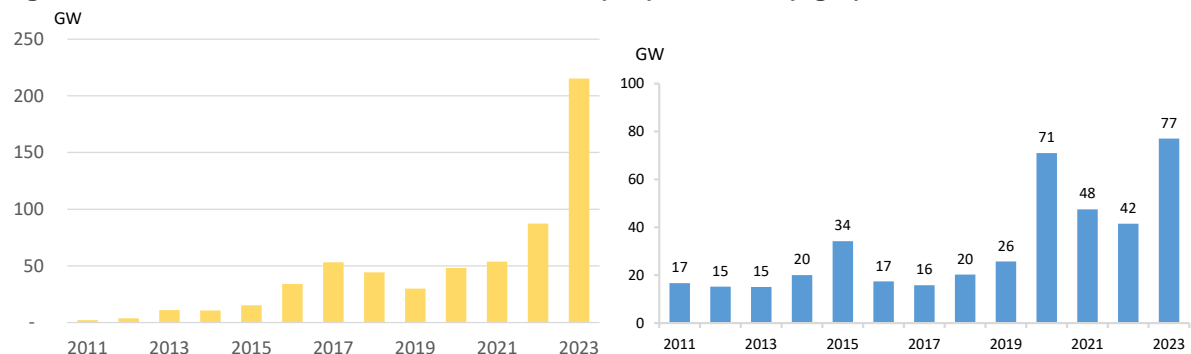
2.1 Solar and wind supported by feed-in tariffs, targets, and mandates

At the end of 2023, China had a total installed solar capacity of 610 GW, having grown by 55 per cent over that year.⁹ The growth in China's solar installations in 2023 of over 200 GW accounted for over half the world's total. For over a decade, China has dominated the manufacture of solar PV equipment. As of 2021, the International Energy Agency (IEA) estimated China's share of global production of polysilicon as 79 per cent, wafers 97 per cent, cells 85 per cent, and solar PV modules 75 per cent.¹⁰ Ongoing investment implies China will continue to retain an 80 per cent share in these fields through 2026, according to a 2023 estimate.¹¹

In the wind power market, China has also long held the record in total installations and in the size of its domestic market. China's wind capacity reached 441 GW at year-end 2023, with additional annual capacity reaching over 60 GW.¹² However, on the manufacturing side, although China's domestic market was almost exclusively supplied by domestic manufacturers, China has only recently achieved a dominant position in global markets, accounting for over half of global wind turbine manufacturing in 2022. For major wind components, such as castings, forgings, slewing bearings, towers, and flanges, China's share exceeds 70 per cent.¹³ In offshore wind, where China had lagged Europe for years, larger turbines and domestic feed-in tariffs have led to an explosion in growth, and China has accounted for over half of global additional offshore capacity every year since 2021. China accounts for over 90 per cent of wind turbine installation vessels under construction¹⁴, and Chinese firms are capable of building offshore wind turbines with world-leading sizes of 16-18 MW – though the size of turbines and blades along with local content requirements make local manufacturing cheaper for many regions such as Europe. In addition, China also accounts for a large share of permanent magnets needed for many of the largest turbines, especially those used for offshore wind.¹⁵



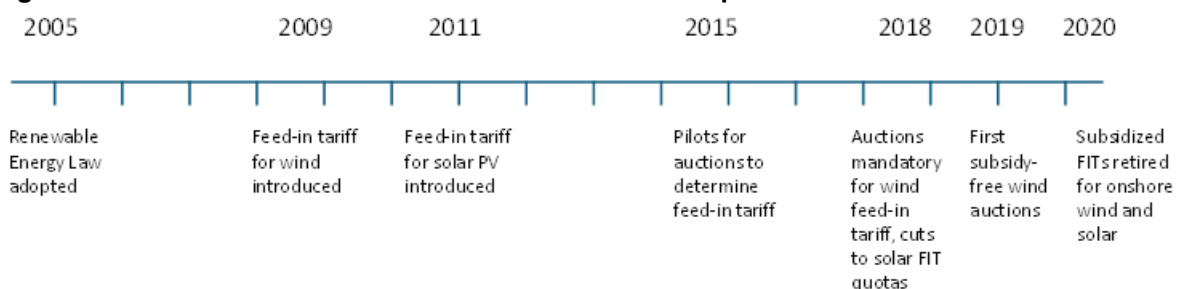
Figure 1: Chinese annual additions of solar PV (left) and wind (right)



Source: author, based on annual National Energy Administration (NEA) publications

These achievements build on decades of government support. China's central government began to explore research and policies to promote wind and solar power in the 1990s, and deployed solar in poor rural areas as an electrification and development strategy. Its first major steps at large-scale deployment began with the adoption of the Renewable Energy Law in 2005¹⁶, the 2007 Mid-to-Long Term Renewable Energy Development Plan¹⁷, and the participation of China's nascent wind power sector in the Clean Development Mechanism¹⁸ (CDM), an international program under the Kyoto Protocol to promote clean energy investment in developing countries. In the mid-2000s, China captured the majority of CDM-supported wind energy funding, and 74 per cent of China's wind projects were supported under the CDM scheme.¹⁹ The first subsidized feed-in tariff was adopted for wind in 2009, and set at relatively generous levels that encouraged rapid growth in domestic deployment, aided by a local content requirement (discussed below; see also Figure 2).

Figure 2: Timeline of China's wind and solar feed-in tariff policies



Source: Anders Hove, 'Steady Progress, Ongoing Challenges: China Energy Transition Status Report 2020', GIZ, 2020

Solar PV has followed a somewhat different path from that of wind power. Though government policy encouraged solar manufacturing as a strategic industry, production was geared mainly for export. Local governments did subsidize the scale-up of manufacturing via low-cost loans, and in some cases shared costs for new manufacturing plants.²⁰ Seeing solar as a strategic industry targeted for national support, local officials intervened with banks to offer low-cost loans for expansion even during periods of overcapacity.²¹ Local governments also offered solar firms that established manufacturing or research centres guaranteed purchase agreements to backstop loans and support their expansion; for example, Suzhou offered to install Canadian Solar panels on rooftops across a new urban zone it had established in exchange for establishing such a centre.²²

The central government also provided low-cost financing and subsidies for the solar manufacturing industry. Solar was among the industries targeted for government stimulus loans in the wake of the global financial crisis of 2008, with decisions about which industries to promote left partly in the hands of local officials. Jiangsu and the China Development Bank offered RMB 10 billion in low-cost loans to solar manufacturing in this period, for example.²³

Government policies to encourage massive domestic solar deployment began as a response to overcapacity issues, in part due to pressure from industry and local governments. A subsidized feed-in tariff was adopted for solar in 2011, and efforts to accelerate domestic deployment accelerated at the



same time as a decline in European demand for Chinese panels and increased trade tensions, including countervailing duties introduced in the US in 2011 and then in the EU in 2013.²⁴ The 12th Five-Year Plan set targets for solar that provided a major impetus for the industry domestically – and these targets were subsequently raised when the industry exceeded them, supported by generous tariffs.²⁵

In terms of absolute amount, feed-in tariffs were likely the main form of subsidy over the past decade, and annual feed-in tariff payment volumes remain large today for projects developed in previous years, even though subsidized feed-in tariffs have now been phased out for new, conventional wind and solar projects. In 2022, the total subsidy funds allocated to wind reached RMB 10.5 billion per year, and for solar PV, RMB 26 billion.²⁶ Feed-in tariff subsidies are allocated by the Ministry of Finance to the grid companies based mainly on revenue raised from a surcharge on retail electricity sales.

The solar manufacturing industry also benefited from positive signals from the central government, such as designating solar as a strategic emerging industry, and setting and revising upwards aggressive targets for new capacity additions. Later, as prices for PV declined, government regulators steadily reduced and then eliminated subsidized feed-in tariffs for new utility-scale solar projects, but kept them in place for targeted fields such as distributed solar. To encourage project developers and manufacturers to upgrade to the latest, most efficient technologies, in 2016 the government established requirements for certain projects to undergo tendering, with some projects to go to more companies designated as 'Top Runners' based on performance and quality. This encouraged companies to compete on both price and quality, while winnowing out local players that were surviving mainly on preferential treatment and support from local government.²⁷

2.2 Stationary batteries promoted recently for renewable integration

In several respects, battery manufacturing in China has followed a similar development trajectory to that of solar PV. China's battery industry began to expand rapidly in the early 2000s as major Asian manufacturers, particularly Korean and Japanese firms, set up manufacturing lines to take advantage of major electronics industry clusters that had already emerged along China's coastal regions. Subsequently, China's battery manufacturing capacity began to rise as new domestic entrants came into the market – especially Ningde, China-based CATL, now the world's leading battery maker. As with solar, falling prices and a policy focus on energy storage as a strategic emerging industry have led to greater efforts to deploy energy storage domestically, including in vehicles and stationary storage. Electric vehicle policies, discussed below, played a major role in promoting domestic battery manufacturing.

Stationary storage has also been a particular emphasis of power sector policy since 2020, as more provinces introduce requirements for new wind and solar projects to include storage²⁸, and the central government promotes integrated projects combining these technologies.²⁹ Given the present structure of China's electricity markets, and the relative cost advantage of pumped hydro storage, battery energy storage is not currently economical as a stand-alone application. Nevertheless, China's domestic installations of stationary battery energy storage in 2023 nearly tripled from the prior year, reaching 31 GW, up from 13 GW in 2022, and already ahead of targets set by the National Energy Administration (NEA) as recently as 2021.³⁰ China's battery industry continued to expand both capacity and output in 2023, both for domestic demand and exports, and to satisfy vehicle and stationary battery markets. Overall output surged over 40 per cent to 778 GWh, of which only half was used domestically, with much of the remainder going to export markets.³¹ The industry's expansion remains a major focus of policies at the local level, with several provinces pursuing battery manufacturing as a development strategy going into 2024.³²

2.3 Electric vehicle policy began early, but accelerated only when industry achieved success

In the field of new energy vehicles, which since 2010 has grown in tandem with battery manufacturing and become the dominant consumer and source of growth for batteries in that time, China has seen an even more impressive expansion. By the end of 2023, new energy vehicles accounted for roughly 40 per cent of annual domestic passenger vehicle sales, far ahead of government targets for New Energy Vehicles (NEVs) to reach a 20 per cent share by 2025. Overall domestic sales of over 8 million grew by 33 per cent in 2023, and by an impressive 110 per cent in 2022. While the Chinese vehicle industry has suggested the domestic NEV market share will reach 40 per cent for the full year of 2024³³, past



experience and current EV manufacturer plans suggest the reality could surprise by being even further to the upside. In terms of both numbers and market penetration, China has the largest EV market, and the country has become a major exporter of EVs to both Europe and the developing world, especially Southeast Asia. While many of China's exports are made-in-China Tesla vehicles, domestic Chinese brands have recently gained a foothold in several regions, as diverse as New Zealand, the Middle East, Southeast Asia, and Europe.³⁴

China's success in the fields of batteries and electric vehicles is more recent than that of wind and solar, and shows both similarities and differences. The role of public policy has been prominent in all cases. Policy-makers began to promote EVs in the early 2000s, on the advice of leading officials who argued international automakers were lagging in this field and that China could build on its competitive advantages in manufacturing to leapfrog ahead of foreign players.³⁵ This resulted in the inclusion of NEVs in China's Mid-to-Long-Term Development Plan for Science and Technology 2006-2020³⁶, as well as the launching of several pilot programs at the local level, particularly in the use of buses. Electric buses and taxis were also piloted in the lead-up to the 2008 Beijing Olympic Games.³⁷ Major battery technologies were also listed in government catalogues of R&D priorities.³⁸ Chinese firms were encouraged to invest in R&D centres abroad and to acquire technologies.

