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Software versus hardware: how China's institutional setting helps and hinders the clean energy transition

Introduction

The global low-carbon energy transition will require major changes to institutional practices and energy industry paradigms – and will have implications for non-energy industries, consumers, and society writ large. Considering the scope of the energy transition, a country's existing institutional pattern inevitably shapes the transition, and helps or hinders its progress. This is perhaps especially so in state-dominated systems such as China, which have historically considered energy as a strategic field for state dominance and control, for reasons of both security and economic development.

China has already taken steps to embrace clean energy, even as the country remains the world's largest consumer of fossil fuels: Indeed, it is the world's leading producer and consumer of renewable energy in absolute terms today, and its leaders speak of encouraging a revolution in energy consumption and production, in line with new targets announced in 2020 to achieve carbon neutrality by 2060. But how successful will China be in introducing the sweeping changes that are commonly assumed to be required? At the technological level, such changes could include not only replacing fossil fuels with renewable energy sources, but shifting from centralized to distributed forms of production, greatly improving energy efficiency and consumption flexibility, and adopting digital technologies throughout the sector. At the institutional level, these shifts could entail major market reforms and changes to the structure of the Chinese energy sector, dominated now by SOEs and administrative planning.

In this context, China's pledges to decarbonize its energy system will prove transformational not just for its energy use but also for its economy and institutional set-up. When considering the extensive political science and economics literature that has emerged relating to energy transitions over the past three decades (putting forward the concept of a low-carbon or clean energy transition generally implying a major change in sociotechnical regime[1]) China poses an interesting case study: it has begun to adapt to the challenges of climate change through domestic policies and has legitimized new technologies, albeit in a largely top–down manner. Meanwhile, the institutional framework for energy governance has only undergone modest changes;[2] reforms aimed at allowing markets to play a decisive role remain some way off, while formal and informal administrative planning plays a growing role.

This paper fits into this scholarship in two respects. First, we argue that China, in common with all countries undergoing a low-carbon energy transition, has a unique mixture of institutional advantages and disadvantages. Clearly, certain attributes and policy choices have enabled China to become the largest producer of solar, wind, and batteries but can these same attributes and choices translate to other aspects of the energy transition, such as scaling down coal or enabling energy demand flexibility?

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ENERGY TRANSITION CHINA

Second, we review scholarship on China's technology innovation system through both a technological and an institutional lens, pointing out areas in which China's various institutions can mobilize resources for change. At the same time, these same institutions could lead to a potentially inefficient or imperfect transition – one that over-emphasizes supply-side investment in centralized resources to the detriment of changes implied by the Ecological Civilization or Energy Revolution paradigms emphasized by the central leadership.

While we argue that several institutional characteristics in China could hinder a clean energy transition, despite strong central government support and high institutional capacity to adapt to major sociotechnical change, a more complete comparative analysis would be needed to establish that the barriers to such a transition in China are materially greater than those in other countries or regions. In Europe and North America, decades of entrenched political division, industry lobbying, and opposition from powerful local interests have hindered climate and clean energy progress. It would be unfair to call out barriers in one country without noting that unique and powerful hindrances exist elsewhere as well. But identifying potential obstacles is an important element in overcoming them.

The purpose of this paper is to examine how China's institutional setting contributes to or hinders the energy transition – with a particular emphasis on the energy sector, to limit the scope of the analysis. In many cases, writers on China's institutions have tended to assume that certain features of China's energy sector – such as interventionist management of the economy and dominance of state-owned monopolies – will primarily hinder the transition, as they limit market forces and private enterprise. Others point to China's strong central state and high-level commitments to the environment to suggest that China's institutions are better suited to addressing environmental problems than those of liberal democracies – and indeed, that China will 'save the planet'.[3]

This paper dispels the binary view of China's governance and the energy transition – in which central government commitment is portrayed as the sole determinant of success – while also setting out a preliminary framework for analysing the areas where technological and institutional factors make change more likely to be lasting and transformative, versus areas in which resistance will likely remain strong. Historically, China has been better at building out energy supplies and adding the 'hardware' of energy infrastructure, while having greater difficulty adjusting the 'software' of institutional and societal change or practices related to energy demand and energy efficiency. We would argue that China is likely to continue to expand the hardware side: It is driven by strong institutions devoted to investing in supply and can be managed through state support and policy, but the country will struggle with the software as this relies on a demand pull, market incentives, and greater coordination among stakeholders and between sectors. This is especially the case in fields that have a more distributed nature or are focused on demand-side measures, such as distributed solar, storage, electric vehicle charging, smart grid, smart building, or building energy efficiency.

