THE OXFORD INSTITUTE FOR ENERGY STUDIES

February 2025

Hydrogen in China: Why China’s success in solar PV might not translate to electrolyzers

OIES Paper: CE 16

Xiaohan Gong, OIES-Aramco Fellow

ISBN 978-1-78467-264-5

Acknowledgements

The author extends deep gratitude to Dr. Michal Meidan, Mr. Anders Hove and Mr. Martin Lambert for their invaluable mentorship and insightful feedback throughout this research project.

Abstract

China's manufacturing prowess and progress in lowering electrolyzer costs have raised hopes – and concerns – about its potential to lead electrolyzer manufacturing and exports globally, accelerating the clean energy transition worldwide. The dramatic cost reductions achieved in solar photovoltaics (PV) and China's subsequent dominance of these supply chains are often cited as an example of how things might play out in the hydrogen space.

This paper explores whether China can replicate its success in solar with electrolyzers, considering government support, learning rates of PV and electrolyzers, Chinese corporate strategies, and the external environment for exports. It finds that:

- China's mature systems of manufacturing innovation and government support have enabled significant cost reductions for alkaline electrolyzers, and made it possible for Chinese manufacturers to catch up in proton exchange membrane (PEM) electrolyzers.
- However, supportive policies for boosting manufacturing capabilities alone cannot guarantee further significant cost decreases or enable Chinese companies to dominate global electrolyzer supply chains.
- Unlike solar PV with its mass-manufacturing characteristics, the complexity of electrolysis systems means that cost reductions from technology innovation cannot be solely achieved through scaling up standardized manufacturing capacity. The same complexity makes it harder to benefit from technology transfer in PEM electrolyzers.
- While learning rates in electrolyzers could approach those of solar PV, uncertainty remains high. Unlike PV, the cost of electrolyzers is only one factor in the cost of renewable hydrogen, which also depends on the price of renewable electricity. Therefore, rapid learning rates may not themselves be sufficient to enable competitiveness with fossil-fuel derived hydrogen or other energy sources.
- Rising trade protectionism also challenge China's electrolyzer exports, marking another major difference from the development and deployment trajectory experienced by PV.

Contents

Figures

Tables

1. Introduction

Several organizations and commentators have posited that China's hydrogen and electrolysis industry could follow the path of solar PV, which experienced rapid cost reductions and led to China dominating the field.[1] However, this paper argues that this analogy is overly simplistic and may not play out in the field of PEM electrolyzers due to multiple factors.

To start with, the domestic policy environment for hydrogen today differs from that for solar PV in the mid-2000s. Solar PV and renewable hydrogen are both viewed by China as areas with high potential for industrial upgrading and both benefit from state support, particularly at the provincial level. However, they have been developed with a different outlook, with hydrogen slated for domestic value chains whereas solar PV products were initially designed for export. Moreover, a favourable policy environment is only one element in the solar industry's success story, and the same is true for hydrogen. Other factors need to be considered, including technological attributes, corporate internationalization strategies, the global context for trade and innovation, and the availability and nature of direct government support.

Among the two competing electrolyzer technologies, China is catching up in proton exchange membrane (PEM) electrolyzers. Meanwhile, China's manufacturing and export focus is on alkaline electrolyzers, where its advantage is likely to remain the most significant and where, similar to solar PV, government support has enabled sharp reductions in costs. With increasing experience in overseas energy investments, Chinese energy equipment manufacturers can export alkaline electrolyzers. But in the coming years, further cost declines in alkaline electrolyzers may be difficult to achieve because the learning rate for alkaline electrolyzers is likely to level off. Most of the cost reductions are estimated to be greatest in their current, initial, development period.

Also, the complexity of PEM electrolyzers distinguishes their development from PV cells and modules. The complexity of electrolysis systems suggests that foreign investment in manufacturing may do little to promote innovation, especially in PEM electrolyzers, in contrast to solar PV development which benefitted much from the transfer of standardized manufacturing lines. In addition to uncertainties around the trajectories of cost reductions and China's ability to develop PEM electrolyzers, China's export potential will depend on various factors, including the supply-demand balance domestically and globally, as well as protectionist policies around the world.

The uncertainty around China's ability to replicate its success with solar may allay Western concerns that China will dominate global renewable hydrogen supply chains. It also suggests cost declines that would help accelerate deployment may also be more limited.[2] Furthermore, China's decision-makers are focusing on domestic deployment rather than exports. All these factors point to a different growth trajectory for electrolysis, as compared with solar PV, at least over the next five years.

The aim of the paper is to highlight the similarities and differences between these two sectors, acknowledging, however, that they are at different levels of development: China's renewable hydrogen sector is still nascent compared with the more mature solar industry.[3] As such, this comparative analysis focuses on the early developmental phases of solar and renewable hydrogen. Specifically, the early stage of solar PV development primarily refers to the period from 1970 to 2004. The timeline for hydrogen electrolysis development is complex, tracing back to 1986 with a focus on fuel cell vehicles (FCVs). But the complexity of the hydrogen value chain and the uncertainty around its application (especially in transport where it struggled to compete with electric vehicles) hindered hydrogen technology development, leading to periods of growth and decline.[4]

Since 2016, as China's decarbonization strategy began to gain momentum, and the Chinese government has placed greater emphasis on the development of hydrogen value chains, including renewable hydrogen production and electrolyzers, the hydrogen industry has witnessed a renewed development push. Since 2020, the field has become more concerted and focused.[5] Therefore, although the early development stages for hydrogen span a long period, from 1986 to now, this paper focuses on the period after 2016, particularly after 2020, because of the many new policies adopted and heightened government attention since then.

This paper is organized as follows. Sections 2 and 3 summarize the historical development of solar PV and renewable hydrogen, while Section 4 compares their development trajectories. Section 5 delves deeper into government support and its role in boosting manufacturing of solar products and electrolysers. Section 6 looks beyond government policy and examines the technological characteristics of solar PV and electrolyzers and how these relate to their cost-reduction patterns. Section 7 examines the early stages of international cooperation on solar PV and renewable hydrogen, exploring how solar PV manufacturers and hydrogen companies have interacted with global supply chains in practice. This section also assesses the implications of a shifting global landscape for exporting electrolyzers. Building on these insights, Section 8 summarizes and highlights the implications of China's electrolyser development for its role in the supply chains of renewable hydrogen.

2. Development of Solar PV in China: An export-oriented industry led by the private sector

The development of China's solar PV industry can be divided into four stages:

- The slow-development stage (1970–2004);
- The wild-growth stage (2004–2008);
- The high-speed-development stage (2009–2018); and
- The grid-parity stage (2019–present).[6]

In the first two stages, Chinese companies were active in the labour-intensive mid-stream (for example, cell production and PV module encapsulation). This was driven by the huge demand for solar PV products in Europe, enabled by technology transfer from industrialized countries (such as Germany, Australia, the US, and Canada)[7] and by local government support. But Chinese companies were weak in the upstream sector, specifically in the manufacture of purified polycrystalline silicon which was dominated by foreign companies. Manufacturing solar cells was therefore costly.[8] Starting in 2009, in the face of decreasing exports, anti-dumping investigations issued by the European Union (EU) and US, and the global financial crisis, the Chinese government began to help the solar PV industry shift from an export-oriented manufacturing industry to one fulfilling the domestic deployment of solar, and issued policies on market consolidation and technology advancement to foster the domestic solar market.

2.1 Solar PV's initial phase featured start-ups and basic policy support for an emerging export product

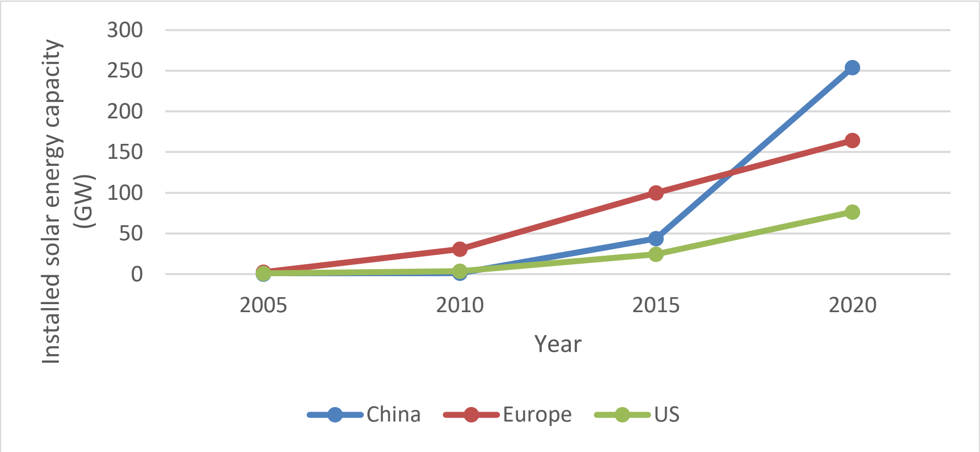
The development of China's solar PV industry between 1970 and 2004 saw the emergence of first-wave start-ups supported by local governments to capture external demand for solar PV products, despite general central support for renewable energy. In 1997, the State Planning Commission (the former National Development and Reform Commission, or NDRC) issued *Interim Measures for Managing Basic Construction Projects for New Energy*, an administrative regulation, aiming to accelerate the localization of manufacturing of new energy equipment including solar PV products.[9] This was the first time that the central government officially supported the solar PV manufacturing industry as part of broader efforts to develop renewable energy technology.[10] In addition, the policy on 'Electrification in Western Villages and Towns' adopted by the State Planning Commission in 2002, helped electrify remote areas with solar,[11] as solar PV was increasingly seen as a way to increase electricity supply.[12]