The speed and success of these efforts gave policymakers confidence that China held comparative advantages in the field and could successfully localize EV and battery manufacturing and technology, and led to the adoption of additional policies, such as the more ambitious local EV pilots under the 'Tens of Cities, Thousands of Vehicles' program.³⁹ To localize technology, market access terms for foreign automakers were adjusted, and NEV targets were developed with the industry. Coordination of EV policy was achieved in part through EV 100, an industry organization set up with the guidance of the State Council to coordinate between industry and government. NEVs were included as a Strategic Emerging Industry in 2010⁴⁰, and prominently featured in the 'Made In China 2025' policy, adopted in 2015.⁴¹ Already in 2014, President Xi Jinping noted that EVs were central to China's strategy of transitioning from a 'big car country' to a 'strong car country'⁴², and that EVs offered the potential to leapfrog Western carmakers. All of these policies, leader statements, and generally supportive policy signals from the central government guided state-led investments in EV manufacturers, battery R&D, and the scale-up of manufacturing capacity up and down the supply chain.⁴³

For EVs and batteries, subsidies have also played a major role, and probably helped spur local government interest in switching to EVs. China's largest EV maker, BYD, is estimated to have received \$2.6 billion in subsidies from 2007 to 2022.⁴⁴ According to one estimate, China's EV industry received has subsidies of \$47 billion since 2009.⁴⁵ This includes tax breaks and purchase subsidies for NEVs, and also low-cost loans and other direct support to battery and EV makers.

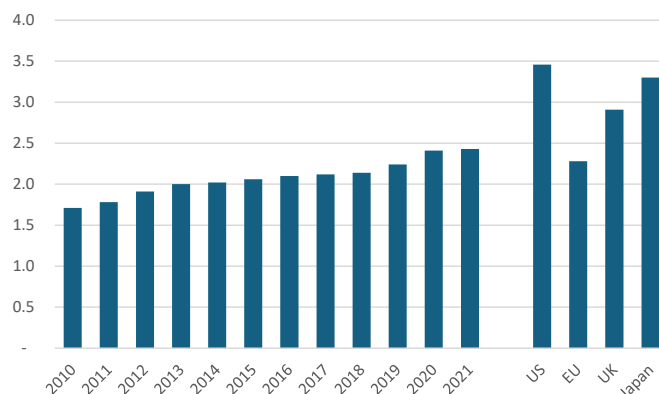
2.4 R&D funding and supporting policies steadily ramped up

For wind, solar, batteries and EVs, innovation has been critical, and to some extent, this innovation has been guided and driven by government. Innovation and R&D have been key policy priorities of the central government, and were increasingly highlighted in Five-Year Planning documents going back to 2000, and especially since 2011, when the 12th Five-Year Plan included specific targets related to indigenous innovation, including R&D funding as a share of GDP, patenting, and educational achievement.⁴⁶ Innovation and R&D have also been steadily boosted in key plans and programs, such as the 1986 'National High-Tech R&D Program' (also known as the '863 Program'), the 1997 'National Basic Research Program' (973 Program), and the 2006 'Medium-to-Long-term Program for Science and Technology Development'.⁴⁷ China's estimated public and private R&D spending as a share of GDP is comparable with those of many advanced economies, albeit below that of the US – and has shown a consistent rise over the past decade (see figure 3 below). During the 14th Five-Year Plan, the government set a goal of increasing R&D spending by 7 per cent annually. China's government R&D spending is especially strong in the energy sector, where its share of the global total government R&D spending on energy has risen from 25 per cent in 2019 to over 34 per cent in 2023, larger than any other country or region.⁴⁸ The central government coordinates R&D activities at various levels, including directly funding strategic research fields under various State Key Laboratories, at universities, and state-owned enterprises (SOEs). Generally, funding research priorities are coordinated by the Ministry of Science and Technology (MOST), but all top ministries, including the National Development Reform Commission (NDRC) and the NEA, contribute to setting of research priorities and guiding investment in



fields under their purview. Local governments and state-owned banks are also guided to support firms engaged in R&D in strategic fields.⁴⁹

Figure 3: R&D spending as a share of GDP in China (2010-2021), and comparison to other countries/regions in 2021



Source: author, based on data from the World Bank, 2024

Local policy-makers have increasingly looked to clean energy manufacturing as a way to boost employment and tax revenues, and show progress towards the level of industrial upgrading desired by the central government. Especially since the real estate sector and revenues from land sales fell off markedly in 2023, local governments have focused even more on clean energy as a growth strategy.⁵⁰ This trend appears set to continue through 2024, based on provincial and local development plans.

2.5 Clean energy policy continuity aided industrial transition, with occasional abrupt shifts

While this brief outline of the key supportive policies and various forms of central and local subsidies suggests overall similarity and continuity, policies have in some cases lagged developments in industry, or evolved over time in response to developments at home or abroad. Chinese energy and industrial policies have guided both investment and innovation – playing the lead role in the *guidance of search* that scholars have long identified as a key variable in technology innovation systems. Guidance of search is defined broadly as ‘activities within the innovation system that can positively affect the visibility and clarity of specific wants among technology users’⁵¹, and can include government policies, the opinions of top technology experts and futurists, or trends in investor preferences in capital markets.

While China has adopted a sequence of far-sighted strategic industrial policies and followed up with high levels of administrative and financial support, the consistency of China’s support policies should not be exaggerated. Each of the clean energy sectors China now dominates has undergone booms, busts, and periods of stagnation as a result of short-term policy shifts, such as the sudden and devastating overnight cut to solar feed-in tariffs in 2019 known as the ‘May 31’ policy⁵², or the 2016 investigation of subsidy fraud in the EV and battery space that led to major changes in that program and slowed the NEV market for a time. While there have been ups and downs, however, China has never undergone a significant policy-driven clean energy deployment slowdown comparable to those seen in some European countries or the US over the past two decades.⁵³

Overall, central government policies play a major role in guiding the behaviour of local officials, determining the sectors favoured for investment by state-owned enterprises and banks, and ensuring industries remain viable even during downturns that might have staggered their counterparts in North America or Europe. Yet these policies also have ad hoc, experimental aspects. In some clean energy sectors, such as biofuels for example, where industry scale-up has been more difficult or costly than expected, policy support has dwindled over time. The success of wind, solar, battery and EV technology policies has not been linear, nor have policy developments always gone according to plan. Coordination between central and local government has often proven difficult. The central government has at various times instituted limits on provincial build-outs of wind and solar⁵⁴, criticized local governments for starting too many low-quality manufacturers to capture subsidies⁵⁵, tamped down on overcapacity and forced locally-supported clean energy industries to consolidate⁵⁶, compelled provinces to purchase renewable



energy⁵⁷, or outright intervened to crack down on subsidy fraud.⁵⁸ Some policies, such as the original design of the green energy certificate, have failed outright.⁵⁹

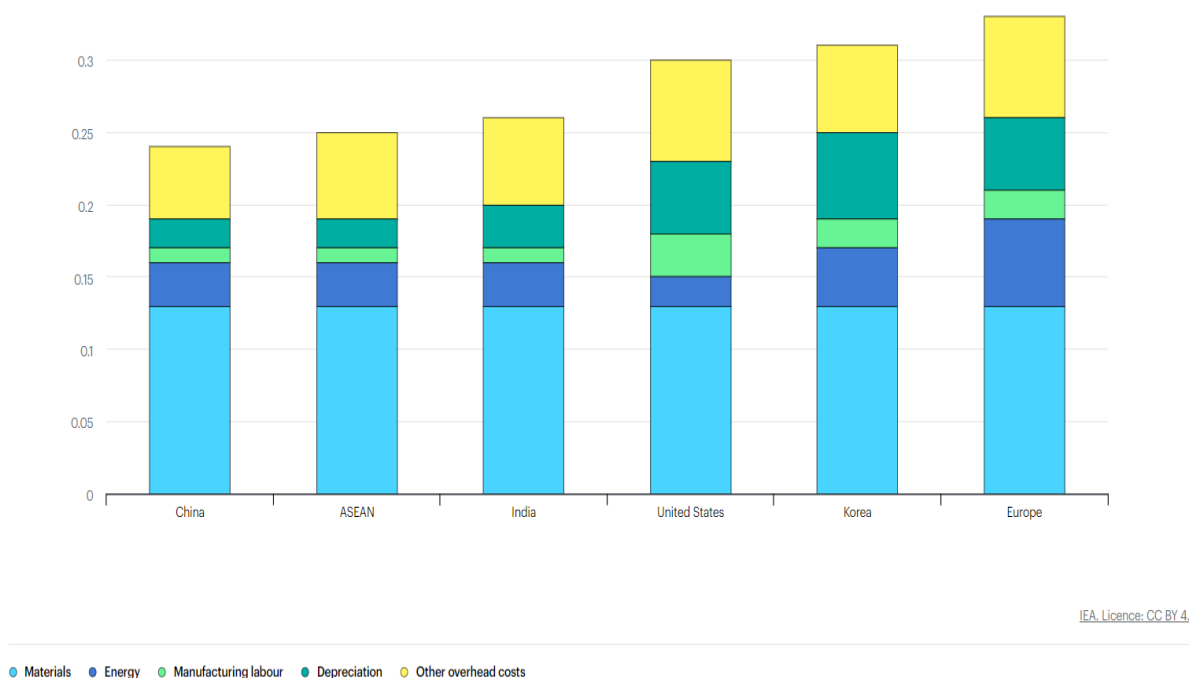
Not only has policy never been perfect, clean energy technology in China also benefitted from other aspects that aided its scale-up and promoted successful learning and innovation, as the following sections will discuss. The three aspects of China's success considered here are:

- 1) China's resilient and adaptive supply chains,
- 2) China's strong links with global innovation networks, and
- 3) China's human capital in key fields, including its dynamic corporate ecosystem of innovative and fiercely competitive private entrepreneurs, both of which operate within a framework of state support and often partnership with SOEs throughout the economy. These are the topics of the next three sections.