1. Drivers behind China's environmental pledges

The motivation of China's top leadership in pursuing carbon neutrality is central to whether that transition will succeed. We assess the motivation as high, and furthermore note that the state is pursuing the low-carbon energy transition for several overlapping motives, which in turn contributes to the sustainability of this policy commitment in the face of significant obstacles. China's clean energy transition is supported from the highest ranks of the country's political leadership: The overall task of the central government is to manage political and economic stability and the development of the country, and that has typically entailed a heavy focus on managing economic growth. The energy sector has played a starring role in China's economic rise, both in powering other sectors and in absorbing huge capital investment flows. As such, energy has become a critical sector economically and politically. In terms of policy, efforts have, first and foremost, focused on meeting surging demand in support of economic activity, while also attempting to diversify energy sources and improve energy efficiency.[4] In the recent two decades, clean energy and climate change have gradually entered the discussion, and reached centre stage following President Xi Jinping's September 2020 announcement that China would target carbon neutrality by 2060.

The following five factors have motivated China's clean energy policies in recent years:

1) Industrial development: Sustainable development and renewable energy began to be included as national economic and industrial development priorities in the 1990s, and this trend accelerated after wind and solar began to achieve scale between 2005 and 2010. China's wind industry development preceded the Clean Development Mechanism (CDM), but CDM projects played a role in scaling up the industry and reducing costs, leading Chinese energy analysts to forecast that wind could become economically competitive with coal. A similar process took place with solar, where the industry developed initially around exports and transitioned to become a domestic energy source over time. Battery energy storage, new energy vehicles, high-voltage transmission, and hydrogen have all been developed for a combination of economic and industrial development reasons, with low-carbon being just one of several attributes that make these technologies appealing to central government officials.

2) Energy security and geopolitics: Policy makers' concern to reduce exposure to potential oil import disruptions and oil price volatility has contributed to China's efforts to curb oil demand in the long term by, among other policies, developing electric vehicles. Over the past decade, several scholars have suggested that a transition to clean energy would benefit China by reducing reliance on imported oil and gas, enhancing domestic energy production of non-fossil sources, diversifying energy sources, and boosting Chinese manufacturing and resource production.[5] Though China only became a net importer of oil in 1996, today the country imports over 70 per cent of its consumption, and China is now the world's largest oil importer, creating new physical energy supply bottlenecks.[6] By becoming a supplier of wind, solar, and energy storage, China also positions itself within an emerging energy industry. And by dominating the production of key minerals, such as rare earths, China in turn could even become a new global chokepoint for the development and deployment of wind, solar, and batteries.[7] To the extent that developing non-fossil fuels in China can help mitigate the vulnerabilities associated with imports, they are an important policy goal for the government.

3) Environmental quality: Concern relating to environmental quality has risen steadily, becoming a top national priority in recent years. In the 1980s and 1990s, economic development policy, especially at the local level, often took little account of environmental impacts. Environmental quality as an objective in itself for the central government became especially apparent after the introduction of the paradigm of the Ecological Civilization, which was promoted by President Hu Jintao at the 17th National Congress of the Chinese Communist Party in 2007.[8] The definition of Ecological Civilization is extremely broad, embracing water, air, and soil quality; clean energy and climate change; food security and health; and ecosystem health.[9] Notwithstanding the Ecological Civilization paradigm, it is widely recognized that China's environmental and clean energy policies have mainly targeted local environmental concerns, such as air quality, with climate change or clean energy being only secondary considerations, particularly during the period of the War on Air Pollution in the mid-2010s.[10] Alleviating public concerns and social instability related to air quality has been a major driver of energy policy.[11]

4) Climate change: Though some aspects of the energy transition relate mainly to energy security or economic development, climate change has played an increasingly central role over time. China's White Paper on Climate Change Science, published in 2008, recognized the country's unique vulnerability to climate change, noting that temperature increases in China have exceeded the global average, and citing the country's immense demand for food production on relatively limited agricultural land, and regional imbalance in water availability.[12] In 2021, extreme weather events highlighted the risks of climate change and their impact on China's food security. Chinese and international atmospheric scientists have shown that many of China's air quality policies have benefits for reducing greenhouse gas emissions as well.[13] A combined approach to air quality and climate results in lower overall cost and fewer investments that might be stranded or otherwise rendered obsolete by future policies on greenhouse gas emissions.[14]