The early development of solar PV in China was boosted by privately owned enterprises (POEs), such as Suntech and Yingli, set up by experts who had returned from overseas with knowledge of modern green-energy technology,[13] or having expertise in manufacturing scale-up.[14] Local governments granted various forms of support to local solar businesses within their jurisdictions.[15]

However, it was the huge export markets for solar PV, such as Spain and Germany, that stimulated the development of China's solar PV industry.[16] From 2004 to 2008, the manufacturing of solar cell experienced a 'wild growth' phase, increasing from 50 MW per year of production volume in 2004 to 2000 MW per year in 2008.[17] In parallel, China's share of the global PV cell market share rose from less than 1 per cent in 2004 to nearly 45 per cent in 2008.[18]

Industry development in this phase was enabled by a number of factors. The surge in demand for PV in Europe also spurred a rush of speculative investments by private companies to meet that demand.[19] Chinese companies imported turnkey production lines, raw materials, and second-hand equipment.[20] Solar POEs processed the imported purified polysilicon into wafers, cells, or modules for re-export.[21] This, in combination with support policies in solar PV manufacturing, the country's cheap labour[22], and Chinese companies reaping economies of scale in the manufacturing process led China to gain a competitive advantage in PV products.[23] Around 95 per cent of solar PV made in China were exported to Germany and the US.[24] (see Figure 1)

Figure 1: Installed solar energy capacity in China, Europe, and the United States (GW)



Source: Author, based on 'Installed Solar Energy Capacity', Our World in Data, last updated on 12 December 2023, accessed on 14 June 2024 at https://ourworldindata.org/grapher/installed-solar-pv-capacity?facet=none&country=OWID_WRL - CHN - USA - OWID_EUR

During the same period, the central government began to stress the strategic importance of the solar PV industry and to develop the domestic solar market.[25] Although *The 11th Five-Year Plan* (2006) did not view the solar PV industry as an area for China's industry upgrading,[26] the *Outline for National Middle and Long Term Scientific and Technological Development Plan (2006–2020)* published by the State Council in 2006, and the *Directory of High and New Technology Products* (2006) issued by the Ministry of Science and Technology (MOST) prioritized the R&D and manufacture of high-cost-performance solar PV cells, modules, power controllers and inverters, along with their application technologies.[27] By the end of 2007, the central government had identified the solar PV industry as a 'high-tech industry' which could help China restructure its national economy and enhance its overall industrial competitiveness.[28] This increased the central government's focus on the solar PV industry as a component to China's industrial strategy.

The emphasis on accelerating the industrial upgrading of the solar PV industry also prompted the central government to foster the domestic market for solar PV products. The scale-up of manufacturing and learning-by-doing in the fields of PV, along with deploying large-scale, grid-connected PV plants in China enabled costs to decline steadily, which in turn drove more widespread adoption of solar across China.[29] By requiring grid companies to take renewable electricity and setting quantitative targets for solar power deployment, the *Renewable Energy Law adopted in 2006 and the Mid-to-Long Term Renewable Energy Development Plan (2007)* helped improve the domestic market for solar PV.[30] Given central government support and the success at penetrating overseas markets, by 2007 more than half of all major Chinese cities had established PV industrial policy priorities or targets, viewing the sector as an opportunity for both growth and employment.[31]

2.2 Domestic deployment of PV only accelerated after 2009

At the high-speed-development stage (2009–2018), the Chinese government strengthened its efforts to foster the domestic solar market and restructure the solar PV industry. These efforts were prompted by the desire to support the sector in the face of weaker international demand following the 2008–2009 financial crisis, the anti-dumping investigation on China's solar panels after 2012,[32] as well as the cessation of production and even the bankruptcy of several domestic solar companies since 2011.[33] In 2010, the State Council emphasized again the importance of the solar PV industry for China's industrial upgrading, and recognized the solar PV industry for the first time as a 'strategic emerging industry' that could help China seize the commanding heights of the new round of economic and technological development.[34]

Later, the first five-year plan specifically addressing the solar industry – *the 12th Five-Year Development Plan for Solar Power* (2012) – demonstrated that the central government sought to boost solar power generation and demand for solar PV products,[35] and reduce the cost of solar power.[36] Policy actions included introducing the Large-scale PV Power Station Concession Bidding Programme,[37] the Golden Sun Programme,[38] and a generous feed-in-tariff for domestic PV projects.[39] The newly-introduced PV feed-in tariff of up to around US$ 0.17/KWh was significantly higher than the average rate for coal-fired electricity (around US$ 0.05/KWh) and was thus expected by the government to incentivize investments in solar power generation.[40] With the decrease of solar power prices, the *Notice on Matters Related to Photovoltaic Power Generation* (2018) was adopted to gradually reduce subsidies.[41] Subsequently in 2019, the National Development and Reform Commission issued the *Notice on Actively Promoting Subsidy-Free Grid Parity for Wind Power and Solar Power Generation*, marking the beginning of the era of subsidy-free grid parity for solar power generation.[42]

2.3 Rapid scale-up and technology innovation have played critical roles in cost reductions and enabled Chinese dominance in solar

The development of the solar industry has led to technology upgrades and enhanced conversion efficiency of PV systems.[43] Both the scale-up of wafer manufacturing and the improvement of the conversion efficiency of cells have been essential for cost reductions, with manufacturing scale-up particularly critical.[44] As production increased, the cost of solar modules per watt of capacity fell in China from $4.25 to $0.36 between 2006 and 2017.[45]

The conversion efficiency refers to the efficiency of transforming solar energy into electricity. For every 1 per cent increase in photovoltaic power conversion efficiency, the cost per kilowatt-hour decreases by 5 per cent to 7 per cent.[46] The conversion rate of monocrystalline silicon solar cells has increased from around 18 per cent in 2012 to around 24 per cent in 2023.[47] For China, as it looks to achieve its 2060 carbon neutrality goal, the main problem now is how to integrate solar power into power grids and how to best use decentralized solar power rather than how to reduce the cost of solar power.[48]

In sum, at the outset, before being recognized as an economic sector for fostering China's industrial competitiveness, China's solar PV industry primarily flourished as an export-oriented manufacturing sector. Its success can be explained by the transfer of mature and standardized turnkey manufacturing lines, by the external demand in the European Union (EU) that acted as a catalyst for the sector's growth in China, and then by central government intervention for industry development and consistent support mechanisms implemented by local governments.

3. The development of hydrogen in China: a domestic industrial and decarbonisation policy

3.1 The Evolution of China's hydrogen policy

Whereas the solar industry started as a niche export manufacturing industry, China's consideration of hydrogen as a fuel began as early as 1986 with R&D for hydrogen fuel cells[49] with no consideration of the carbon footprint of hydrogen. Hydrogen development was an industrial strategy. The view was that promoting hydrogen fuel cell vehicles (FCVs) could help China in its new energy vehicles industrial strategy and reduce vulnerabilities related to the import of oil and gas.[50] However, the complexity of hydrogen value chains and unclear applications limited progress in hydrogen technology development, resulting in little enthusiasm from the Chinese government.[51]

In the early 2000s, Japan's progress in commercializing fuel cells and Chinese policymakers' concerns about the country's oil import dependence raised hydrogen again in the energy policy agenda, as demonstrated by the first domestically made FCV launched in 2003.[52] Also, in 2006, the *National Mid-and-Long Term Development Plan of Science and Technology (2006–2020)* saw efforts to develop other segments of the hydrogen value chain, and identified hydrogen storage and transport as an emerging energy technology.[53] Because of expensive hydrogen technologies, this renewed interest did not lead to sustainable investment or scalable development in China.[54] Between 2010 and 2014, the development of FCVs fell behind the development of electric vehicles due to factors such as insufficient technology development and the high costs of hydrogen infrastructure.[55]

During 2015 and 2019, there was a rapid development of FCVs, along with R&D for hydrogen production, storage and transport crucial for refuelling FCVs. This was likely due to China's efforts to catch up with neighbouring countries like Japan and South Korea in FCV development, in part by introducing new subsidy regimes for purchasing FCVs.[56]

Since 2016, in the context of geoeconomic competition for clean energy supply chains,[57] significant moves by the government at the central and local levels have accelerated the industrial development of all types of hydrogen and all segments of hydrogen value-chains. To seek leadership in the industry, the *13th Industrial Development Plan of Strategic Emerging Industries* (2016) identified hydrogen production and storage and hydrogen refuelling stations as 'strategic emerging energy industries'.[58] This designation suggests that developing hydrogen would be integrated in national economic development plans and benefit from state guidance and support, as strategic industries are at the heart of China's industrial transformation.[59] In light of this, policies such as *Action Plans for Energy Technological Revolution and Innovation (2016–2030)* have provided guidance to priority areas for promoting hydrogen technology, such as renewable hydrogen production.[60]