3. China's industry clusters, the unsung heroes that helped achieve scale and contributed to innovation

Since China's accession to the World Trade Organization, not only has China's economy opened up and trade increased, but China has become known for its ability to rapidly scale up manufacturing and develop integrated supply chains.⁶⁰ While initially the movement of supply chains to China benefitted from low labour costs and an abundant supply of workers, an advantage in labour cost has been only a minor factor in China's dominance of clean energy. In many fields, such as solar, labour costs are a minor factor, and the economic gains from scale, flexibility, and immediate access to related parts of the supply chain have held greater importance.⁶¹ As far back as 2011, research has shown China's solar scale-up could be attributed to manufacturing scale and supply chain localization, rather than labour costs or other country-specific advantages (see figure 4).⁶² Indeed, as Nahm and Steinfeld (2014) showed, China's dominance of solar was achieved largely due to the speed of scaling up, which has enabled this and other industries to both benefit from and accelerate the learning rate for manufacturing-intensive technologies.⁶³

Figure 4: Total production costs for mono PERC c-Si solar components by input, 2022



Source: International Energy Agency 2024⁶⁴



Clusters and innovation

The relationship between China's success in scaling up clean energy manufacturing has a clear link to innovation as well. Economists have long seen advantages to establishing industrial clusters in specialized fields, as exemplified by historic policies to concentrate and virtually imprison glassmakers in Murano, Italy, in the 1200s, or establish monopolies for porcelain in Sevres or Limoges, France. In 1890, Alfred Marshall famously wrote that in cities and other industrial centres, new ideas and practices spread rapidly, and 'the mysteries of the trade become no mysteries; but are as it were in the air, and children learn many of them unconsciously'.⁶⁵ Even in modern economies, technology innovation and diffusion appear to have a geographical component, related to the physical concentration of knowledge spillovers. In advanced technologies as well, agglomeration economies – defined broadly as economies in which greater population density correlates with faster growth, but also associated with clustering of economically related industries – are believed to play a role in fostering innovation and promoting technology diffusion. Silicon Valley is a classic case of an innovation-driven agglomeration economy, noted for the rapid diffusion and recombination of technological advances, in part driven by high job turnover and consequent sharing of know-how among firms and related industries.⁶⁶

The importance of industrial clusters and their relationship to innovation has been questioned and debated, with various scholars noting the poor definition of clusters, a lack of specificity of how clusters promote innovation or technology diffusion, and under-appreciation of how clusters may lead to technology lock-in and inertia, especially in established industries.⁶⁷ The benefit of co-location in clusters is connected to the importance of tacit knowledge exchange, which requires direct personal interaction – not only in the knowledge economy or R&D activities, but in manufacturing as well, such as in the auto sector.⁶⁸ This includes China, where research has shown industry clustering benefits new product design, industrial upgrading, and technology catch-up – in short, all the keys to advancing in emerging technology or industry.⁶⁹

3.1 Manufacturing-intensive clean-energy technologies favour close supply chain links

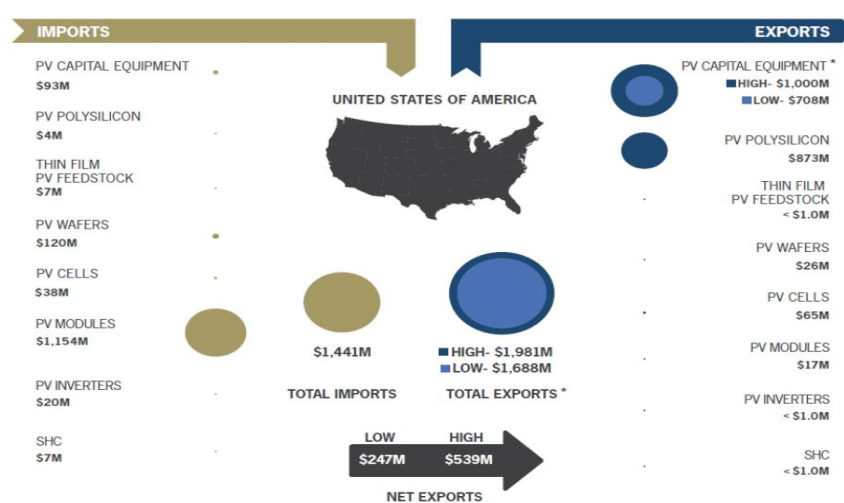
China's innovation in certain fields, such as wind and batteries, has concentrated on process- and manufacturing-oriented innovations, reflective both of China's latecomer status and its role in manufacturing supply chains.⁷⁰ To many, this may appear to represent a lower value aspect of innovation, distinct from breakthroughs achieved through basic science and university laboratory research, which may carry greater prestige and result in an entire technology being viewed as 'invented' in a given country or company – as in the case of the three Nobel Prize-winning inventors of the lithium-ion battery, or the patenting of the first solar cell.⁷¹ However, as the history of solar and batteries shows, the commercialization and scale-up of technology require ongoing innovation, leading to new intellectual property and know-how that are essential to developing an industry that can compete with incumbent technologies.⁷² After a standardized design is established, and commercialization achieved, innovation may accelerate due to improved perceptions of a technology's legitimacy, value to society, and prospects for growth.

As Daniel Breznitz has shown,⁷³ many countries and cities have pursued long-term policies to foster innovation as an economic development strategy, and although efforts to recreate Silicon Valley have often failed, these efforts have nevertheless proven successful at establishing major R&D clusters, incubating and growing important technology startups, and attracting venture capital and other investment. However, Breznitz argues that the regional economic gains to such innovation clusters have fallen short of expectations because once the scale-up phase begins, most regions lack an integrated supply chain or the know-how to efficiently dominate production. The forces of classical economics then seem to take over, driving production to regions with comparative advantages in labour or capital productivity. Investors and managers alike see advantages in disaggregating production as quickly as possible, in order to beat out competition and reduce costs. This implies a constant tension: reducing costs quickly may push companies to disaggregate production, but this leaves them vulnerable to missing out on the ongoing interactions needed throughout the supply chain to remain at the technology frontier in manufacturing-intensive technologies.



If disaggregation were solely the result of firm specialization and slow-changing regional or national comparative advantages and cost savings, then technology diffusion would likely remain low. Economies like those in East Asia would have remained perpetually on the technological periphery, consigned to mass production and dependent on external networks for the latest designs or production processes – just as China was dependent on imports of turnkey solar production lines in the early 2000s, or as Latin American countries became dependent on imports of expensive tools when attempting import-substitution policies in the 1970s and 1980s. As recently as 2011, researchers at the US National Renewable Energy Laboratory reported that the value of US exports to China of advanced manufacturing tools for solar outweighed imports of solar modules and panels from China (see figure 5 below).⁷⁴ However, this analysis – which carried the implicit conclusion that the US would retain the higher value elements of the solar supply chain for many years – ignored the importance of manufacturing know-how as a driver of ongoing innovation in fields such as solar and batteries.

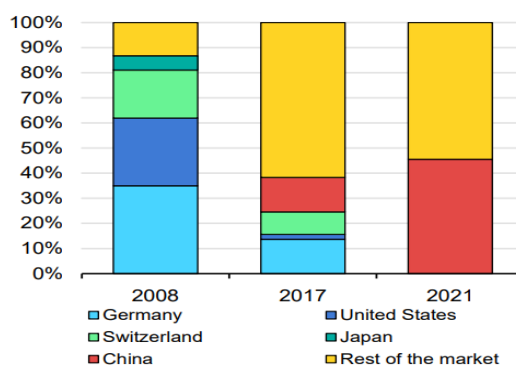
Figure 5: US-China solar trade balance in 2011 – Solar imports from China to the US, versus estimated exports from the US to China



Source: Alan Goodrich et al., National Renewable Energy Laboratory, 2011

It is perhaps little surprise that things have changed since 2011, and that the higher-value parts of the supply chain have moved to China as well: a 2023 International Energy Agency report on solar PV supply chains noted that whereas the US, Germany, Japan, and Korea accounted for almost all manufacturing of PV-related tools in 2010, in 2022 the top PV equipment manufacturers were all located in China, which held 45 per cent of the global market (see figure 6 below).⁷⁵ In China, specialization in innovation related specifically to production and assembly has offered regions such as Shenzhen or the Yangtze River Delta a key advantage in building regional economic clusters, initially around consumer electronics, and then in solar, then in EVs.

Figure 6: Revenue share of top 10 solar equipment-making companies by country



Source: International Energy Agency, July 2022



3.2 China's policies have supported supply chain integration

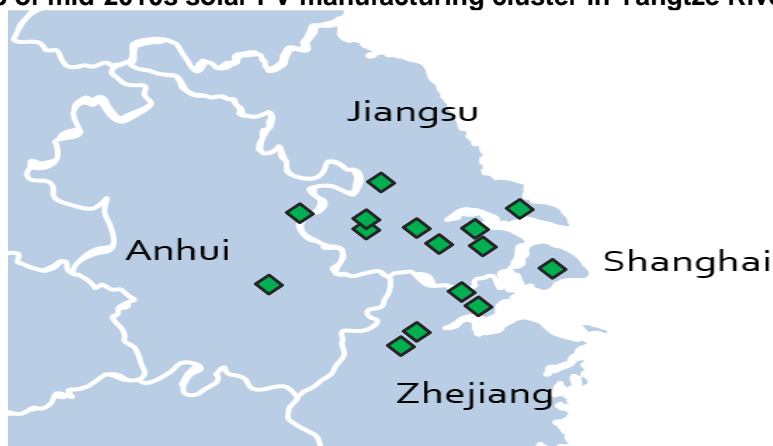
Whereas innovation policy in other countries often focuses on novel technologies, basic research, and investment in startups offering to marry new technologies with better business plans or marketing approaches, China's national and regional policymakers have tended to focus on promoting innovation connected with manufacturing clusters. In many cases, this type of strategy has been explicit. When designing electric vehicle subsidies, in 2016 the Ministry of Industry and Information Technology defined three requirements for regions to receive subsidies: a high initial level of NEV production, active local policies to promote the purchase of EVs, and investment in charging infrastructure. Additional subsidies were made available to provinces and cities that showed the most progress in these respects.⁷⁶ Local governments have also encouraged clustering and supply-chain integration. Besides offering solar manufacturers cheap land, Guangzhou province also designated industrial parks and clusters for solar. Guangzhou even required the previous firms occupying the sites to move out to make space for solar firms – in some cases, without compensation.⁷⁷ Local government also directly supported R&D and innovation, often by simply paying to establish research centres at manufacturing sites, as in the case of Yingli in Hebei province.⁷⁸ In other instances, as in Suzhou, the local government used cheap loans and demand-pull policies to encourage individual companies to establish local research centres connected to manufacturing.⁷⁹

Such policies certainly had their risks, and amounted to 'picking winners' – and in some instances, spectacular losers, as in the case of failed solar leader (and local government-backed champion) Wuxi Suntech. But in other cases, attracting a single company and building up its supply chain and research prowess simultaneously produced fantastic results, as happened with Jinko Solar, a company founded by an entrepreneur with experience making firefighting gear,⁸⁰ which now holds the laboratory record on several different types of solar cell efficiencies, and is perhaps the leading tier 1 solar manufacturing firm in the world.⁸¹ From early on, even while acquiring foreign technologies, Jinko focused on developing a vertically integrated manufacturing model, including wafers, cells, and modules, all based in China – and often concentrated in a single locality.⁸²

Vertical integration also played a key role in the rise of BYD as a leader in battery innovation. The company's decision to vertically integrate was taken far before it entered the automotive market and was based on what its management learned from manufacturing chips and parts for leading mobile phone makers like Motorola and Nokia in the early 2000s. Essentially, BYD found itself unable to meet quality and performance expectations without mastering each aspect of the manufacturing process. Today, BYD sources 90 per cent of its parts from its own company.⁸³ BYD's strategy of vertical integration has resulted in the development of a major manufacturing cluster in Shenzhen, drawing on the region's existing expertise in electronics and electrical equipment.

The following maps (figure 7 and figure 8) display regional manufacturing clusters related to solar and battery manufacturing.