5) Environmental diplomacy: China has a long history of participation in international negotiations on environmental issues, and the central government has consistently treated the topic as an important aspect of international relations. After 2007, when China became the world's largest annual emitter of carbon dioxide, its position in climate talks began to attract controversy.[15] Over time, the country's position evolved: In 2014, President Xi leveraged the climate issue to reach a bilateral climate accord with US President Barack Obama, which laid the groundwork for the Paris Climate Agreement the following year. In the years that followed, China's position evolved rapidly: Xi Jinping, at the 19th National People's Congress in 2017, stated that China would take a 'driving seat in international cooperation to respond to climate change' and become a 'torchbearer' in creating an ecological civilization.[16]

These five drivers of China's low-carbon energy transition – industrial development, energy security, environmental quality, climate change, and international relations – now converge to a greater extent than previously. Several factors could explain this convergence: The cost-effectiveness and global competitiveness of China-made wind and solar, the near-term potential to develop an electric car industry for both domestic consumption and export, the greater experience that China's national, local, and economic leaders have with clean energy technology and policy, and the risk that China could fall behind technologically if it can't follow other leading economies in decarbonizing its economy and society.

2. China's institutional setting both helps and hinders the energy transition

Whereas in the previous section we showed that China's central government has several strong motivations to pursue a long-term, low-carbon energy transition, in this section we look in detail at its government institutions at various levels, highlighting aspects that either help or hinder this transition. At the broadest level, it is widely understood that China's central government drives the country's low-carbon energy transition, and the strength of the policy signal from Beijing will determine the overall policy direction and commitment to the energy transition.

China has historically featured a strong and hierarchical government, and a political culture that largely accepts a strong, central government structure with the ability to exercise direct or indirect control over wide aspects of government policy, public welfare, and individual behaviour. Within the energy and environment field, the central government's trend towards adopting stricter policies favouring lower emission and low-carbon energy has been described as having the features of authoritarian environmentalism – that is, top–down policies driven by central government environmental and energy goals, with relatively low contribution of public inputs or societal dialogue.[17] Still, there are many aspects of the organization and capability of the central government which temper this understanding of China as a highly centralized state power including, particularly, within the energy sector. Elements within the bureaucracy and local government at times have incentives to either go slow on low-carbon policy or promote high-carbon or energy-intensive industry as a development strategy. Limited capacity at key institutions, fragmentation of authority, and structural economic incentives could work against the energy transition in the short- and medium-term.

Fragmentation: Delegation of policy decisions and implementation to powerful bureaucratic actors, including state ministries, state-owned enterprises, and industries, leads to a situation that has been long described as 'fragmented authoritarianism'.[18] Responsibilities for managing aspects of the energy transition policy are split across various ministries and agencies responsible for energy prices, competition, regulation, land use, project approval, and reforms.[19] Yet there exists a high degree of competition among Chinese government bureaucracies, as well as resistance from provincial officials and SOEs engaged in local protectionism.[20] This fragmentation is also exacerbated by the central government's limited capacity.

Limited capacity: The limited capacity of central regulators hinders their ability to manage a complex energy transition that sometimes conflicts with powerful local and SOE interests. The regulatory function of the National Energy Agency (NEA – China's de facto Ministry of Energy), which in 2019 had an

administrative staff of 240 people,[21] is also constrained by the power of provinces and large energy SOEs to mainly regulate themselves, particularly in the field of power system design and operation.[22] Though provincial officials and SOEs are supposed to follow overall central government guidance, when policies are ambiguous, energy companies – including oil and gas companies, electricity generators, and transmission grid companies – can circumvent or slow-walk central policies and objectives.[23] Moreover, limited central government capacity means that corporate actors and industry associations provide administrative support for the policy making process and provide technical inputs. This, in turn, influences the ability to design and implement energy transition-related policies and overcome resistance.