Since 2020, policy makers have focused more on upstream hydrogen. Following China's pledge, issued in 2020, to peak carbon emissions before 2030 and reach carbon neutrality by 2060, the hydrogen economy has received new emphasis, with renewable hydrogen and electrolyzers now a rising priority for Chinese policymakers.[61] In 2021, more than 30 industrial policies (for example, the *14th Five-Year Plan of Energy Technology Innovation*)[62] issued at the central level incorporated guidance on hydrogen.[63]

The most important policy document so far in the hydrogen sector – the *Mid- and Long-Term Hydrogen Industrial Development Plan* (2022) – articulated the aims of improving efficiency of renewable hydrogen production and of scaling up the productivity of related production equipment, such as electrolyzers.[64]

More specifically, *The 14th Five-Year Plan of Energy Technology Innovation* (2021) set the objectives of improving technological capacities for manufacturing PEM electrolyzers and solid oxide (SO) electrolyzers.[65]

Local government strategies have been mixed, with some emphasizing FCVs, and others electrolysis. Prior to the implementation of the *Mid- and Long-Term Hydrogen Industrial Development Plan* (2022), some local governments were already promoting innovation and the electrolyzer manufacturing[66], even though the emphasis remained on the development of hydrogen fuel cells.[67] For example, Beijing and Changshu city, in Jiangsu province, are promoting the advancement of PEM and SO electrolyzer technology, while also seeking to improve the efficiency of alkaline electrolysis.[68] Similarly, Ningbo city in Zhejiang province announced plans to support hydrogen equipment manufacturing for both alkaline and PEM electrolysis.[69] Accordingly, similar to the electrolyzer markets of other states, which are dominated by PEM electrolyzers and alkaline electrolyzers,[70] China is catching up in PEM electrolysis and continues to improve the performance of alkaline electrolysis (see section 5 for more detailed analysis of government support for electrolysis).

3.2 Strategies for hydrogen have shifted from a niche industry towards a key contributor to industrial decarbonization

Hydrogen has been used as a chemical or a raw material in China's chemical and refinery industry for decades. As such, China is the world's largest consumer of hydrogen, mainly derived from coal.[71] Since 2020, China has considered viewing hydrogen as an energy carrier in its legislation by easing the regulatory requirements associated with its categorisation as a hazardous chemical.[72] Under the 2002 *Regulation on the Safety Management of Hazardous Chemicals*[73], hydrogen production requires special licenses[74] and projects are limited to chemical industrial parks.[75] The complex procedures associated with meeting the safety requirements have stalled some renewable hydrogen projects.[76] However, China's *Energy Law*, approved in November 2024 and in effect on 1 January 2025, should ease the regulatory burden of hydrogen production, given that it is now considered an energy carrier. However, hydrogen has not yet been removed from the *Catalogue of Hazardous Chemicals (2022)*.[77] How the dual status of hydrogen is dealt with in hydrogen projects remains unknown.

The importance of hydrogen as a decarbonization strategy is increasingly evident in policy documents, too. *The 14th Five-Year Plan of Modern Energy System* (2022) and *the Mid- and Long-Term Hydrogen Industrial Development Plan* (2022) highlighted the importance of renewable hydrogen as part of China's goal of carbon neutrality.[78] According to *the Mid- and Long-Term Hydrogen Industrial Development Plan* (2022), 'the focus of China's hydrogen production system is the development of renewable hydrogen', with a quantitative target for producing 100,000 to 200,000 tons of renewable hydrogen per year by 2025.[79] This target is really quite conservative,[80] given that China's demand for hydrogen per year is projected to be 40.58 million tons by 2025. But setting a numeric target for renewable hydrogen still sends an important signal to the market.[81] *The 14th Five-Year Plan of Renewable Energy Development* (2022) further specified that renewable hydrogen production should be located in regions where renewable electricity prices are low and where there have been demonstration projects for hydrogen storage, transport and use (see Figure 2).[82]

Figure 2: Central-level ambition for renewable hydrogen development

The Mid- and Long-Term Hydrogen Industrial Development Plan (2022)

- The promotion of renewable hydrogen production and the manufacture of relevant equipment

The 14th Five-Year Plan of Renewable Energy Development (2022)

- The production of renewable hydrogen in places with cheap electricity prices
- The integrated development of renewable hydrogen production and its transportation, storage, and use

The 14th Five-Year Plan of Energy Technology Innovation (2021)

- The pursuit of technology innovation for PEM electrolysers and SO electrolysers

Source: Author, based on hydrogen-related policies adopted at the central level

Figure 3: The number of renewable hydrogen projects in China, by province

Source: Author; Based on a research report;[83] The map of China is retrieved from ‘Discover the 23 Provinces of China’, ThoughtCo., 7 June 2024, accessed on 19 June 2024 at https://www.thoughtco.com/china-provinces-4158617

Note: The data is last updated on 31 December 2023. Provinces without specified numbers indicate either the absence of renewable hydrogen projects or fewer than ten such projects. This map is for illustrative purposes and is without prejudice to the status of or sovereignty over any territory covered by this map

Hydrogen strategies have a strong regional component, often linked to renewable resource availability. In response to this, the governments of cities or provinces with rich renewable energy resources have adopted hydrogen development plans.[84] As demonstrated in Figure 3, most of China’s renewable hydrogen projects are located in Northwest China, Northeast China and North China, with Inner Mongolia having the most. According to the World Economic Forum, if the price of renewable electricity falls below 0.15 yuan/KWh, compared with the current average of 0.5 yuan/KWh, the production cost of renewable hydrogen can decrease from the current 33.9-42.9 yuan/kg to 15 yuan/kg within the current technological framework, making it possible to compete with fossil-fuel-based hydrogen.[85] Already, some local governments relaxed the hazardous chemical regulations and allowed renewable hydrogen production outside chemical industrial parks.[86] For example, hydrogen refuelling stations with on-site renewable hydrogen production have been in operation in Provinces such as Xinjiang, Hunan and Anhui.[87]

3.3 SOEs playing a leading role in China’s hydrogen market

Energy state-owned enterprises (SOEs) have played a significant role in large-scale, capital-intensive demonstration projects for renewable hydrogen production, both domestically and internationally. For instance, Sinopec has invested in a renewable hydrogen production project in Beijing using PEM electrolyzers, while the State Power Investment Corporation has made renewable hydrogen investments in Brazil, utilizing centralized solar and wind power generation facilities.[88] Meanwhile several large private companies are investing in domestic renewable hydrogen production (Table 1).[89] Despite this, most private companies are investing in less capital-intensive hydrogen projects, such as the R&D and manufacturing of hydrogen-related equipment (Table 2). The top three electrolyzer manufacturers accounted for around 80 per cent of China's electrolyzer market in 2022.[90] With the exception of PERIC Hydrogen, which is an SOE, all other companies are privately owned or foreign controlled.

Table 1: Leading corporate players in renewable hydrogen production

	Name of companies	Ownership	Production methods
Renewable hydrogen	Sinopec	SOE	Hydrogen production based on solar and wind power
	State Power Investment Corporation		
	LONGi	POE	Hydrogen production based on solar power
	Ningxia Baofeng Corporation		
	Jinfeng Science and Technology Corporation		Hydrogen production based on wind power

Source: Author, based on reports produced by securities companies[91] and media[92]

Table 2: Top 5 electrolyzer manufacturers in 2023

Number	Name of companies	Ownership	Electrolyzers	Shipment volume	Maximum hydrogen production rate per unit	Declared production capacity
1	PERIC Hydrogen Technologies Co.,Ltd.	SOE	PEM & Alkaline electrolysers	205-230 MW	2000Nm3/h	1.5 GW
2	LONGi	POE	Alkaline electrolyzers	180-205 MW	1000Nm3/h	1.5 GW
3	John Cockerrill	Foreign company (Belgium)	Alkaline electrolyzers	230 MW	1500Nm3/h	1 GW
4	SAIKESAISI Hydrogen Energy Co.,Ltd.	POE	PEM electrolyzers	Less than 160 MW	1200Nm3/h	Near 1 GW
5	Suzhou Qingqiji Co., Ltd.	POE	Electrode catalyst	N.A.	1500Nm3/h	N.A.

Source: Author, based on an industry survey[93]

3.4 Deployment is lagging behind electrolyzer manufacturing

Alkaline electrolyzer technology in China has become relatively mature with high localization rates for the key components, allowing this technology to be used in China's renewable hydrogen projects.[94] According to the International Energy Agency (IEA), as of the end of 2022, known global electrolyzer manufacturing capacity reached 13 GW/year, half of which was located in China and an additional fifth in Europe.[95] However, the deployment of electrolyzers in China only reached 800 MW in 2022, of which alkaline electrolyzers made up 776 MW , with only 24 MW of capacity constituting PEM electrolyzers.[96] In 2023, only 1.5 GW of electrolyzer capacity in China was earmarked for domestic projects and exports, even though manufacturing capacity had increased by 23 GW.[97] Manufacturing capacity now far exceeds deployment and is dominated by alkaline electrolyzers. If deployment fails to gather momentum and export options are limited, companies may reduce production.