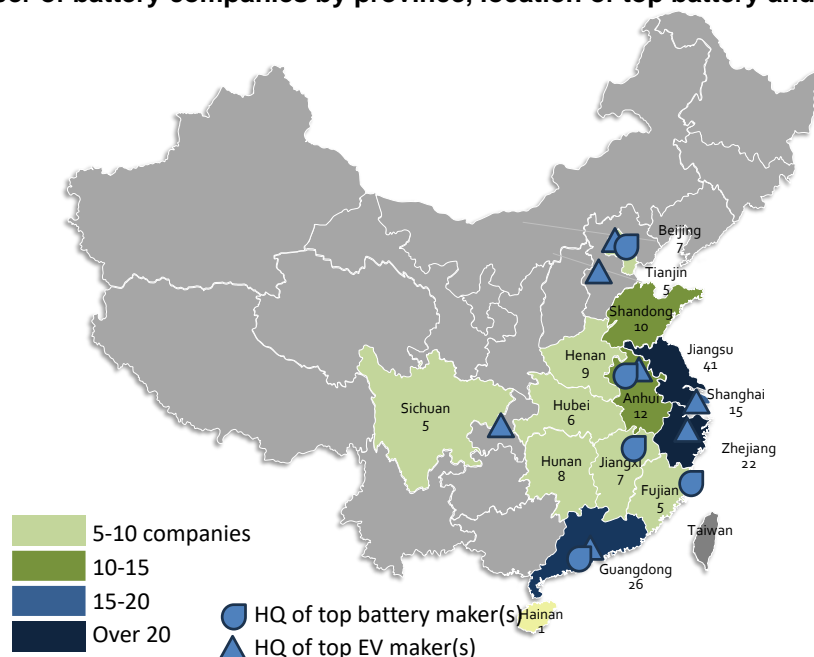
Figure 7: Map of mid-2010s solar PV manufacturing cluster in Yangtze River Delta



Source: Jeffrey Ball et al., 'The New Solar System', 2017, and BNEF



Figure 8: Number of battery companies by province, location of top battery and EV firms, 2021



Source: OIES, based on data from Boy Lüthje et al., 'China's New Energy Vehicle Battery Industry', 2021

3.3 Many patterns of supply chain clustering and interaction

It is of note to compare the case of BYD against that of the Tesla Gigafactory in Shanghai. While Tesla is sometimes known in the US for its relative willingness to produce parts in-house, one of the strengths of Tesla's production in Shanghai has been its partnership with the local government to attract suppliers and build up a local supply chain and industrial cluster around the Gigafactory. While Tesla was given rare freedom to use non-Chinese batteries or parts in its cars, its willingness to shift to Chinese components was a key factor that led to Shanghai's decision to lobby the government in favour of loosening restrictions to bring Tesla in. Today, 95 per cent of Tesla Shanghai's suppliers are Chinese.⁸⁴ Tesla is generally willing (and was implicitly expected) to engage and train local suppliers in order to enable them to meet the technical requirements of Tesla, and thus, gradually develop a local value chain not only for batteries, but also for other components specific to electric vehicles such as electric engines, battery management systems, or battery temperature regulation systems.⁸⁵

Tesla's experience to some extent replicates the strategies that led European solar companies to establish production in China. In PV, solar startups and multinationals sought to locate production where it could operate with the greatest speed and productivity, and near the technology frontier.⁸⁶ This took place gradually, in stages, as the solar industry developed – leading to what authors have called the *co-evolution* of solar technology, building on industrial clusters in China with relevant firms and expertise.⁸⁷

In the well-known 2017 Stanford study of China's solar industry, 'The New Solar System', Jeffrey Ball and colleagues found that 'China's solar industry is a textbook lesson in the power of manufacturing clusters.'⁸⁸ At the time of the study, China's leading manufacturers were midway in the process of mastering the tools and equipment needed to fully localize the solar supply chain. While many of the most efficient tools came from German or other European suppliers, and Chinese equipment was reportedly less reliable, solar factory managers noted that the locally-made equipment was not only 50-60 per cent less expensive, but faults were also easier to diagnose and repair due to locally available technicians and language commonalities. The report cited examples of how proximity to suppliers and assembly lines directly accelerated the commercialization of new innovations that might have otherwise gotten stuck at the lab stage. Furthermore, Chinese tools and equipment were advancing rapidly, due to their close links with cell and module makers:



*'Module manufacturers typically work closely with their suppliers to diagnose problems and to develop new materials and parts. Trina is one example. Ten of its suppliers' factories sit in the same industrial park as Trina itself. The proximity allows engineers from Trina and its suppliers to meet to discuss their ongoing joint R&D projects on a weekly basis.'*⁸⁹

In their study of China's rapid scale-up of solar, Nahm and Steinfeld also noted that multi-directional interaction among firms was critical, not only to production speed, but also to innovation:

*'In the emerging industries [namely, solar], both the products and production processes are new and relationships between upstream design, manufacturability, scalability, cost, and ultimate product functionality are still highly uncertain. Therefore, the network must involve more than just highly specialized firms focusing internally on their own assigned tasks, and then handing off the results to the next partner in line. Instead, there has to be the capacity for multidirectional inter-firm communication, learning, and collaborative problem-solving. We argue that this capacity is central to Chinese innovative manufacturing.'*⁹⁰

Less than a decade later, Chinese firms dominate the production of the most advanced solar technologies, with new record solar conversion efficiencies being announced regularly by Chinese manufacturers, including for materials still in the lab stage such as perovskite tandem cells,⁹¹ as well as for fully commercialized technologies such as bifacial, PERC, and n-type monocrystalline PV.⁹² Patent analysis suggests that Chinese firms and patent holders are now at the centre of global solar innovation networks.⁹³ As China's manufacturers upgrade and expand production lines, costs continue to fall: in 2023 alone, China's solar PV production costs fell a massive 42 per cent, to \$0.15 per Watt, compared with \$0.40 in the US.⁹⁴

Industrial clusters have also reportedly played a role in the development of China's battery and electric vehicle industries.⁹⁵ Major clusters for NEVs are located in Guangdong, Fujian, and Zhejiang, with the lithium-ion battery industry particularly concentrated in the Pearl River Delta region. Many of these clusters have been designated by local governments:

*'One major characteristic of China's emergence of a battery industry is (the) clustering of the battery manufacturing activities at a regional level across the whole country. In fact, almost each provincial government has elaborated ambitious plans for developing an NEV industry, including its battery supply industry ... Promoted by industrial policies of local governments, [a] local cluster can contain a relatively complete value chain of NEV battery-making from upstream segments, such as material production, through cell and pack production, to downstream applications of battery packs to different fields, especially electric vehicles. Thus, an OEM [original equipment manufacturer] can easily find the whole supply chain from one local cluster.'*⁹⁶

3.4 Clusters and competition contribute to the pace of innovation

Not only do clusters enhance technology diffusion, but they also involve high degrees of competition within the cluster itself, much like the accelerated competition seen within Silicon Valley. Within the Pearl River Delta NEV- and battery-manufacturing mega-cluster, individual local governments and companies compete even while remaining highly interdependent. So just as duplication of favoured policies results in redundancies and waste at the national level, this can also occur within provinces.⁹⁷

In the EV space, proximity to local supply chains and intense competition have contributed to accelerating the pace of innovation and new product cycles, which are critical to growing and maintaining market share in China's ultra-competitive markets. China's NEV makers can move faster than their US and European counterparts. Recent media reports indicate that Shanghai-based EV startup Nio can turn out a new model in 36 months, while Geely's Zeekr sub-brand can produce a new model in 24 months – both far faster than their counterparts abroad.⁹⁸ Chinese EV models average just 1.3 years of market life before updates or new versions are released, compared with the 4.2-year cycle of foreign brands. In addition, the strong consumer interest in top-notch onboard electronics and software leads to especially strong innovation and rapid turnover in this field, relative to US and European firms, whose EV customers are more focused on range and battery performance.⁹⁹



There are several explanations as to how China's carmakers can make products so quickly. These include: (1) longer experience with and greater long-term commitment to EVs as a core business strategy than legacy automakers; (2) more direct relationships with suppliers, including tier 2 and tier 3 suppliers and especially suppliers in the crucially-important onboard IT systems; and (3) greater choice and willingness to switch suppliers when problems arise. In some cases, such as Nio's partnership with Hefei-based JAC, access to a legacy automaker's production line without responsibility for managing its entire business has given Nio greater flexibility over design and marketing.¹⁰⁰

Vertical integration in the Chinese battery and EV space has also contributed to innovation in the upstream, where Chinese officials and companies remain concerned about the security of supplies. Over the past decade, not only has China accelerated the approval of lithium mining operations and rapidly expanded lithium output as well as processing, but EV and battery companies have invested in upstream production, and over 400 Chinese companies are now involved in battery materials processing. The results have not only taken the form of increased output from new mines, but innovation has increased output at existing facilities and reduced costs at new processing facilities – giving China an edge in this crucial space, even when China must rely on imports of raw minerals to feed such facilities.¹⁰¹

3.5 Proximity to a large demand base further supports innovation

While integrated local supply chains have been crucial, especially for solar, batteries, and EVs, direct access and proximity to the largest market for each technology has unique benefits, depending on each technology's characteristics. Design-intensive technologies, such as wind turbines, vehicle motors (EV or otherwise), or consumer products have typically benefitted from access to large markets and proximity to customers. Whereas historically Japanese carmakers benefitted from testing out and perfecting new technologies in their home markets, leading to advances in high-quality and fuel-efficient sedans and hybrid vehicles¹⁰², today this advantage seems to benefit China, where a large proportion of new car buyers seek brands perceived as on the cutting edge of technology, including EVs.¹⁰³

Lastly, overcapacity in each clean energy sector has led to high levels of competition and a race to drive down prices through manufacturing efficiencies and battery performance. In other countries, boom-bust cycles may lead industry leaders to preach capital discipline and efficiency – or even fire sales of key technologies to Chinese players, as happened in solar and batteries in the early 2010s.¹⁰⁴ In China, the availability of capital for the largest players, even during periods of contraction, means that its clean energy firms continue to lead and advance. Sustained financial backing for clean energy industry players, even during hard times, takes various forms, and can include state intervention of local policymakers with SOE banks, support from partner firms including SOEs, and simple cash subsidies. Above all, government: officials, financial institutions, and large firms look to the central government for signals about which industries to finance and support; state-owned and private firms in strategic sectors enjoy preferential access to capital, including both debt and equity, and perceive the need to boost R&D spending to remain competitive.¹⁰⁵

Given this, even downturns can lead to industry upgrading. China's solar industry is currently undergoing a major round of upgrading to the most efficient cell and module types, even though the top players with fully upgraded capacity are still operating at low utilization and are barely surviving.¹⁰⁶ The situation is similar in the EV space – even rapid expansion has seen the rise and collapse and rise again of certain players. Bigger companies have all weathered major downturns in the past, using various strategies. For example, BYD survived a slow period for EVs by investing in plug-in hybrid electric vehicles (PHEVs) and pursuing cheaper lithium-iron phosphate, or LFP, battery technology.¹⁰⁷ Currently, despite falling EV prices and a sea of competition, leading players such as Xpeng are investing in R&D to stay ahead of the competition.¹⁰⁸ BYD's R&D spending surpassed Tesla's in 2023, reaching \$5 billion compared with Tesla's \$4 billion, and up from under \$1 billion in 2016. Startups Geely and Nio are also in the same league, as are SOEs such as GAC and SAIC.¹⁰⁹ A wave of consolidation is anticipated in spite of the rapid expansion of both domestic sales and exports in the past two years. Yet in earlier rounds of consolidation, even players thought to be in danger have managed to hold on. WM Motors, which finally filed for bankruptcy in October 2023, managed to hang on for years, despite increasing losses and drastically falling sales since 2020.¹¹⁰ In some respects, overcapacity and government support mean



the market can have difficulty determining which are the strongest players and which need to be shaken out. In the battery space, most new battery production capacity is of recent vintage, and there is no outdated capacity to close, some smaller players are likely to close while the largest consolidate.¹¹¹

In summary, China's clean energy supply chain story has several elements: local supply clusters that reduce logistics costs but more importantly accelerate innovation by increasing the rate of interaction between suppliers and manufacturers; efforts by companies and local governments to establish industry clusters and raise vertical integration (even if not located within the same firm) to enable technology mastery and industry upgrading; and proximity to the largest centres of demand leading to more direct feedback, and subsequent innovation, to meet market needs.