Provincial government: The provincial power structure has resulted from an ad hoc process, largely driven by provincial governments and provincial officials themselves, which had the incentive to build local power bases to ensure performance against economic evaluation indicators. The central government largely acquiesced in this system because it solved the twin problems of employment and revenue.[24] From the early days of the Reform and Opening period, provinces had incentives to encourage the start of new companies, including both spinoffs of government institutions and purely private companies, which would often receive subsidized land, tax incentives, or other preferential treatment. The result is known as 'local state corporatism'.[25]

Local state corporatism not only resulted in rapid build-out of new companies in sectors targeted for development, but also in duplication and segmentation along provincial and regional lines. At various times, including in recent years, provinces have pursued policies that resulted in excess production capacity and over-investment in coal, steel, and renewable energy production. There is a clear connection between state planning and overcapacity, which is especially strong in provinces with a lower proportion of private enterprise, likely because SOEs benefit from preferential access to finance, land, and political connections.[26] Provincial grants of land, tax incentives, and other interventions to favoured industries can result in industrial overcapacity.[27] Since local governments often allocate resources to failing firms, and grant non-monetary incentives to businesses with low productivity, the result can work against innovation and efficiency.[28] Further, SOEs at the local level have close links to local officials: Local SOE managers are often promoted to local government positions.[29] Local and regional protectionism has also led to siloed technology adoption, with mandates or subsidies for taxis, buses, and government fleets targeted at locally-made EVs, and with EV manufacturers sourcing parts and batteries only from local firms.[30]

Yet the provincial power structure has also had benefits for development, by enabling experimentation and competition among provinces. The central government often initiates pilots at provincial or local levels and encourages experiments with different designs for new market institutions, such as in the case of carbon, green finance, electricity demand response, and electric power spot markets. Provinces also pilot new technologies, such as wind, solar, and electric vehicles. While piloting does enable experimentation and diversity, at the same time, China's provincial and local pilots are hardly a free-for-all. A 2016 study of China's innovation policy by Chen and Naughton found that most pilot policies emerge from above, and provinces adopt such frameworks with only minimal adaptation or specialization.[31] A 2016 study of solar promotion at the provincial level in response to central government guidance found that provincial officials in Jiangsu and Zhejiang province either adopted central policies unchanged, or with only minor changes, seeing provinces as restricted to an 'assistant's role'.[32]

Overall, provincial governments have a potential to both hinder and help the energy transition. For economic structural reasons, and because of their role in planning industrial growth, they have tended to pursue energy-intensive models of development. While provinces and localities have also fostered new energy industries and new technology strategies, it is unclear whether this will translate to all sectors needed for the low-carbon energy transition. The outlook differs between provinces, depending on their resource endowment and industrial structure, as well as political leadership.

3. China's central government can mandate changes to the hardware of energy supplies …

Just as with China's formal government institutions, the country's unique economic institutions are a mixed bag in the extent to which they tend to help or hinder a low-carbon energy transition. On one hand, the state is a central player in the energy sector, which is dominated by state-owned companies expected to respond actively to policy requirements. On the other hand, by the active role they play in setting policy, and their conservative instincts as guarantors of energy security and economic stability, state-owned companies may be slow to embrace revolutionary structural or technological change. And while the private sector has been key to China's economic growth and technological development in the past four decades, including in energy technologies such as solar and batteries, the role of the private sector in China's future energy transition is more ambiguous.

3.1 The mixed role of SOEs in implementing the low-carbon vision

Much like regional governments, incumbent industries have immense power within this system as centres of employment, drivers of regional economic development projects and investment, and holders of expertise and specialized knowledge. Large companies, and especially SOEs, directly participate in the setting of long-term plans through the five-year planning process and other processes. While some five-year plans are broken down by policy topic – such as energy or the environment – many are organized around areas of production and supply, such as coal, hydro, or steel. Plans are elaborated by central government officials in concert with industry associations as well as government-owned think tanks, which are often organized on a sectoral basis and may derive revenue from serving companies in those sectors.[33] Industrial associations also play a role in the policy making and planning process. Many industrial associations were originally carved out from state ministries in 2003, were initially staffed by former government officials from ministries, and exercise functions equivalent, or similar, to government agencies.[34] Government agencies also organize similar associations for newly emerging industries.