The technological development of China's PEM electrolyzers still lags behind leading economies such as the EU.[98] For the key components for PEM electrolyzers, China still relies on imports of proton exchange membranes and precious-metal catalysts, whereas alkaline electrolyzers use domestically sourced materials and equipment.[99] Furthermore, new policy measures and protectionist policies banning technology transfer and international trade for high-tech equipment[100] could limit the development of PEM electrolyzers in China. Still, the Chinese government is seeking to promote R&D and demonstration projects for PEM electrolyzers, despite concerns about import dependence, suggesting that for now it is prioritizing electrolyzer development over technology independence.

Also, the central government has since 2019 sought to attract foreign companies to manufacture hydrogen-related equipment in China, as part of its efforts to foster a domestic hydrogen manufacturing industry. The *Directory of Encouraging Foreign Investments* issued that year includes hydrogen equipment,[101] has enabled partnerships such as that between Sinopec and Cummins, a U.S. company, for the manufacture of PEM electrolyzers at the end of 2021.[102] Starting from 2022, *The Mid- and Long-Term Hydrogen Industrial Development Plan* (2022) began to stress hydrogen cooperation as part of China's Belt and Road Initiative (BRI), including cooperation on hydrogen technology and equipment, and the formulation of standards for FCVs.[103]

4. Comparing China's hydrogen and solar development trajectories

Despite the long history of hydrogen development in China, its official recognition as a strategic emerging industry in 2016 marks a turning point and coincides with the inception of the domestic electrolysis industry. Since then, the development of renewable hydrogen in China has been driven by the central government's ambition for industrial upgrading, by cheap renewable electricity prices, by the urgency of the energy transition, and by local governments' ambition to take leading positions in developing the domestic industry. Both SOEs and POEs are playing important roles at this early stage of development with the Chinese government now also seeking international cooperation in hydrogen. So, even though both solar PV and hydrogen have benefitted from government support, it is important to unpack the drivers and nature of these support mechanisms.

In the early stages of solar PV and electrolyzers – defined as 1997 to 2004 for solar and 2016 to the present for electrolyzers – both sectors benefitted from supportive policies for manufacturing at the local level and broader development of industry. In addition, both sectors benefit from China's natural resource endowment (namely, primary industrial silicon for solar PV and renewable energy for electrolyzers). But there are also notable differences:

4.1 PV was initially a niche export industry, whereas hydrogen is part of a domestic decarbonization strategy.

The solar PV sector was designated as a strategic emerging industry during the third stage of its development, roughly from 2009 to 2018, and relatively late on in its development. This designation matters because a 'strategic emerging industry' is considered central to China's industrial upgrading and its core competitiveness and as such, receives significant state support. Even though the concept of 'strategic emerging industry' was first articulated in *The Decision on Accelerating the Foster and Development of Strategic Emerging Industries* (2010),[104] support for such 'high-tech industries' had already started in the 1990s.[105] But it was only in 2007, in light of the increasing maturity of the solar PV industry, growing attention to global demand for clean energy, and the economic strategy of developing domestic markets in all economic sectors[106] that it was deemed critical to China's economic development and then incorporated in the 'strategic emerging industries'.

In contrast, renewable hydrogen production was classified a strategic emerging industry by the central government in 2016, during its early stages. China's electrolyzer manufacturers are perceived to be part of the national effort to develop green industries.[107] This implies that funding will be allocated to the R&D of hydrogen technologies, that supportive policies will be adopted to incentivize investments, and that international cooperation is welcome.[108] Moreover, *The Energy Law of the People's Republic of China (PRC)* states that the Government will actively develop hydrogen.[109] This provision lays a legal foundation for China's development of hydrogen and has significantly boosted domestic confidence in the hydrogen business.[110]

4.2 Private start-ups took a leading role in driving cost reductions for solar PV during the early stages, whereas hydrogen is dominated by large SOEs and bigger renewable players.

The commercial landscape for renewable hydrogen in China is complex. SOEs are leading investors in renewable hydrogen production but POEs are playing a crucial role in cost reductions for electrolyzers. The different commercial landscape is likely related to the technological characteristics of solar PV and hydrogen and to the nature of China's energy economy. While POEs have been crucial players in manufacturing – with contributions from foreign investors – SOEs dominate China's energy sector and are critical in developing strategically-important, large-scale energy infrastructure.[111] From 1997 to 2004, solar PV developed as a manufacturing industry and did not require the construction of large-scale infrastructure, providing opportunities for POEs and foreign companies.[112] By contrast, the complex systems and products associated with renewable hydrogen production,[113] not to mention complex hydrogen value chains, necessitate the involvement of various stakeholders with different capacities. SOEs rely on their existing infrastructure[114] and are better equipped to deal with the bureaucratic approval procedures required for hydrogen projects[115], especially if these cut across provincial borders. POEs, however, are important for electrolyzer development given their experience in manufacturing energy-related equipment.

4.3 Hydrogen production is located near low-cost energy inputs, rather than industrial clusters aimed at exports.

In the initial phases, most renewable hydrogen projects are located in North China where renewable electricity prices are low, because electricity costs are a significant component of the overall cost of renewable hydrogen production. Similarly, the solar PV industry was first developed in locations where local governments were highly supportive, offering tax incentives and low electricity prices for manufacturing, and close to abundant resources of primary industrial silicon.

In sum, while both solar PV and renewable hydrogen projects benefitted in the early stages from local government support and being developed in proximity to key inputs, there are inherent differences in their development trajectories: solar started as a niche manufacturing industry for export markets, dominated by private firms which received government recognition and support as a strategic industry only at later stages of development. This also coincided with growing emphasis on decarbonization. Hydrogen, meanwhile, started as a strategic industry aimed at supporting China's decarbonization goals. And while private firms are active in electrolyzer manufacturing, SOEs play a significant role in hydrogen deployment and development given the need for large infrastructure investments, which are harder for private actors to undertake.

5. The role of government support in the development of Solar and Hydrogen: A comparison

While government support has been a significant contributor to the development of emerging industries in China, the support mechanisms have been different. For example, the initial development of the solar PV industry occurred in a relatively decentralized manner, driven predominantly by local governments.[116] In contrast, the issuance of *the Mid- and Long-Term Hydrogen Industrial Development Plan (2022)* suggests that hydrogen development is a priority of the central government, and even though local governments are taking the lead in establishing domestic hydrogen value chains, they are taking their cues from the central government.[117] Unlike in solar, where there were clear commercial benefits to supporting manufacturing (initially for exports and then for domestic deployment), the hydrogen sector is more reliant on domestic policy signals. Table 3 compares the support mechanisms for each sector, highlighting that the early development of renewable hydrogen benefits from more support at both the central and local levels than solar PV did, and that these support mechanisms are more varied.

Table 3: Comparison of support mechanisms for the early development of solar PV and renewable hydrogen

Industries / Support mechanisms	Solar PV	Renewable hydrogen
Central support		
Funding for R&D	√	√
Tax incentives	√ (Exemption of custom duty for importing PV equipment)	X
State financing specifically for the development of a certain clean energy technology	X (general financial support for all kinds of renewable energy)	√ (Vague statement: bank loans to develop renewable hydrogen and the manufacture of relevant equipment)
Subsidies	X	√ (Vague statement: cheap electricity prices to renewable hydrogen projects)
Simplification of administrative procedures	X	√
Subsidies for creating demand	X	√ (Subsidies for the purchase of FCVs and pilot regimes for FCVs)
Local Support		
R&D funding	√	√
Tax incentives	√ (Exemption of corporate income tax)	√ (General tax incentives based on companies setting up in specific locations)
Land benefits	√ (Refunding land transfer fees)	√ (Discounts on land transfer fees in certain places)
Cheap electricity prices	√	√ (With detailed electricity rates)
Cash rewards	X	√ (Cash rewards for setting up enterprises in certain places)
Simplification of administrative procedures	√	√ (Relaxation of strict requirements for hazardous chemicals in select locations)
Subsidies for creating demand	X (With the exception of Jiangsu provincial government)	√ (Subsidizing the use of renewable hydrogen)

Source: Author, based on central and local hydrogen policies

5.1 Instruments for the Early Development of Solar PV

The priority at the early stage was the manufacture of solar PV hardware (as detailed in section 0), rather than solar PV project installation.[118] In 1982, MOST began funding R&D for renewable energy technology and related equipment, including solar PV systems.[119] Since 2000, *National Plans for the R&D of High Technology* have made more funding available for the development of solar cells,[120] including for example up to Yuan 100 million ($13.6 million as of January 2025) available to small and medium companies for their basic research in the solar PV sector.[121] However, this amount was relatively small compared with the over Yuan 10 billion allocated to wind power development between 1996 and 2000.[122]

Furthermore, no funding was specifically allocated for solar PV development. But considerable government support was directed at technology transfers and localisation: imported PV equipment was exempted from customs duties according to the 1997 *Notice on adjusting the tax policy on Imported Equipment*.[123] The *Directory of High and New Technology Products Encouraging Foreign Investments* (2003) also encouraged foreign investors to invest in the manufacture of solar PV systems.[124] That said, the solar industry benefited from general financial support for renewable energy,[125] but the central government did not issue sector-specific development plans or introduce specific incentives for promoting investment in the solar PV industry and solar energy production[126] (see Figure 4).