4. China's innovation benefited from global links and technology transfer

Technology transfer and global innovation networks have been a particular focus of study on China's rise to dominance in clean energy technology. In part, this is because the process was so unanticipated by existing economic literature, which posited that advanced economies would be the first to commercialize and scale up emerging and not-yet-economically-competitive technologies – especially those targeted at achieving environmental objectives.¹¹² China's swift and massive entry into the wind and solar spaces came first, followed much later by the battery and EV sectors. In all cases, China's dominance came about not due to one-way technology transfer, or merely to process-level innovation and manufacturing scale-up, but rather due to multi-level and iterative processes of interaction and collaboration over many years. There were also many different processes of learning underway (see Table 1), and these shifted and changed depending on the technology, its maturity, and the stage of the market's development.

Table 1: Historic top tech transfer and global innovation factors by sector: wind, PV, batteries, EVs

	Domestic content requirement	Mandated tech transfer	Licensing	R&D partnerships	Returning experts	Turnkey production lines
Wind	x		x	x		x
Solar			x	x	x	
Batteries	x		x	x	x	
EVs	x	x			x	

Source: author



4.1 Technology transfers were a first step in wind and solar innovation in China

China's wind sector achieved take-off in China in part owing to the Clean Development Mechanism (CDM), a United Nations-administered carbon credit programme that offered carbon emissions credits in exchange for clean energy investments in developing countries, and China's adoption of local content requirements for wind turbines. When these requirements were introduced in the mid-2000s, most foreign equipment manufacturers established manufacturing and development facilities and centres in China, as well as joint ventures (JVs), in an effort to localize production to qualify for the policy's 70 per cent domestic content requirement.¹¹³ Foreign direct investment, therefore, constituted an important first step in technology transfer.

However, local players such as Sinovel, Goldwind, and Dongfang – all of which were spun out of existing firms in related fields – quickly entered the market, often utilizing a combination of equipment sourced from foreign companies (including those with facilities in China) or technologies licensed from foreign technology providers. This was not always quite so legitimately arrayed – in 2018, Sinovel was convicted in a high-profile case of intellectual property theft that took place in 2011, after which Sinovel's own business experienced an abrupt decline.¹¹⁴ However, as Chinese firms' market share rose, their relationships with licensing firms and European design houses gradually evolved; while Chinese players continued to draw upon European technology and design firms, the relationship evolved into one of mutual learning and co-design,¹¹⁵ as turbine designs continued to evolve rapidly and as China became the largest and most lucrative wind market globally. Goldwind in 2008 acquired Vensys, a European wind design firm,¹¹⁶ and other Chinese manufacturers have followed suit by acquisitions (such as Darwind by XEMC), licensing European technologies (such as Dongfang licensing technology from RePower), or joint development (such as United Power and Ming Yang with Aerodyn).¹¹⁷ For many years, the design and engineering aspects of Chinese firms continued to have strong connections with Europe, with Chinese firms establishing or partnering with design offices located abroad and employing foreign engineers.¹¹⁸

Wind power constitutes a complex product system, requiring thousands of parts as well as competence in heavy construction and logistics. Wind projects typically involve hundreds of firms. In contrast, solar PV involves few parts, only a few sequential process steps, and a modular product that can be shipped as standardized, commoditized items and installed by third parties without specialized relationships with the supplier. For this reason, technology transfer and learning in the wind sector require more time and greater acquisition of tacit knowledge.¹¹⁹ This difference has not prevented technology catch-up, however. As the largest wind market and largest power market, China could gradually absorb tacit knowledge, and contribute to innovations in the wind sector that ultimately led to cost reductions over time. While global innovation networks were important to Chinese industry, however, studies have shown that rapid cost reductions were achieved mainly through manufacturing scale-up, learning-by-doing, competition among new entrants and low costs of capital. Innovation and R&D played a less important role.¹²⁰

Solar featured an important role in contract manufacturing: European countries sought to contract for cheaper imports of cells and modules from new Chinese startups, and these startups were able to acquire turnkey manufacturing equipment from Japanese and German suppliers, along with training on how to set up production.¹²¹ In the initial phases, European solar manufacturing firms sought to resolve temporary shortages of cells and modules by contracting with manufacturers in East Asia, including China. Chinese firms working with European companies purchased manufacturing equipment that was accompanied by specialized consulting services for setting up and commissioning production lines. After 2006, turnkey production equipment from Japan enabled more rapid expansion, including at new entrants and lower-tier manufacturers.¹²²

While this process is sometimes portrayed as a single-directional process of technology transfer, Nahm and Steinfeld noted in 2014 that China's localization of PV manufacturing was a bidirectional or even multi-directional process.¹²³ As in the case of wind power, Chinese solar firms not only licensed technology or acquired turnkey production lines, but also set up multidimensional international research collaborations with European, East Asian, and Chinese research centres.¹²⁴



4.2 Batteries and EVs benefitted from licensing, joint ventures and localisation rules

Like solar and wind, batteries and EVs involved major elements of international collaboration and learning networks, with some analogous aspects. Just as local content requirements drove the localization of wind technology, EV technology benefitted from JV requirements, and battery localization was spurred by both tacit and explicit requirements for local content. Battery manufacturers used licensing and acquisitions to gain access to foreign technology.

In terms of domestic innovation, the technology characteristics of batteries and EVs have resulted in different levels and kinds of innovation. Although in the early stage of the development of lithium-ion technology, in the 1970s through the 1990s, international battery innovation and technology breakthroughs were tied to cross-disciplinary experience, international cooperation, and inter-company collaboration across multiple industrial fields.¹²⁵ Although battery technology has continued to evolve, relatively standardized designs have emerged early on for batteries, including for multiple applications in consumer electronics, vehicles, and stationary storage.¹²⁶ Innovation in breakthrough technologies continues, but much of the progress in cost reduction and technology scale-up has resulted from process-oriented developments connected to manufacturing know-how. The modular and standardized design and relative maturity of lithium-ion battery technology facilitated new entrants in China's protected market, while playing to China's advantages in manufacturing supply chains.

A mix of policies pushed carmakers to expand production while localizing key technologies, and technology transfer was a central element. Policies adopted in the 2000s required foreign carmakers to form JVs with local players to gain access to the Chinese market. Later, when China launched its New Energy Vehicle program in 2009, subsidies for EV and EV battery production were tied to technology transfer, and qualifying recipient firms had to demonstrate mastery of one of three core elements of EV manufacturing: batteries, motors, or control systems.¹²⁷ In particular, for batteries with energy density suited for EVs (over 110 Wh/kg), the minimum domestic content was set at 50 per cent.¹²⁸ Subsequently, a battery 'white list' was established for companies qualified to receive NEV subsidies, and no foreign automaker ever qualified for the list until shortly before the list was cancelled altogether in 2019, at which point China already dominated battery supply chains.¹²⁹ These policies pushed Chinese carmakers to shift battery purchases from leading Japanese and Korean suppliers to domestic players. Later, in 2017, requirements for recipients were set even higher, requiring domestic firms to demonstrate mastery of all core areas of EV production, ruling out the specialization of the Chinese supply chain in just one element of the making of EVs, and in effect localizing the industry from top to bottom.¹³⁰

In terms of fundamental technology, licensing of battery patents was an important factor, including in LFP batteries, where a unique patent case played an outsized role in China's eventual dominance in the space. In a 2010 patent dispute adjudicated in the Chinese courts, Canadian electric utility Hydro-Quebec was unable to enforce its LFP patent claims against a Chinese manufacturer.¹³¹ In the competing battery-chemistry tech field of nickel-manganese-cobalt (NMC) batteries, Chinese auto parts manufacturer Wanxiang, a company with strong links to the government, acquired American LFP battery startup A123 in 2013. In the competing NMC battery chemistry, Chinese firms were able to license foreign technologies, encourage US and other firms to establish JVs with Chinese partners (such as that between Umicore and Jinmen Xinchang for NMC production) and localize this battery technology.

Tesla is the one major exception to China's policies requiring EV JVs and the localization of technology. The Tesla case is perhaps illustrative of how intense domestic competition and technology transfer have gone hand in hand – and how EVs, like wind and solar, have involved multidimensional learning rather than single-direction knowledge transfer. In 2019, the granting to Tesla of the right to manufacture in China without a 50 per cent JV partner took place at a time when Tesla was clearly dominant in EV technology and was viewed as an aspirational EV brand for Chinese consumers, who already had several domestic models to choose from. By manufacturing locally, Tesla could reduce costs and expand sales, taking advantage of the already growing local supply chain for batteries and components. Although domestic players would face a stronger competitor, they would be forced to upgrade their products, while also potentially benefitting from knowledge spillovers from local workers and suppliers. Former Minister of Industry and Information Technology Miao Wei referred to the strategy as the 'catfish effect': like throwing a catfish into a pond of smaller fish, they would be forced to swim faster or be gobbled up.¹³²

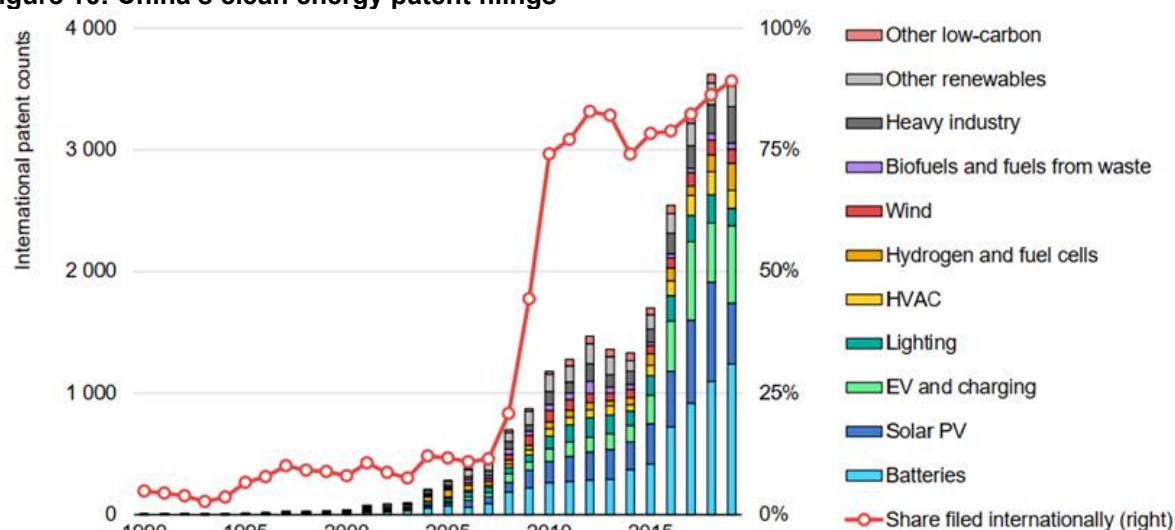


Longer-term learning networks have also played a role in the development of China's EV sector, including in vehicle design. Geely, China's first private automaker, began to seek the acquisition of Volvo more than two decades ago, and the merger was completed in 2010. Soon after, Geely and Volvo established the China Europe Vehicle Technology Center (CEVT) in Sweden, and Geely sought to benefit from both manufacturing and management know-how from the European player.¹³³ While such exchanges were initially aimed at raising standards and quality at Geely to compete successfully in the Chinese market, their ultimate aim was to make Geely a global player and ensure its designs and products could appeal to customers outside of China.