Since China's dual carbon pledge, SOEs have been issuing their own carbon peaking plans and looking to align with the latest priority from the central government. One recent review has found that SOE plans released so far lack specifics, and suggests that many firms are waiting for more direct, industry-specific signals from central leaders.[35] Several power generation SOEs have announced dates for peaking emissions and plan to increase investment in renewable energy. State Grid's 2021 Carbon Peaking Plan mentions a new target of reaching 50 per cent renewable energy on new transmission lines.[36] Meanwhile, China's oil companies have made initial plans for carbon neutrality, although they have not aggressively sought to transform their businesses.

Many incentives –particularly those relating to personnel and management incentives – at China's SOEs encourage a go-slow approach and risk-aversion. Management personnel at Chinese SOEs differ markedly from those at large firms outside China. For large industrial firms, virtually all upper managers have been Party members from a young age, and were recruited into their industry from engineering or science majors. Career tracks of upper management typically remain within a single industry, often within a single business group.[37] Manager advancement depends on achieving multiple performance indicators, many of which are short-term in nature, and subject to political bargaining, giving managers with closer political relationships greater operational flexibility.[38] These factors contribute to information asymmetry, leading to principal–agent dilemmas for government management of the state sector.[39] SOE management policies, as well as cross-cutting pressure from local officials, favour delivering services and preserving social stability, and discourage risk-taking.[40]

Still, the incentive structure at SOEs is more fluid than this description fully captures. As key actors within powerful organs of state policy, SOE managers operate within a networked hierarchy of SOEs which have pervasive linkages to other state institutions. The privileged position of SOEs within the economic structure, especially in the energy field, enables such firms to make investments in new fields with the assurance that such plans, when aligned with central government objectives, will not result in losses – and this is reflected in the major renewable energy investments made by SOEs in the past two decades.[41]

Going forward, the role of China's SOEs in the energy transition will depend on central government policy and whether they receive clear policy guidance and strictly enforced mandates. In the absence of strong policy signals – including personnel policies and incentives structures – the SOEs will likely tend towards risk-averse decisions, protecting existing business activities, and hindering innovation.

3.2 Is there a role for the private economy?

The creation of a thriving private sector has been a central feature of China's economic growth over the past four decades. Though much of the country's energy infrastructure remains in the hands of SOEs, and will likely remain so, the private sector is also involved: private wind, solar, energy storage, and electric vehicle manufacturing firms have grown rapidly. Various energy transition literature or innovation literature suggests that new entrants – likely private – are more likely to pursue disruptive technologies.

However, it is important to recognize that the distinction between public and private firm behaviour in China is relatively blurred. Studies have found that SOEs and private-owned enterprises, particularly large ones, are difficult to differentiate.[42] The largest private companies in many fields owe their prosperity to tight government connections, monopoly rents, and protection from competition. In many cases local governments or local state-owned companies own shares in the private companies. Provincial and local officials encourage the development of local champions in key fields, and use project approval, land-use rights, and subsidies to direct revenues and profits to favoured firms. Private companies with political connections have favourable access to SOE bank loans[43] and to stock listings.[44]

In summary, SOEs are likely to remain dominant actors in the energy sector for years to come; their private peers rely heavily on government connections and mandates, and in many respects resemble SOEs. The prevalence of a strong state sector would imply risk aversion and therefore tend to hinder adoption of new 'software' for the energy transition. Yet China's private companies are likely to be only part of the solution, with the SOEs still playing a large role, for as long as central government signals continue to point in the direction of the energy transition.

3.3 Could finance become an enabler of the energy transition in China?

China's unique and powerful financial sector has played a major role in accelerating the scale-up of China's new energy industries. In general, the financial system favours investments in long-lasting physical infrastructure. Such investments are mostly SOE-owned, and represent projects approved on regular cycle by provincial DRCs, based on various quotas and planning priorities set out by the central government. These projects have predictable cash flows, and benefit from preferential treatment in form of cheap land or tax breaks. Beyond SOEs, banks prefer to lend to large firms, particularly those connected to large infrastructure investments that enjoy government sponsorship. Regarding the energy transition, the result of these biases in the financial system is mixed. On one hand, it likely reduces the funding available for new entrants, small businesses, and innovation focused on smaller, more modular technologies, equipment, or software with clean energy or efficiency benefits. On the other hand, the relative availability of low-cost capital for large projects has undoubtedly helped build out China's wind, solar, and EV industries, as well as its growing network of high-voltage transmission lines. Low capital costs for large companies will likely favour the development of carbon capture and hydrogen infrastructure, potentially making China the largest market for these technologies and encouraging further technology transfer from countries where such projects are still prohibitively expensive.