Figure 4: The early-stage promotion of the R&D for solar PV through general support mechanisms for all renewable energy technologies

National Key R&D Program (since 1982)

- MOST granted funding to the innovation for clean energy technologies, including solar PV.

National Plans for the R&D of High Technology (since 2000)

- MOST granted funding (up to 100 million yuan) to mid-and-small companies for their basic research of solar PV.

The Notice on adjusting the tax policy on Imported Equipment (1997)

- State Council exempted import duty for imported PV system to promote technology transfer.

The Directory of High and New Technology Products Encouraging Foreign Investments (2003)

- MOST and MOFCOM promoted foreign investments in manufacture of solar PV systems in China.

This was also the case at the local level. Local government supported solar PV development as part of policy calls to develop high-tech industries,[127] by leveraging various high-tech support schemes set up by Beijing.[128] Before the massive growth of the solar PV industry in 2007, only a few pioneering local governments had allocated funds for basic solar PV research to be carried out by POEs.[129] They helped these companies reduce production costs by refunding land transfer fees, exempting corporate income tax, and granting cheap electricity prices. For example, as early as 2004, the provincial government of Jiangsu was considering developing a local solar PV market.[130] The *Opinions on Using Price Leverage for Sustainable Development* adopted in Jiangsu in 2005 aimed to incentivize investments in solar power generation by offering solar power higher prices and exempting it from electricity market competition.[131] During the same period, Wuxi city's municipal government was exploring support for high-technology industries such as solar PV through government-led funds.[132] Additionally, with the approval of the State Council, those local governments were able to waive import duties on highly-purified silicon which was not widely available in China.[133] For instance, in 2009 the Jiangsu provincial government introduced an exemption on import duties for materials or equipment that were in short supply domestically.[134]

5.2 Instruments for the Early Development of Renewable Hydrogen

Both the central government and local governments have adopted various instruments to support the development of renewable hydrogen and electrolysers, though local governments are more ambitious.[135]

5.2.1 Central Government Support

To support the basic research of renewable hydrogen, in 2021 MOST issued a program for 'Hydrogen Technology' development which has supported seventeen projects focusing on various challenging hydrogen technologies, including renewable hydrogen production and electrolysers.[136] Likewise, the National Natural Science Foundation of China (NSFC) issued a specific funding regime (2023–2025) for off-grid renewable hydrogen production.[137] Foreign companies are also invited to engage in the manufacturing of equipment for renewable hydrogen production, according to *Catalogue of Industries for Encouraging Foreign Investment* adopted by NDRC.[138] By partnering with foreign companies, China's companies can fill the capability gap of manufacturing PEM electrolyzers.[139] For example, Cummins Inc. and Sinopec are collaborating on technology innovation for PEM electrolysers. At the local level, some local governments (for instance, the provincial government of Shanxi and the municipal government of Chengdu) have established industrial funds which blend public finance and private finance to support R&D for hydrogen value chains in general.[140]

At the same time, the policy focus extends beyond manufacturing as the *Mid- and Long-Term Hydrogen Industrial Development Plan* (2022), which looks to promote renewable hydrogen investments with electrolyzer applications, has pledged support for hydrogen development through bank loans and industrial funds, although it does not explicitly support renewable hydrogen.[141] The *Green and Low-Carbon Transition Industry Guidance* (2024) stressed that projects for renewable hydrogen production or for the manufacturing of relevant equipment would be eligible for support via preferential loans, subsidies, and simplified administrative procedures. This guidance also however does not provide specific details.[142]

5.2.2 Local Government Support

The vaguely framed support at the central level contrasts with local government activity. Local government entities have actively attracted hydrogen investments through cash grants and the creation of industrial parks. The local finance administrations of Chengdu, Ningxia, and Jiaxing have incentivized competitive hydrogen companies with cash grants.[143] For instance, Jiaxing municipal government granted cash grants to the establishment of Meijin Guohong (Zhejiang) Hydrogen Technology Co., Ltd.[144] The cash grant varies according to the amount of the invested capital. Other local governments, for instance Tianjin municipal government and the Autonomous Region of Ningxia, have also established industrial parks to boost their manufacturing capacities for renewable hydrogen value chains.[145] Hydrogen companies then establish new subsidiaries or projects in these industrial parks as local governments offer preferential treatment for land use and streamlined administrative processes.[146] The 'Renewable Hydrogen Production Base' in Zhangjiakou, Hebei, serves as a prime example, where a comprehensive renewable hydrogen value chain - encompassing production, transportation, deployment, and associated manufacturing - is being developed.[147]

Local governments also offer lower electricity rates to promote renewable hydrogen production and the use of electrolyzers. In Foshan, the off-peak electricity rate to produce hydrogen has been set at 0.26 yuan/kWh since 2017.[148] Between 2020 and 2023, the incremental electricity consumption of hydrogen producers in Chengdu was subject to a unified transmission and distribution price of 0.105 yuan/kWh.[149] Meanwhile, since 2019, hydrogen production from water electrolysis in Zhangjiakou has also been subject to electricity rates of no more than 0.36 yuan/kWh.[150] But for renewable hydrogen to compete with fossil-fuel-based hydrogen, renewable electricity prices need to fall below 0.15 yuan/kWh (as discussed in section 3). Therefore, only renewable hydrogen produced in Chengdu is currently competitive with fossil-fuel-based hydrogen.

Prior to late 2024, local governments also supported hydrogen development by lifting regulatory barriers: hydrogen was classified as hazardous chemical which constrains its use (as discussed in section 2). The central government allowed local governments to set up some renewable hydrogen projects outside the chemical industrial parks and/or to cancel the requirements for applying for safety production licenses (Table 4).[151] In November 2024, China approved its long-awaited Energy Law which changed the classification of hydrogen and will now ease this regulatory burden but, as discussed above, hydrogen is still listed in *the Catalogue for Hazardous Chemicals 2022*. Support from local governments to ease these regulatory constraints therefore remains key.

In a similar vein, local governments are subsidising hydrogen use. The pilot city regime for fuel cell vehicles[152] sets a carbon emission standard for hydrogen of less than 15 kg CO_2 for every 1 kg of hydrogen[153] with no distinction between fossil-fuel based hydrogen and renewable hydrogen. The China Hydrogen Alliance, an industry alliance consisting of SOEs and Universities, has proposed the emission standard for renewable hydrogen at 4.9 kg CO_2 per kg of hydrogen[154]. This standard has not been adopted in any central or local policy documents. While the nationally-set requirement is less stringent, the CHA standard is a nod toward the use of hydrogen with low CO2 emissions. At the local level, since 2023, the government of Ningxia subsidizes the use of renewable hydrogen (5.6 yuan/kg) up to 3 years.[155] As a result, in 2023, the price of renewable hydrogen in China was around 25 yuan/kg for electricity costs of 0.4 yuan/kWh, or 15 yuan/kg in the case of electricity at 0.2 yuan/kWh.[156] Although these subsidies do not disclose the CO_2 level for renewable hydrogen, these subsidies effectively reduce one-fifth to one-third of the cost for renewable hydrogen use. This illustrates the crucial role of electricity prices as a cost input for renewable hydrogen, as compared with solar PV, where cell and model prices form the main cost input in electricity produced.

Table 4: Local experimentation for promoting renewable hydrogen production

<table>
<tr><th>Provinces/Cities</th><th>Issuing dates</th><th>Local governments’ efforts to relax the regulatory requirements governing hazardous chemicals</th></tr>
<tr><td>Wuhan</td><td>2022</td><td>Projects for hydrogen production are allowed to be operated outside chemical industrial parks.[157]</td></tr>
<tr><td>Shandong province</td><td>2022</td><td rowspan="2">Projects for renewable hydrogen production are allowed to be operated outside chemical industrial parks.[158]</td></tr>
<tr><td>The district of Dadong in Shenyang</td><td>2023</td></tr>
<tr><td>Hebei province</td><td>2023</td><td rowspan="4">Projects for renewable hydrogen production are allowed to be operated outside chemical industrial parks.[159]
No safety production permit for renewable hydrogen production;[160]</td></tr>
<tr><td>Jilin province</td><td>2023</td></tr>
<tr><td>Xinjiang</td><td>2024</td></tr>
<tr><td>Inner Mongolia</td><td>2024</td></tr>
</table>

5.2.3 Comparison of Policy Instruments

In some respects, policy support for electrolysis and hydrogen is greater than that for solar. Clear and consistent support mechanisms have in the past accelerated the production and deployment of clean energy technology by scaling up manufacturing and promoting R&D,[161] thus impacting exports and potentially enabling a leadership role in global industrial supply chains. As part of this, designation of hydrogen as a strategic emerging industry results in generous state support. Interestingly, though, until the early 2000s, the central government focused more on wind energy development, compared with solar PV.[162] Ironically perhaps, the solar PV industry was developed by a few companies receiving provincial support with clear commercial incentives overseas, rather than due to national-level schemes.