4.3 Rising Chinese dominance evident in batteries and EVs

As of 2020, a joint IEA and European Patent Office study of global battery innovation found that Japan and South Korea dominated patent and intellectual property filings across the battery industry, including for individual components and various chemical compounds of batteries, such as NMC and LFP, though China's rising share of LFP patent filings was already evident.¹³⁴ Since that time, China's battery patent filings have grown significantly, and in 2023 China accounted for more than half of advanced, non-lithium-ion battery filings. One patent analysis showed that the rate of filing for Chinese power-train battery patents outpaced those of the US by a factor of three in the 2Q of 2023.¹³⁵ However, overall battery patent filings in 4Q 2023 showed the US still in the lead with 21 per cent of patents, followed by China at 20 per cent. CATL dominated the list of patent filings, followed by BYD, but Panasonic and Samsung remained in the top five corporate filers.¹³⁶ The leadership of CATL in the patent race could reflect, in part, the decision of the Chinese government to set up a special patent review branch in Fujian, where CATL is headquartered.¹³⁷ However, in terms of patent citations (see figure 10 below), Korean and Japanese battery patents still lead China's, though China has come closer to parity in the field of LFP-related battery patents. China also leads in the field of EV charging-related patents.¹³⁸

Figure 10: China's clean energy patent filings



IEA. All rights reserved.

Source: 'Tracking Clean Energy Innovation: Focus on China', IEA, March 2022

5. Talent, human capital and entrepreneurs were instrumental to clean energy's rise

In recent years, the history of China's rapid industrial development has often been told in the context of government policy, official targets, five-year plans, and long-term strategies. This framing is appealing to both external critics of China's dominance of the field of clean energy technology, who may seek to promote countermeasures such as trade restrictions or subsidies, as well as to policymakers in China, who seek to credit China's success to well-crafted policies.

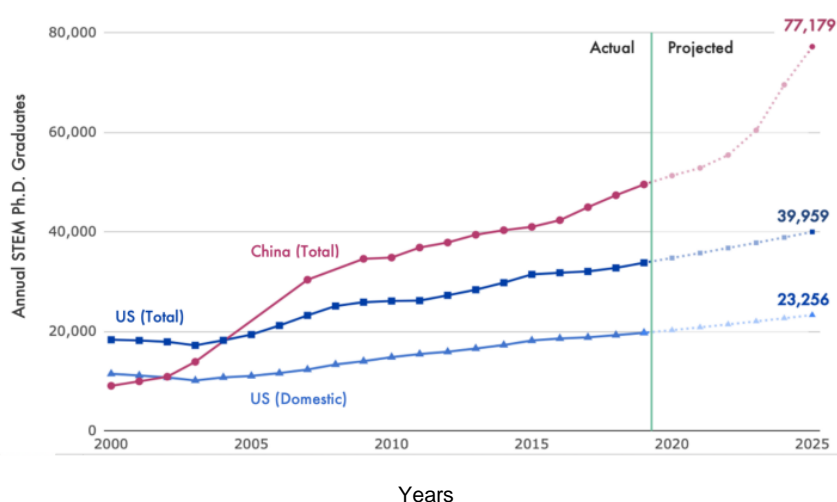


Human capital, entrepreneurship and individual initiative have also played a major role in China's clean energy sector, and this relates to the rise of a dynamic private business sector since the inception of China's Reform and Opening Era. This includes three aspects: (1) a large and growing base of skilled workers; (2) efforts to train and attract top science and technology talent; and (3) risk-taking entrepreneurs.

5.1 The extraordinary rise in China's skilled worker base

A base of skilled workers and technicians is the foundation for China's success in clean energy innovation. Since 2000, China transitioned from having just 5 per cent of the world's undergraduates, with just 2,000 science and engineering graduates per year, to having the world's largest numbers in each field. Whereas in 2000 the US awarded more than double the number of science, technology, engineering and medicine (STEM) doctorates compared with China, by the mid-2010s China had outpaced the US and is on track to more than double the number of awards given by the US in these areas by 2030¹³⁹ (as well, one-third of US PhD recipients hail from China). The number of Chinese students abroad, and their focus in technical fields, has also led to a steady supply of returning scholars and entrepreneurs. Indeed, statistics from the mid-2010s show that most Chinese scholars returned to China on completion of studies or after – as many as 89 per cent, compared with just 24 per cent in the 1980s.¹⁴⁰ The number of high-impact scientific papers by China-based scholars surpassed those of US-based researchers for the first time in 2022, and the country reached the top rank in Nature magazine's Natural Science index for the first time that year as well. China's score was just one-third that of the US in 2015.¹⁴¹

Figure 11: PhD graduates in STEM fields, historic and forecast to 2025

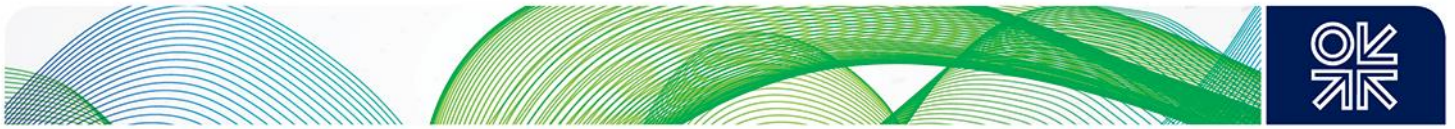


Source: 'China is Fast Outpacing US STEM PhD Growth', Center for Security and Emerging Technology, August 2021

5.2 Attracting science and technology talent helped seed new industries

Perhaps more importantly, the Chinese government has long placed a heavy emphasis on encouraging leading scholars and technical experts to return to China, including to set up businesses. The 2015 Opinions on Deepening the Reform of the Institutional Mechanism for Talent Development, issued by the State Council and the Central Committee, targeted expanding the number of top technical returnees by building on past successes in creating leading research institutions and university programs. The government estimates that at least 16,000 had returned under the program by 2018.¹⁴²

Returning scientists have played a significant role in either founding clean energy companies or contributing to technology transfer in fields such as solar and EVs. This was particularly true for solar, where the return to China of experienced, foreign-trained Chinese scientific professionals from North America and Australia seeded many of the top Chinese solar firms; prominent returnees included the CEOs of Suntech and Canadian Solar and the CTO of Yingli.¹⁴³ In the 2010s, most board members at the top Chinese solar firms had studied abroad. In addition to the impact of these top talents, China's



clean energy industry also relies on an ample supply of skilled workers at all levels. These workers are naturally clustered in the main centres of clean energy manufacturing. For example, Shenzhen-based BYD has nearly 600,000 employees, roughly the same as the worldwide workforce of the Big Three US automakers.¹⁴⁴

5.3 Risk-taking entrepreneurs played a key role

Entrepreneurship is an additional layer that builds on the various structural factors that support both innovation and rapid industry scale-up. While the story of the entrepreneur as a scrappy risk-taker and skilled inventor is often exaggerated, there are a number of examples in the clean energy space that appear to fit this mould.

In the case of solar photovoltaics, timely risk-taking endeavours on the part of experienced business leaders appear to have been decisive in enabling China's electronics manufacturing hubs to capture a major slice of a favoured industry. Several of the initial wave of leading PV entrepreneurs came from fields seemingly unrelated to PV, semiconductors, or energy. Instead, they had experience in such industries as cosmetics, detergent, fire-fighting equipment, and protective suits. Their success in solar can be attributed to understanding techniques for rapidly scaling up line manufacturing processes, and developing manufacturing plants in regions with an established supporting electronics supply chain and workforce.¹⁴⁵ These entrepreneurs also had experience working with local government and could take advantage of relationships to gain access to land, capital and other support. In other words, while government support was instrumental, it didn't act on its own, and without initiative from private individuals and firms.

While savvy entrepreneurs in the solar space have included several leaders without backgrounds in the energy, or specifically the solar industries, as mentioned above there are many other instances where Chinese solar firms attained success by drawing on those with backgrounds in the field – often from research or manufacturers abroad.

In the battery space as well, entrepreneurial activity has evidently played a role in establishing China's dominant position, as illustrated by the success of China's battery champion, CATL. The founder and CEO of CATL, Robin Zeng, has a PhD in physics and initially founded Chinese lithium-ion battery technology company ATL (Amperex Technology Limited) in 1999, which was later sold to the Japanese company TDK. According to Zeng's own account, an approach from BMW's Herbert Diess – then head of purchasing and later CEO – persuaded Zeng that making larger batteries for electric vehicles could become a major market, and this led him to spin out CATL from LDK as its own company, with BMW as one of its first major clients.¹⁴⁶ Zeng's technical knowledge and experience supplying BMW led CATL to compete in the field of NMC batteries then becoming dominant in the global EV battery space. This strategy also enabled CATL to grow quickly at a time when China's EV subsidy policies began to prioritize higher energy density in batteries, which NMC batteries offer. In Zeng's case, a combination of business acumen, knowledge of industry trends, and his technology background proved a winning combination – enabling CATL to achieve scale first and dominate the EV battery industry in a way no other company (Chinese or otherwise, SOE or private) can approach.

Several of China's leading EV companies also formed around charismatic, business-savvy founders with unique stories and ambitions, such as BYD's Wang Chuanfu or Geely's Li Shufu, as discussed below. China's entrepreneurs had already begun building the industry when China's policymakers identified the sector as a space where China could develop policies that would enable Chinese firms to leap-frog other major international players. In particular, BYD and Geely established leadership positions in the EV field early on, before it was settled as a strategic priority at the national level.