Since the mid-2000s the central government has led a push towards introducing green finance measures throughout the country's financial system, culminating in the People's Bank of China's 2016 Guidelines for Establishing the Green Financial System.[45] Efforts to green the financial system have only been underway for a short period, and analysts generally agree that it will take time for various policies in the financial system to catch up with policy measures underway to peak carbon emissions and achieve carbon neutrality. While there have been steady efforts to promote green financial

instruments and environmental disclosures, transparency remains weak, investor interest is unclear, and most efforts have been led from the top down.

4.… but mandating changes to the software are harder

While strong mandates to provincial governments and energy companies can lead to change, mainly in the hardware of new supply-side investments, the institutional framework guiding the 'software' seems harder to change. Despite calls by the government to deepen market reforms, these have been progressing slowly and China's energy transition seems unlikely to be able to rely solely on market signals. The slow development of market reforms, and the relative dominance of state-owned actors in the design and orientation of those market reforms that are underway, tends to hinder more thoroughgoing changes to the structure of the low-carbon energy transition. That said, China officially remains committed to introducing markets into the energy and environmental sectors. According to the communique issued after the Third Plenary Session of the 18th CPC Central Committee in November 2013, markets should play a 'decisive role' in allocation of energy and environmental resources.[46]

In the electric power sector, a new phase of market-oriented reform began in 2015, with the publication of a new reform framework and agenda that is still underway today. Similarly, China has introduced a national carbon market within the electric power sector, although it is still at an early phase of development. These reforms have moved gradually, leaving the existing industrial players largely intact, and the timeline remains unclear as to when wholesale energy or electricity prices or carbon prices would substantially affect investment. On both carbon and electricity, administrative planning and targets currently guide investment and production, and planning may even assume a greater role as coal phases out and large-scale changes in employment and industrial structure come to the fore.

Moreover, with market transparency constrained by a number of political, social, and institutional barriers, markets' ability to facilitate an energy transition with a large number of diverse stakeholders could be impacted. While environmental disclosure has increased in China, restrictions on information sharing remain, with public participation limited at times. In the energy sector the participation of new entrants and energy consumers, and the ability of new technologies to match supply with demand, could require greater transparency on pricing, supply, and demand. China's power sector presently does not have a public information platform that could offer information on the real-time electricity supply, load curve, or generation mix, either at the national or provincial levels.

In addition, China's legal system tends to place private firms and public interest litigation at a disadvantage versus state-owned enterprises or government bodies. Such weaknesses are likely to undermine the development of markets for electric power and carbon allowances – and would tend to hinder private sector participation at a level of equality with well-connected state-owned entities.

Finally, academic advisors and civil society also play a limited role in bringing about broader change. The public and civil society organizations have played a role in energy and environmental policy, with NGOs and international actors supporting central government policy by coordinating the input of experts with sector-specific professional knowledge. University departments and top academic experts play a central role in developing five-year plans and other long-term plans. But often, they can only operate within a narrowly restricted political space. In general, the Chinese government sees NGOs as a means of transmitting and achieving government policy objectives rather than as autonomous entities.

As a result, China's institutional settings will both help and hinder the energy transition. While much depends on the consistency of the messaging from the Party–State over time, China's institutional framework is capable of some adaptation. Since the Party–State can mobilize resources and galvanize the state-owned banking and industrial sectors, the incumbents can become part of the change, benefitting from and investing in the energy transition.

But equally, there are limits to the state-dominated system's capacity for change. With the role of the market, transparent flows of information, and the legal system and civil society constrained, China's

energy transition is unlikely to be a system- and society-wide transformation, and it is unlikely to unfold in an economically efficient manner, even though the energy mix is likely to evolve considerably.

Assessing progress in the elements described above will help gauge the speed and depth of the transition and, based on the initial framework laid out here, we do not expect it to be a smooth or linear path. At the outset, China will likely make greater progress in areas related to the hardware of the energy transition, as these are usually able to satisfy a larger number of political and economic interests. But changes to the software of market reforms, demand-side management, and disruptive technological innovation will likely prove more challenging.