By contrast, the development of renewable hydrogen and electrolyzers currently seems more reliant on a favourable institutional setting at both the central and local level. The official recognition that hydrogen production and the manufacturing of relevant equipment are crucial for China’s industrial upgrading[163] and the need for China to catch up with global hydrogen technology development[164] are likely to maintain support for industrial development even in the absence of a clear commercial incentive. Based on government signals, Chinese manufacturers can seek to develop and mature electrolyzer technologies for the domestic market even as electrolyzer exports remain minimal.[165] That said, fierce competition in the domestic electrolyzer market, demand from foreign hydrogen markets such as the EU, and corporate strategies for internationalization will still provide an impetus for electrolyzer exports.[166]

However, the specific instruments adopted in the electrolyzer sector are different. Unlike the early advancement of the manufacturing capacities for solar PV, the central government does not exempt custom duties for importing key equipment or raw materials for PEM electrolysers. While the government is still experimenting with hydrogen regulations and support mechanisms[167] and could still introduce tax breaks for imports, for now it may still intend to develop renewable hydrogen-related technological capabilities through domestic innovation (see section 3). Moreover, the extent to which tax breaks will be successful in attracting foreign companies is an open question. Foreign companies are now more cautious than in the early 2000s about technology investments in China. They have stressed the need for ‘protecting their intellectual property and market status’[168] as foreign investments in Mainland China have fallen due to a combination of concerns about over-dependence on Chinese high tech goods and IP transfers.[169] Despite this, the Chinese government has continued adopting regulations (say, the *Directories on Encouraged Foreign Investments* issued by NDRC) to promote foreign investments, to rebuild foreign investors’ confidence and to ensure the inflow of advanced know-how and technology.[170]

6. Cost Reductions and Technological characteristics

Multiple factors influence the future cost-reduction path of renewable hydrogen. These include technology learning rates (learning-by-doing), ever-changing input costs, and the availability of the required raw materials.[171] In the learning-by-doing process, when manufacturers accumulate experience and innovate in a repeated manufacturing process over time, a domestic industry can reduce costs while scaling up output capacity. Studies on learning rates have examined cost declines for clean energy technologies over time when cumulative production doubles.[172] Usually, the learning rates are high at the early stages, then level off and may stagnate or even decline because doubling production requires more time at later stages.[173] This suggests that new technologies can experience a sharp cost decline before becoming mature, but the rate of later reductions may slow down or cease. Put simply, cost reductions are usually not linear.[174] The higher learning rates are, the steeper the cost reductions.[175] Technologies with relatively higher learning rates are more likely to experience rapid cost declines necessary to achieve commercial scale and widespread deployment, potentially displacing incumbent technologies, compared with technologies with relatively lower learning rates.[176]

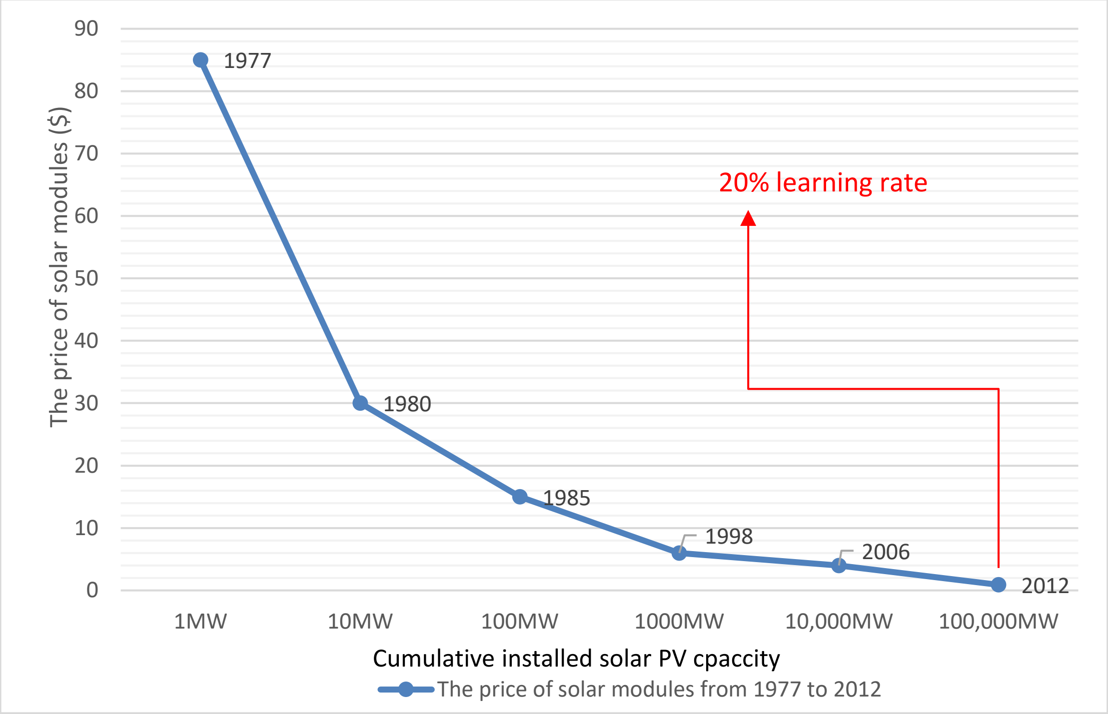
Technological characteristics can impact the learning-by-doing process, ultimately influencing the cost-reduction trend for clean energy technologies.[177] Based on innovation processes, clean energy technologies are usually categorized into manufacturing-intensive technologies, design-intensive technologies, and technologies with complex products and systems.[178] The development of the manufacturing-intensive technologies requires continuous learning through large-scale manufacturing and innovation in production equipment,[179] but innovation in these technologies is rapid because they are typically standardized.[180] In contrast, the learning and innovation of the deployment of design-intensive technologies depends on the operation of energy technologies.[181] Because they tend to involve complex systems and different product-architecture,[182] the feedback from the application of components, sub-systems, and systems helps stimulate learning and innovation in the design of these areas.[183] Yet, learning and innovation in design-intensive technologies and in technologies with complex products and systems can vary by application, making the process more complicated.

As such, learning rates of manufacturing-intensive technologies are usually high and continuous manufacturing experimentation enables rapid cost declines.[184] Moreover, strong market competition accelerates cost reductions.[185] Conversely, learning rates for design-intensive technologies and technologies with complex products and systems tend to be lower.[186]

6.1 Learning rates in solar PV

Solar PV is categorized as a manufacturing-intensive technology.[187] The innovation of solar PV relies on the advancement of capabilities for manufacturing relevant equipment.[188] It has high learning effects because solar power generation requires the repeated manufacture of standardized modules.[189] At the nascent stage of China’s solar PV development, the global learning rate for solar PV reached between 9 per cent and 10 per cent (with the multiple-factor model),[190] while the forecasted target learning rate for PV is around 20 per cent,[191] (see Figure 5). Although the data on the learning rate for solar PV in China at that time was not available, it could have been below 9 per cent in the initial phase due to the leadership of European states and Japan in global PV development.[192] But in 2004, solar cell production volumes in China quadrupled year-on-year,[193] enabling cost reductions for solar PV panels at later stages.[194] Because of high learning effects, in 2007 China’s solar panel price was around \$4.8/W,[195] similar to the world price of solar panels (\$4.83/W).[196] But with substantial central government policy support starting in 2009, China achieved a cost decline of more than 80 per cent, 'helping solar PV to become the most affordable electricity generation technology in many parts of the world.'[197] In 2023, solar cell costs hit record lows because of the significant cost decreases achieved in China.[198] Such dramatic cost declines for made-in-China solar PV could be an exception compared with typical cost-reduction patterns for clean energy technologies, where reductions can decelerate and eventually plateau as the technology matures.