Similar to the case of CATL's Zeng, Wang Chuanfu, the founder of BYD, came from a technical background. Originally from a poor farming family in central China, Wang obtained a master's degree in research on batteries at the relatively obscure Beijing Non-Ferrous Metal General Research Institute, after which he became a research scientist. Not long after, in 1995 he relocated to Shenzhen, then developing as a Special Economic Zone, to found a company to develop cheap batteries for cell phones and other electronics, based largely on designs from leading Japanese players.¹⁴⁷

While BYD focused on keeping costs down to capture market share in the growing cell phone market, Wang early on sought to expand the market for its products, founding BYD Auto in 2003 and developing the E3 car based on the Toyota Corolla, which was one of the most popular cars in China. BYD's growth



was supported by policies from the Shenzhen government, which turned Shenzhen – already a global electronics assembly powerhouse – into one of the first cities to focus on promoting EV adoption for taxis and other vehicles. BYD was able to capture investment from Warren Buffett's company, Berkshire Hathaway, a sign of international recognition that may have helped the EV field gain legitimacy across China.¹⁴⁸

After the central government began to support the New Energy Vehicle sector, BYD focused on keeping costs down and creating mass-market products, at first aiming not to dethrone Tesla or major international brands, but rather at creating a mainstream market for NEVs –especially through PHEVs using less-expensive LFP batteries.¹⁴⁹ Eventually, BYD's strategy culminated in an ambition to 'demolish' old brands and create international brands based in China: 'China has yet to create a single international marque of its own that is universally recognised and respected,' Wang said at an industry event in 2023. 'It is time for Chinese carmakers to upend the order of the global automotive industry and chart a course into a new, vast territory.'¹⁵⁰

Geely is one of the most successful of the Chinese private EV startups, as noted having acquired the Volvo brand and launched its sub-brands Polestar and Lynk & Co. The company's founder, Li Shufu, is a serial entrepreneur whose start in the manufacturing field traces back to a small freezer manufacturing firm he founded and later sold. Subsequently, due to the difficulties obtaining a license for manufacturing cars, Li started a firm producing small scooters, before acquiring a defunct five-ton truck manufacturing plant located at a former prison in Sichuan, giving him his first legal access into the car market. Geely's first major product was a replica of the Daihatsu Charade, a low-cost Japanese car popular in the Chinese market in the 1990s and early 2000s.¹⁵¹

To be sure, entrepreneurs have taken advantage of state support, and both local and national policymakers have directed resources and R&D funding to the private sector. China's energy sector has long been viewed as the preserve of large state-owned companies, particularly in the electric power sector. SOEs are also leading players in the automotive and electronics industries. Many of the most powerful SOEs have a regional base and benefit from local government support, which they can use to monopolize local markets and stifle new entrants from the private sector.

Yet in other cases, private entrepreneurs can launch businesses in fields left open for competition, or even partner with SOEs to scale up production, with mutual benefit – as in the case of Nio, as cited above. While the private sector has been credited with China's success in solar and battery development and production, and several private EV startups have sought to imitate the style of Silicon Valley entrepreneurs, recent studies have pointed out that as many as 65 per cent of private sector companies have significant degrees of state ownership, and this includes small- and medium-sized enterprises, not just larger players.¹⁵² So while entrepreneurship and the private sector have played important roles, and not simply slotted into government programs funded as a unified grand strategy under 'China Inc.', the private sector is better understood as part of a mixed economy – variously described as State Capitalism or a Socialist Market Economy. Entrepreneurial leadership and innovation are key factors that feed back into the design of policy, instead of private firms simply following plans or guidance from above.

6. Looking ahead: Is China's lead in cleantech innovation unassailable?

This paper has sought to group the various factors responsible for China's dominance of the clean energy industry, and subsequent innovation lead in these fields, into a handful of explanations, namely: (1) consistent policy support at various levels of central and local government; (2) a focus on encouraging and facilitating technology transfer, implemented as a matter of policy and corporate strategy; (3) advantages at manufacturing scale-up and process-level innovation, facilitated by efforts to develop integrated technology and manufacturing clusters; (4) the integration of China's economy and technology innovation system with global networks; and (5) human capital, including both technical expertise and entrepreneurial risk-taking.

Evaluating the relative importance of these factors, and their likelihood of continuing, is inherently subjective. This section will summarize some of the variables that are at play and assess potential shifts over time.

Policy support will likely continue, but faces contradictions: Investment in innovation depends partly on their perception of policy support, in China even more than elsewhere. Consistent policy



support for the low carbon energy transition is perhaps the easiest to gauge, since even with ups and downs the central and local governments continue to position clean energy – specifically, the ‘New Three’ industries of solar, batteries, and NEVs – as one of the main planks (along with AI and chipmaking) of China’s strategy for coping with the threat of a sustained economic slowdown.¹⁵³ From the beginning, these sectors were viewed as more of an economic development strategy than as an environmental or energy policies, giving them relatively greater heft as a policy priority than is the case in North America and Europe, where ‘green’ is equated more with environmental and climate policy. The recent promotion by Chinese leaders of the phrase ‘New Productive Forces’, defined as ‘advanced productivity that is freed from traditional economic growth mode and productivity development paths, features high-tech, high efficiency and high quality’,¹⁵⁴ is a continuation of policy focus on innovation and growth in new technologies exemplified by the Three New sectors.

While support will continue, there are major challenges. NEVs now constitute more than 40 per cent of China’s domestic vehicle market, and once the market share surpasses 50 per cent, growth in said market share could slow, barring more aggressive targets or policies to phase out conventional vehicle sales. Solar and battery manufacturing are already experiencing overcapacity. Most crucially, China’s power sector researchers and grid officials have expressed concerns about the cost of integrating wind and solar into the country’s electricity system to achieve carbon neutrality.¹⁵⁵ The slow pace of market reform and the inflexibility of China’s power system are likely to raise the overall cost of the energy transition and could affect the willingness of top leaders to sustain the pace of the wind and solar build-out. Recent decisions to grant coal power plants an administratively set subsidy, to be paid by ‘other generators’,¹⁵⁶ and statements from grid officials that wind and solar curtailment are likely to rise,¹⁵⁷ show that the financial and economic risks for these two sectors are increasing.

As for batteries and EVs, market saturation implies these will rely to a larger extent on exports for sustained growth – which is not entirely determined by policy support at home. To the contrary, these industries all face growing headwinds to their expansion in the EU and the US given the rise of local green industrial policies. They are increasingly targeting emerging economies, but protectionist policies will complicate their growth trajectory. While central government officials have criticized countries for adopting subsidies and domestic content requirements or pursuing tariffs or trade investigations, calling this ‘bullying under a green banner’, Chinese companies have proven willing to set up operations in the US and Europe, potentially competing with industry back home in China.¹⁵⁸

Technology transfer – now that the direction of travel is reversed: In most fields of clean energy, China is now either at or near the technology frontier, especially in aspects related to process- and manufacturing-related innovation. Experts outside of China with concerns about technology transfer in the clean energy space may need to focus less on preventing transfer of Intellectual Property into China and more on whether firms outside of China can obtain the necessary knowhow, components (cathodes, anodes, batteries, cells), or material inputs from Chinese players that dominate the space. Western companies are actively developing partnerships to source Chinese technology, not only as equipment imports, but through licensing and setting up local operations outside of China. For example, Tesla was recently reported to be buying CATL battery-manufacturing equipment for its Nevada facility, bringing in Chinese technicians to set up the equipment, which Tesla will own and run – an almost exact parallel to the turnkey production lines that initially helped Chinese manufacturers set up production so quickly in the mid-2000s.¹⁵⁹ Similarly, Volkswagen battery subsidiary PowerCo has purchased a stake in Chinese battery maker Gotion to support building battery plants in Germany.¹⁶⁰ Startups are seeking Chinese know-how as well. Israel-based StoreDot, which is developing fast-charging battery anodes for several global automakers, has partnered with Shenzhen-based EVE on manufacturing, as it seeks to build out manufacturing in its target markets of the US and Europe.¹⁶¹

Indeed, China has even sought to limit tech transfer outside of China in the field of polysilicon refining¹⁶² – a field it began to dominate less than a decade ago, relatively late in the shift of the solar industry to China. True, Chinese firms and R&D institutions may not lead in every aspect of clean energy technology, but their ongoing growth and innovation do not depend on additional tech transfer, as such. For firms active in the Chinese market, or seeking to develop new technologies in fields prioritized by China, this does not imply less need for intellectual property protection, nor does it alleviate government concerns about officially-state-sanctioned technology theft.¹⁶³ However, it also presents a dilemma, if technology and innovation stop at national borders, it may be more difficult for countries and firms to catch up in areas that China dominates.



Will China retain its manufacturing cluster and scale advantages, or could these migrate? As this and earlier studies have noted, China's industry strategy succeeded in part because of consciously designed industry clusters and the supply chain advantages that resulted – not only in terms of cheap labour or logistics but in terms of innovation and speed. While low-cost capital was an enabling factor as well, the focus on industry clusters depended on the recognition that attracting a single large firm, or incubating startups and labs, are insufficient to create a self-sustaining industry in a competitive field like clean energy.

Now that China has established such clusters, there is some possibility that the lead it has obtained through first-mover advantage could be impossible to overcome, just as it has never been possible to (fully) replicate Silicon Valley elsewhere. On the other hand, as China's market growth slows and other countries actively seek to emulate aspects of the Chinese model of industrial development in clean energy, it appears inevitable some clean energy manufacturing clusters will be established abroad – and indeed, that is already taking place to a limited extent. Unless countries abandon efforts to achieve a low-carbon energy transition or opt to rely solely (or mainly) on imported Chinese equipment to enable this transition, they will seek to establish some parts of the clean energy supply chain closer to home – both as a political and economic strategy, and also simply as a matter of reducing labour and logistics costs in an increasingly mature technology field. Even some Chinese experts have recognized that China's shares of certain fields, such as solar, are bound to decline as other countries scale up their own energy transitions.¹⁶⁴ For wind, the size of the main components and logistics of shipping also tend to mitigate against Chinese dominance. In other areas, such as EV and battery manufacturing, there is already considerable geographic dispersion, even if many of the key players are simply Chinese firms with a portion of their production located nearer to demand centres.

If we assume that manufacturing will diversify geographically, does this mean that innovation will follow – that new technology and innovation clusters will emerge, with similar supply chains to those that exist in eastern China? As China's growth slows, will Chinese domestic players be locked into existing formats or designs and lose touch with the technology frontier? Up to the present, the trend does not appear to support the idea that complete supply chains will relocate or that foreign firms will catch up. According to the IEA's 2022 study of solar PV supply chains, although several Chinese PV manufacturers have set up assembly operations in Southeast Asia and elsewhere, these facilities source almost all their inputs from China.¹⁶⁵ While various policies and incentives adopted under the US Inflation Reduction Act support domestic manufacturing, there is little evidence of a sustained effort to master complete supply chains or bring about technology transfer *from* China. Even the relatively modest effort to license CATL technology for the US EV industry has faced immense opposition, both at the national and local levels. And China's own efforts to prevent any sharing of data or information that could harm China's own industry are becoming increasingly evident. In any case, regarding policies to encourage or foster technology transfer from China, further research is needed to better understand their value and effectiveness.

Although advanced economies are hardly at the low clean energy technology level of Chinese firms in 1990 or 2000, the obstacles to technology cooperation might imply industry outside of China will largely have to stand on its own or depend on subsidies to compete on the innovation playing field. The challenge is immense, and there are plenty who believe China's lead in key clean energy fields is nearly insurmountable.¹⁶⁶ If competing implies building complete supply chains and catching up on innovation, relying on a large and growing domestic demand for these technologies, the obstacles may be such that only the largest players, such as the US or possibly the EU, could develop a coordinated strategy – and this would be subject to changes in political priorities, elections, and pressure from incumbent industry players in energy and auto manufacturing.