5. The institutions of innovation

For over a half-century, innovation has been a core topic of efforts to bring about an energy transition, and this remains the case today. However, several low-carbon technologies have reached full commercial scale and appear poised to deliver a large part of the technical solution to climate change without a great deal of further innovation. For example, the International Energy Agency's annual technology assessment rates solar PV, wind, battery electric vehicles, and heat pumps as fully commercialized, whereas other advanced technologies in the buildings and heavy industrial sectors are at an earlier stage.[47] Nevertheless, even within fields where commercialization has already taken place, innovation will bring ongoing improvements that will influence the speed and direction of the clean energy transition.

China's success in achieving carbon neutrality will depend on, and influence, global developments in technology innovation, and its own technology pathway will be shaped by systems of innovation – global, national, sectoral, and technology-specific. We find that China's energy innovation system has already helped to develop and scale-up certain modular and manufacturing-intensive technologies, but these successes may not translate to all industrial fields – particularly for future energy systems that require greater consumer interaction, or greater coordination between sectors or between supply and demand.

China's innovation capacity remains a subject of debate, among both policy makers and academics. Within the energy transition literature, scholars have noted that innovation takes place within a technology innovation system. Technology innovation systems differ by sector and by individual technology, and the energy sector includes a variety of technologies, both mature and emerging. Coal, oil, and more recently gas – and electricity derived from these sources – dominate China's existing energy sector, but wind, solar, nuclear, and electric vehicles constitute emerging fields.

China's national innovation system has become more centralized and institutionalized. As Chen and Naughton have shown, in the past decade China's policies on innovation have not evolved towards a 'light touch' approach, but have rather adopted a specific pattern of administrative institutionalization.[48] In this pattern, national leaders determine basic long-term goals, and give broad guidance and indirect signals of their intent. Government ministries and think tanks then draft policy priorities in somewhat greater detail, bringing together experts from throughout the bureaucracy and industry to provide inputs to policy.

While the state and market have mobilized immense resources for R&D investment, there remain considerable questions about the efficiency of R&D in China. To implement central government policies and thereby capture more resources, SOEs tend to favour large, long-term capital projects aligned with those policies, rather than pursuing small, disruptive innovation.[49] Indeed, the tendency of SOE managers to deploy resources in support of empire building, and to focus on maintaining existing assets, would tend to push SOEs towards incremental innovation within existing fields.[50]

In terms of market formation through supportive policy and establishment of market niches, China has been instrumental in scaling up wind, solar, energy storage, and electric vehicles. In these cases, China was a technology follower that scaled up manufacturing first, then shifted to production for domestic markets as the technology reached the potential for commercialization. Commercial enterprises have also supported original niches in fields not targeted by government policy, resulting in new business

models and commercialization pathways, such as for electric bikes, electric shared mobility, and mobile electric vehicle charging.[51]

Why does China lead in some clean energy technologies but not in all, and what does this portend for the future of clean energy in China? Several factors are at work: in terms of the number of patented components, solar and battery technologies appear somewhat simpler, and patent analysis suggests innovation in these fields depends on materials and electronics-related R&D, in comparison to wind power and other technologies that are dependent upon both materials and mechanical engineering innovation.[52]

To date, much of the literature on clean energy innovation has focused on renewable energy. Carbon capture, utilization, and storage (CCUS) and nuclear differ vastly from wind, solar, and storage, both in scale and design complexity, and may have less potential for rapid, solar-type learning curves based on scale-up. While hydrogen electrolysis has potential for rapid learning rates,[53] electrolysis is only one component of a complex hydrogen economy comprising production, transportation, storage, and use. CCUS, nuclear, and hydrogen may be better described as 'complex product systems', which operate at large scale and entail high capital costs and extensive periods of piloting and experimentation.[54] While China's proclivity towards capital-intensive infrastructure investment, coordination by powerful state-owned industries, and its system of provincial pilots could give it an advantage in such fields, these cases display a substantial difference with wind, solar, and energy storage – fields where policies on manufacturing and technology catch-up played the leading role in enabling learning and cost reduction.