Figure 5: The learning rate for the solar PV module globally



Source: Author's own, based on data extracted from Our World in Data[199]

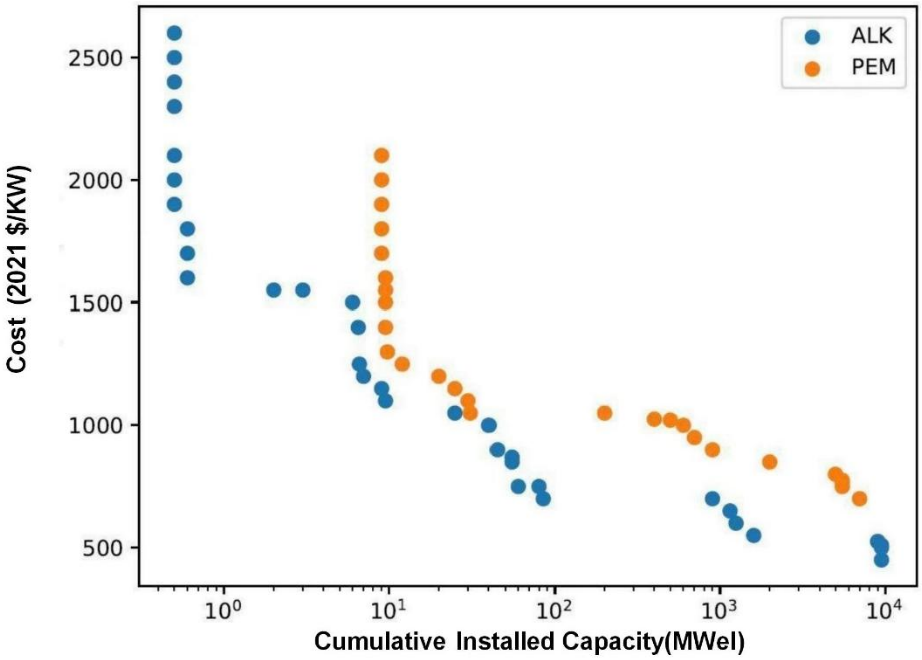
6.2 Learning rates in electrolysis

In contrast, electrolyzers are a technology with complex products and systems, including stacks design, stack manufacturing, and compressor manufacturing, all of which have their own learning rates.[200] Consequently, the estimated learning rates for different types of electrolyzers globally vary. The learning rates for all kinds of electrolyzers range, globally, from 11 per cent to 20 per cent, according to Hydrogen Council and other scholars.[201] Depending on different systems and components, the learning rates for the two major electrolysis technologies, namely alkaline and PEM electrolyzers, are different. The forecasted learning rate for alkaline electrolyzers can reach between 8 per cent and 24 per cent.[202] It means that the cost of alkaline electrolyzers can fall by 8 per cent to 24 per cent when cumulative production doubles. The projected rate for PEM electrolyzers can swing between 7 per cent and 18 per cent,[203] suggesting that the cost of PEM electrolyzers can reduce from 7 per cent to 18 per cent when cumulative production doubles.

Electrolyzers and solar PV exhibit similarly high learning rates.[204] Therefore, innovation in manufacturing may similarly contribute to cost reductions for electrolyzers. The International Renewable Energy Agency (IRENA) notes that, 'it seems electrolyzers have a similar relationship between cost decrease and global capacity as solar PV does'.[205] Furthermore, because at present the estimated learning rate for alkaline electrolyzers is higher than that for PEM electrolyzers, the cost reduction for alkaline electrolyzers is likely to be steeper and more cost-competitive.[206] This aligns with the discussion of the relation between learning rates and cost reduction in the literature on learning rates.

However, electrolyzer cost reductions will not necessarily mirror those of solar PV. First, even after reaching the projected rate, China achieved substantial and unexpected cost reductions in solar PV that were related to both process-innovation and fierce domestic competition.[207] In terms of alkaline electrolyzers,[208] Figure 6 demonstrates that when both electrolysis systems approach their potential efficiency and cost limits, learning rates and cost reductions tend to slow down. This is in line with the common patterns of technological learning, where significant progress is often made in the early stages of technology development, but followed by smaller gains over time.

Figure 6: The learning rate of alkaline and PEM electrolyzers



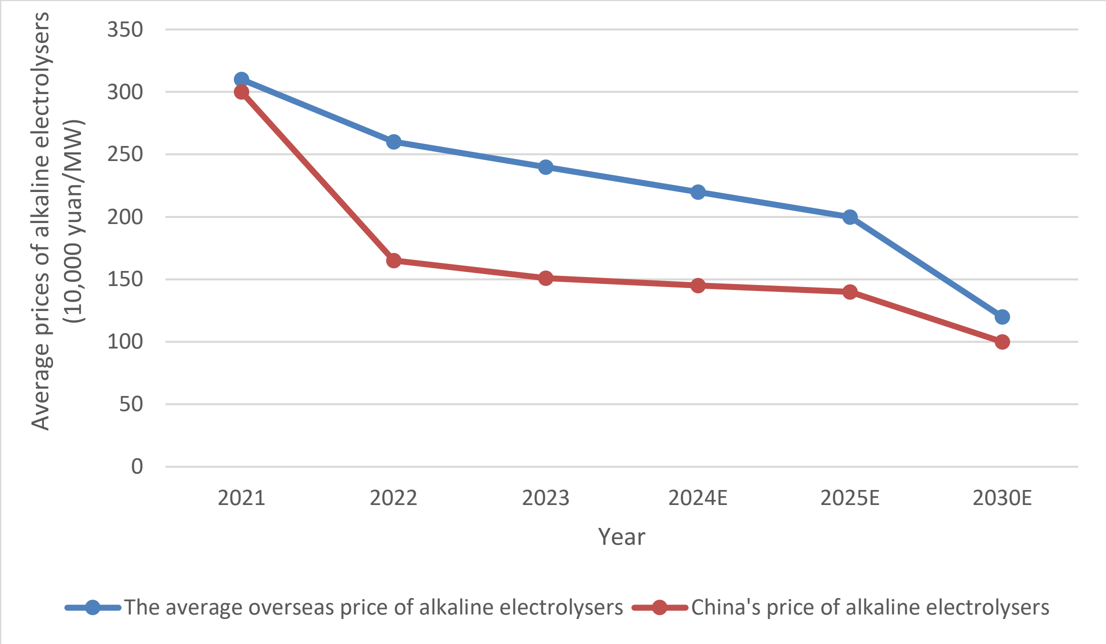
Source: Author, based on scholars' academic estimation[209]

Note: This figure is not precise, only for an indication of the decreasing trend of learning rates

The OECD also notes that 'cost reductions [of electrolyzers] are expected to be largest during the early phase of demonstration which is starting now'.[210] As such, continuous large-scale manufacturing may contribute less to the cost reduction of electrolyzers as they mature. Significantly, because electrolyzers are technologies with complex systems and products, further cost reductions may depend on the adaptation to different applications and require corresponding innovation.[211] It cannot be ruled out that China will achieve greater-than-expected cost reductions over time given its history of industrial overcapacity and support for domestic deployment. But these cost reductions can likely be realized within the country, and may not be as straightforward to export and replicate internationally.

It is also important to note that price trends are likely to differ for alkaline and PEM electrolysers. Figure 7 shows that since 2021, the price of China-made alkaline electrolyzers has been lower than the average overseas price. Moreover, the cost declines over 2021–2022 have been more rapid in China than those made abroad. This is likely due to the intense competition between China's alkaline electrolyzer manufacturers,[212] the country's relatively low labour costs, and the mature manufacturing innovation system where electrolyser manufacturers have the advantage of procuring domestically-sourced materials and components at significantly reduced costs compared with their Western counterparts.[213] Cost declines have since stabilized between 2022 and 2024 (with 2024 data based on estimates). Meanwhile, the cost of alkaline electrolysers manufactured abroad is forecasted to fall more rapidly than in China between 2024 and 2030. In 2030, the price of alkaline electrolyzers in China is estimated to align with average overseas prices. This is likely related to the growing number of global manufacturers, especially as the EU and the US implement industrial policies to bolster electrolyzer manufacturing. Production in Europe and the US can save costs by designing and establishing automated manufacturing lines, in contrast to the handmade production of most electrolyzers in China.[214] The cost savings from automated manufacturing are expected to outweigh China's relatively low labour costs.[215] Although the first automated production line developed by Shanghai Hydrogen Technology Co. Ltd. for alkaline electrolyzers was established in September 2023, automated production lines may not be rolled out nationally before 2030.[216] China is experiencing a transition from labour and equipment to half-automated manufacturing in the alkaline electrolyzer development.[217]

Figure 7: The decreasing trend of the average prices of alkaline electrolysers made both abroad and in China (10,000 yuan/MW)

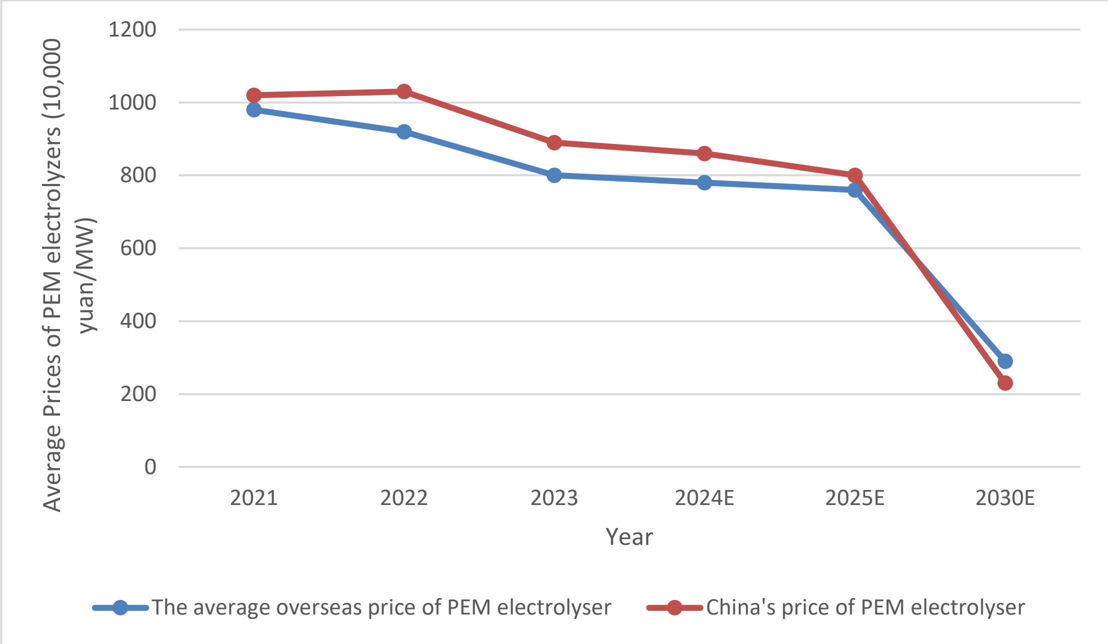


Source: Author's own, based on reports produced by consultancy or securities companies[218]

PEM electrolyzers demonstrate a different pathway. As seen in Figure 8, since 2021, the cost of Chinese PEM electrolyzers has been higher on average than abroad, mainly because of high import prices for PEM electrolyzer components.[219] Prices in China and abroad are forecasted to undergo a sharp reduction between 2025 and 2030 for the first time, unlike alkaline electrolyzers that may have already seen the largest cost declines. This difference between the two types of electrolyzers aligns with their respective learning rates (see Figure 6). This could be attributed to a slower pace in cost reduction due to the relatively lower learning rate for PEM electrolyzers.