Still, there are examples of changes already happening that could serve as a model for how industry might catch up, even in the absence of government policy. Tesla has encouraged the Chinese companies that supply parts to its Shanghai Gigafactory to set up operations near their planned facilities in Mexico.¹⁶⁷ This could prove mutually beneficial, since not only would Tesla improve efficiency at its new plant, but Chinese suppliers could also begin to offer parts and services to other Chinese EV companies that might set up operations in Mexico to supply the North American market.¹⁶⁸ BYD is reportedly considering building a \$600 million facility in Jalisco, Mexico, and exploring working with Chinese auto parts suppliers already located in the area.¹⁶⁹ Chery and JAC are also boosting their presence in Mexico. In the long run, such a cluster could differ from what has happened in Southeast Asia, where assembly plants have served more as a way-station than a technology centre. Even if



clusters emerge in relatively dispersed locations such as Mexico and Morocco – the latter has been the location of major Chinese outbound investments in recent months – these could facilitate the transfer of manufacturing know-how into the global innovation system.¹⁷⁰

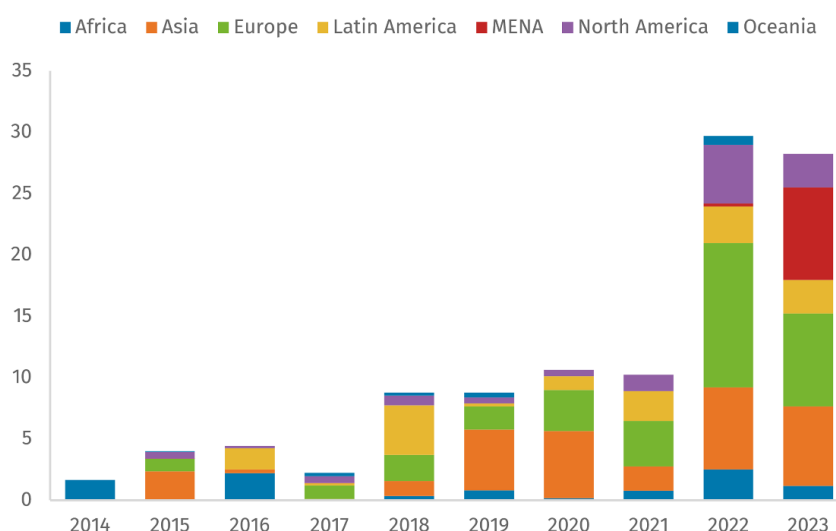
Two additional variables deserve mention regarding this hypothesis. First, the same technology characteristics that have facilitated China's clean energy success could facilitate technology diffusion abroad. While wind turbines, solar PV, batteries, and EVs are all advanced technologies requiring precision design and manufacturing prowess, they have all benefited from rapid learning rates reflecting their relatively simple architecture compared with competing energy technologies such as thermal power or internal combustion engines. Further, batteries and solar are each small, modular manufacturing-intensive technologies that benefit from manufacturing scale – which argues for concentrated production – but the scale of PV and batteries that will eventually be needed for the global energy transition may be large enough to support several manufacturing centres worldwide. As for China, slowing growth and market saturation, along with overcapacity, can drive down prices, but also imply domestic players can no longer rely on domestic demand to drive scale.

A second important consideration is China's development model, which has tended to create extreme overcapacity in favoured fields. Low production costs in China, which result from both its existing scale and barriers to entry, have been shown to suppress investment in innovation in other countries.¹⁷¹ While other governments have begun to attempt to reverse this, the private sector investors, entrepreneurs and manufacturers may be less keen on going head-to-head with Chinese competitors, even in home markets, given how fast and unpredictably Chinese prices can drop – and given that Western government policies and commitment to clean energy industry can be fickle.

However, China's market dominance is so high, that the market has to go abroad to expand – and China's firms will go abroad as well. Indeed, they are compelled to do so, both by policymakers elsewhere and by the desire to take advantage of lower labour costs and lower shipping and logistics costs from globally diverse production base. Chinese EV makers are expanding abroad most quickly. (See Figure 12.) Overseas direct investment by EV-related firms surged in 2022 and 2023, reaching nearly \$30 billion in both years, not including several high-profile investments with unknown price tags.¹⁷²

Figure 12: China battery investments abroad

Billions of USD



Source: Rhodium Group, 2024

Global innovation systems could facilitate catch-up by countries other than China: Up to now, China's clean energy sector has benefited – and indeed, the world has benefitted – from a global innovation system, comprising R&D centres, networks of experts and innovators, global supply chains, multinational firms, and the possibility of global technology cooperation at various levels. As with technology transfer, the shift in manufacturing and innovation to China, and the maturing of clean energy technologies into standardized designs and scaled manufacturing locations, might imply that global



innovation systems carry less importance for China's future innovation path. Or, assuming market players must continue to innovate to remain at the technology frontier and competitive with it, one might conclude that China's manufacturing and innovation position gives it an advantage in a world where both China and its competitors seek to erect new barriers to the networks that have made global innovation a key enabler of clean energy's rise.

While it is undeniable that cooperation has cooled and competition has heated up, it is probably important not to exaggerate the decline in global innovation networks. Multinational firms continue to exist and the top universities in basic research continue to attract global talent, including from China – and some of these experts return, while others bring knowledge and experience abroad, enabling diffusion. The worldwide remote work trend has uncertain impacts on innovation and international knowledge diffusion¹⁷³ – but has certainly enabled some forms of sharing know-how that would have been difficult or impossible in past eras. Censorship of foreign websites has not eliminated Chinese scholarly access to leading academic journals, or the interest in publishing in such journals.¹⁷⁴ Such routes are hardly a substitute for what happened in the past, with the acquisition and relocation of whole companies or production lines and the mutual exchange of technical experts to spin up output. In any case, global innovation networks have been placed under strain, but continue to exist, potentially benefitting firms and regions seeking technology catch-up.

Questions around human capital and the private sector: Most economists would probably agree that decoupling should reduce the global rate of innovation.¹⁷⁵ Innovation is one of globalization's ostensible benefits, in addition to the more obvious and direct benefit of trade that arises from comparative advantage in labour and capital. A larger market means firms have greater incentive to invest in innovation, and a larger pool of talented workers implies a lower cost of innovation. It will be difficult to gauge whether this theory proves true for the clean energy sector as a whole, of course.

As for the impact of decoupling on China's innovation, once again there are diverse predictions. Longstanding reports of talent being reluctant to come to China, or China suffering a brain drain the other way, either never materialized or, at least, have not dented China's innovation drive. Indeed, in 2013, the year several Western media outlets reported top talent leaving China due to pollution, even the newspaper *China Daily* called China's brain drain 'the world's worst'.¹⁷⁶ During and after the Covid pandemic, contradictory media reports emerged of brain drains into and out of China – with both European and American analysts reporting fears that top Chinese scholars or technical experts were leaving, matched against reports that wealthy or talented Chinese were fleeing China.¹⁷⁷ While some statistics support each contention – one study found a steady increase in top Chinese experts leaving the US, while another found that the US remains the top destination of Chinese top talent¹⁷⁸ – it is impossible to draw any broad conclusion about the impact of such movements on innovation inside or outside China at this time.

Restrictions on China's private sector and how this might impact the quality of China's domestic innovation is also an open question. Some years ago, Chinese authors praising China's appeal to global talent wrote, 'China has gone too far down the path toward an open society along intellectual, business, and other dimensions outside of politics for anything short of Maoist insanity to prevent its scientists, engineers, and business entrepreneurs from innovating in China and eventually becoming leaders in global innovation'.¹⁷⁹ Recent moves to crack down on the private sector, on prominent entrepreneurs, or on displays of conspicuous wealth have unclear effects, but they have reportedly affected the interest of young graduates in pursuing careers in the private sector.¹⁸⁰ Increasing restrictions have undoubtedly affected foreign direct investment and international business activity in China, reducing the scope for successful business leaders to pursue global careers.

It is far too early to say if any of these could eventually impact the rate of innovation or entrepreneurship in the fields where China presently dominates. There is certainly no sign of this as yet. Entrepreneurship may seem unimportant now that China already has several major champions in each of the clean energy fields covered by this paper, but turnover in the space has been steady and rapid, and there is little guarantee a new iteration of creative destruction isn't just around the corner – if so, it might not be in China.

Just as change is inevitable, even as the clean energy sector matures, some of the factors that enabled China's success to date will undoubtedly shift – both as a result of China's domestic situation and slowing growth, and resulting from the pressures of de-risking and the need of Chinese firms to go global



to both maintain growth and deal with overcapacity at home. Now that many countries have adopted industrial policies of their own aimed at fostering domestic clean energy supply chains, it will bear watching whether companies and regions actively pursue vertical integration, or continue to push for the disaggregation of production as a cost reduction measure.

For governments looking to develop or deepen cleantech innovation at home, there are lessons to be learnt from China's successes to date. While it is unrealistic to expect any country or region to adopt wholesale China's models of industrial development or state capitalism, fostering manufacturing technology clusters and human capital in critical fields is not out of reach, even as a strategy for individual firms or localities. Countries and firms seeking to catch up or simply compete in the clean energy field may need to consider a broader approach than just reducing costs or scaling up on the backs of subsidies given both the advantages and disadvantages of production disaggregation. As the example of Tesla in Shanghai and Mexico demonstrates, encouraging smaller upstream firms to set up local supply chains can be a viable strategy, if pursued over the long term. As the case of the wind and battery sectors shows, licensing technologies and setting up local manufacturing lines with foreign technologies can help localize these technologies – again, if pursued over a longer time horizon. For the private sector to engage in such long-term thinking and strategic practices, however, more stable policies and greater industrial coordination may be necessary than has been possible to date.



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¹ Abishek Malhotra and Tobias Schmidt, 'Accelerating Low-Carbon Innovation', *Joule*, 4(11), 18 November 2020, at <https://doi.org/10.1016/j.joule.2020.09.004>.

² For example, a 2016 study found that the vast majority of R&D takes place in OECD countries and that this relates to the human capital advantage of advanced economies: See Kul B. Luintel and Mosahid Khan, 'R&D, Scale Effects and Spillovers: New Insights from Emerging Countries', World Intellectual Property Organization, May 2016, at https://www.wipo.int/edocs/pubdocs/en/wipo_pub_econstat_wp_32.pdf; for views on the concentration of venture capital in advanced economies, see Richard Florida, 'Venture Capital Remains Highly Concentrated in Just a Few Cities', Bloomberg, 3 February 2017, at <https://www.bloomberg.com/news/articles/2017-10-03/the-geographic-concentration-of-venture-capital>; Stefan Colimanu, 'Why The US Leads The World In Entrepreneurship And Innovation', Research FDI, October 2023, at <https://researchfdi.com/resources/articles/why-the-us-leads-the-world-in-entrepreneurship-and-innovation/>; Alex Irwin-Hunt, 'The global map of venture capital-powered FDI', FDI Intelligence, 26 June 2020, at <https://www.fdiintelligence.com/content/rankings-and-awards/the-global-map-of-venture-capital-powered-fdi-77759>.

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