Furthermore, in the areas of energy efficiency and ensuring energy demand (such as for EV charging or industry) that can respond to variable renewable energy output, a broader suite of innovation in networks and IT will be needed. These fields require interaction and the open-ended engagement of many stakeholders.[55] Moreover, energy efficiency and demand-side energy technology innovation face large institutional barriers – such as the builder–owner–occupant dilemma (in which building construction firms, owners, and occupants are different entities and hence each lack the incentive to build or operate for energy efficiency or sustainability), lack of consumer awareness, and historical reliance on cheap energy – that likely cannot be overcome by market reforms such as spot power markets or carbon prices.

Historically, China's innovation policy has favoured supply-side innovation,[56] not the moderation of energy demand. For these reasons, while China's technology innovation system has developed highly sophisticated functions in some fields (especially in manufacturing-oriented technologies such as solar and batteries) innovation in fields either dominated by large, conservative, state-owned entities or those requiring stakeholder interaction at multiple levels may be inherently more difficult. This is especially true if China's relations with the US and other Western economies continue to sour and there are fewer international inputs into the innovation process. As such, China's involvement in the international energy and climate system can also help and hinder the energy transition.

6. International energy and climate governance as enablers of the energy transition

China's governance system and domestic interests will be central to its energy transition. But international energy and climate governance also play a role in enabling, and arguably in accelerating, China's energy transition. Formal international institutions such as the UNFCCC, the IEA, and IRENA, despite their fragmentation, are increasingly focused on the energy transition, pointing to greater international coordination on climate change. They have also undertaken specific bilateral cooperation projects with the Chinese government and non-governmental partners on China's power sector reform, carbon markets, and the development of green finance, among other questions. Similarly, major international climate summits are action-forcing events for many countries, with China also timing major climate-related policy announcements to coincide with international events and conferences. This also feeds through to the work of multilateral development banks (MDBs), which increasingly play a role in global climate governance, helping to develop standards related to environmental, social, and

governance issues. MDBs are involved in financing climate change mitigation and adaptation projects in China and related capacity-building efforts, and such efforts directly engage Chinese policy makers, researchers, and private companies.

Bilateral and multilateral government cooperation projects also help shape agendas, while international NGOs support climate governance by advising policy makers, publishing reports, funding and conducting research, and providing technical assistance to both public and private organizations. The global media and international private firms play a mixed role, however. With the international media often portraying China's posture on climate and energy negatively – emphasizing issues related to urban air pollution, coal plant construction, and rapidly rising emissions, and with access to international media in China being increasingly limited – it is unclear whether media coverage – positive or negative – hinders or helps accelerate policies toward the low-carbon energy transition. Similarly, large international companies and investment firms have taken the lead in promoting low-carbon business strategies. At the same time, energy companies, manufacturing firms, and consumer goods companies with large supply chains in China may seek only to comply with existing regulations at the lowest cost, or even to relocate production or investment elsewhere if conditions change.

Conclusions

China's target of peaking carbon emissions by 2030, and of reaching carbon neutrality by 2060, will entail changes throughout the country's economy, particularly in the structure of the country's energy production and consumption. This will require not only a change from one type of energy source to another, but a wider change in the energy sector's sociotechnical regime. While there is strong commitment from the Chinese leadership to undertake this change, and the guiding hand of the State will go some way in advancing the energy transition, it may fall short of the transformational change the energy transition is expected to entail. China's present energy regime evolved around an energy-development pattern supported by, and embedded in, the country's formal and informal institutions related to energy. The State has facilitated and benefitted from the current energy regime.

Even though the Chinese government is introducing institutional changes, including market incentives, which could reinforce the transition, these will remain imperfect and subject to other goals related to economic growth, security policy, and technology policy. Ultimately, achieving a low-carbon energy transition will depend on the Party–State's commitment to this goal, and to the convergence or divergence of various policy goals and institutional factors.

This is also true for innovation. While China has led the world in scaling up clean energy and other related technologies, different types of institutions in the country will help and hinder the ongoing low-carbon energy transition. Historically, China has been better at building out energy supplies and adding the 'hardware' of energy infrastructure, while having greater difficulty adjusting the 'software' of institutional and societal change. As this paper argues, the State-centric model is geared up to expanding the hardware side. But the software, that relies on a demand pull, market incentives, and greater coordination among stakeholders and between sectors, will be more challenging. This is especially the case in technology fields that have a more distributed nature or are focused on demand-side measures, such as distributed solar, storage, electric vehicle charging, smart grid, smart building, or building energy efficiency.

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