Furthermore, after 2025, the price of PEM electrolyzers in China appears it should become increasingly in line with the average overseas price. To date, PEM electrolyzers in China have primarily been used in demonstration projects and are still at the pre-commercialization stage, unlike alkaline electrolysis which is already commercial. This, combined with the need for imported inputs suggests that the cost of PEM electrolyzers in China will struggle to fall below the average overseas price in 2030. That said, there are scenarios in which costs in China fall more rapidly than expected. Such cost declines would require growing efforts to use domestically sourced materials in the upstream and to scale up manufacturing; support for the large-scale application of PEM electrolyzers in coupling with variable renewable power which is crucial for reducing renewable curtailment in China; and more aggressive Government objectives for developing PEM electrolysers (see Section 3).[220]

Figure 8: The decreasing trend of the average prices of PEM electrolyzers made both abroad and in China (10,000 yuan/MW)



Source: Author's own, based on reports produced by consultancy or securities companies[221]

6.3 PV achieved fast cost reductions through massive manufacturing, while cost reductions in electrolysers are more complex.

Considering this, China's mature manufacturing-intensive innovation system[222] – competitive in rapidly scaling up manufacturing for cost declines – may not help electrolyzer manufacturers achieve much of a cost advantage in the future global electrolyzer market. Indeed, China's ecosystem equips electrolyzer manufacturers to fully use domestic industrial capacities for large-scale manufacturing, compared with the early manufacturing of solar PV. It has enabled significant cost reductions for alkaline electrolyzers and allowed the country to keep pace with the global trend of reducing costs for PEM electrolyzers.

However, China's manufacturing still lags behind in areas such as automated production lines. Moreover, electrolyzers consist of systems and components, and their cost reduction is influenced not only by innovations in the manufacturing process but also by factors such as the performance of those systems and elements and their design.[223] Even with large and rapid manufacturing in China, capitalizing on lower manufacturing costs, low electricity prices, and the potential for deployment, the extent to which Chinese electrolysis can be equally competitive abroad is another open question. In addition, the international context in which Chinese companies operate is vastly different.

7. Capturing Global Market Share: Internationalization of Solar PV and Renewable Hydrogen

The export potential for electrolyzers, and the international trade components of the hydrogen supply chain in general, differ substantially from the pathway taken by solar. As discussed in Section 2.1, the early development of China's solar PV industry was stimulated by growing overseas demand for solar PV, in particular prompted by EU policymakers' focus on renewable energy development after 2000.[224] For example, the introduction of the first German Feed-in-Tariff for solar in 2000 created a huge market for solar PV systems and thus laid the foundation for China's boom in its solar PV manufacturing industry.[225] Since 2004, there had been a steady rise in exports of PV equipment.[226] To meet the demand, China's solar manufacturers significantly augmented solar PV output during the period 2003 to end-2005. By end-of 2005, solar cell production capacity exceeded 300 MW.[227] Furthermore, central policy initiatives were geared towards the promotion of exports as well,[228] as part of the broader 'Going Out' policy adopted in 2000.[229] This policy encouraged domestic companies, including energy companies, to expand into overseas markets.[230] Also, companies that exported equipment for solar power generation received tax rebates.[231]

Electrolysis industry exports are part of China's international hydrogen cooperation efforts.[232] For example, in 2021, State Power Investment Corporation (SPIC) and its Brazilian subsidiary signed a US$3.5 million MOU with Brazil's Center for Energy Research for R&D in renewable-electricity-based hydrogen.[233] The renewable hydrogen produced in this project will be used for energy storage and in the production of ammonia and fertilizers in Brazil rather than being exported back to China.[234] Similarly, the *Declaration on China-Africa Cooperation on Combating Climate Change* (2021) includes calls for both China and Africa to provide an investment-friendly environment and financial support for renewable hydrogen projects without disclosing specific investment promotion measures or specific financing amounts.[235]

While there is no explicit policy guidance for exporting electrolyzers, the Chinese government promotes the export of technology, services and equipment to foreign renewable energy projects. The aim is to help domestic energy companies play a role in global renewable energy supply chains and enhance China's influence in global energy markets, as stated in the *Energy Production and Consumption Transition Strategy (2016–2030)*.[236] Already, China's top electrolyzer manufacturers (see Table 2) such as PERIC Hydrogen Technologies, Cockerill Jingli Hydrogen, and Shandong Saikesaisi, are exporting alkaline electrolyzers to overseas markets.[237]

With governments worldwide constantly implementing measures to stimulate demand for renewable hydrogen (like, subsidies for its use), demand for electrolyzers will steadily increase.[238] Despite this, the market is currently oversupplied for alkaline electrolyzers[239] both in China, where companies are seeking opportunities abroad, and globally.[240] In 2022, while the global manufacturing capacity increased by 25 per cent, globally installed electrolyzer capacity only saw a 20 per cent increase.[241] The IEA predicted in September 2023 that new electrolysis manufacturing capacity would reach 5 GW/yr in 2023, while newly installed capacity would rise by 1.1 GW.[242]

In addition, China's electrolyzer exports could also suffer from trade barriers imposed by the US and the EU on Chinese-manufactured goods like solar panels and electric vehicles,[243] for instance the EU's 25 per cent limit on Chinese electrolyzers.[244] These trade barriers take various forms, such as increasing import tariffs or investigations into subsidies provided by the Chinese government.

So, while tax rebates, overseas demand, and the availability of turnkey production lines from international manufacturers allowed the Chinese solar PV industry to catch up with global solar development and gradually begin to export solar cells, the outlook for electrolysis exports is more challenging. Even though there is broad policy support under the 'Going Out' policy and other policies on exporting energy-related products, there are currently no tax rebates for electrolyzer exports. Moreover, the global market is currently oversupplied meaning that protectionist policies could limit Chinese exports, at least to economies that have been early adopters of industrial policies aimed at promoting renewable hydrogen.

Text Box: Export models – solar PV vs electrolyzers

Solar PV: The rise and fall of Wuxi Suntech

With local government support, privately-owned solar PV companies grew rapidly since 2002,[245] many in association with and support from local governments.[246] Suntech in Wuxi was one of the pioneers of China's solar PV industry at the early stage, and as a private company it made use of local government support to expand its shares in foreign solar PV markets.

Suntech was created in 2001 by solar cell expert Zhengrong Shi, with 75 per cent of the company's shares were owned by the Wuxi government.[247] Similar to other first-wave start-ups, Suntech continuously persuaded local governments of the advantages (for instance, the reorientation of Wuxi's economy to high-tech industrial development[248]) of establishing PV manufacturing facilities.[249] To help *the company establish low-cost operations, the Wuxi government granted preferential land-use and tax set-up for the company, allocated substantial start-up grants, and secured a cheap preferential loan of Yuan 100 million.[250] Between 2003 and 2004, the Wuxi government also helped the company compete for national research funds which amounted to more than Yuan 40 million.[251]*

In 2002 Suntech started operating the nation's first production line for solar cells.[252] It was listed on the New York Stock Exchange in 2005,[253] and duly became the world's largest manufacturer of solar PV panels.[254] However, the company went bankrupt in 2013, due to global overcapacity of solar PV, anti-subsidy investigations raised by the EU and US, heavy debts, and more importantly, weak corporate management that heavily relied on government financing.[255] Suntech could not innovate its management and products only by relying on the Wuxi government.[256] The Wuxi government, in turn, did not bail it out because it could not reach an agreement with Zhengrong Shi on how to save the company.[257] Before its bankruptcy, Suntech had reportedly exported more than 13,000,000 solar panels to over 80 states[258] such as Germany, Japan and the US.[259] Arguably, the export tax rebate played a crucial role in incentivizing these exports, significantly improving the profitability and business prospects of the company.[260]

China Energy Engineering Corporation Limited (CEEC) and LONGi

Unlike in solar PV, the hydrogen space in China is dominated by a combination of SOEs and POEs carrying out demonstration projects for renewable hydrogen development and exporting electrolyzers to foreign markets. Projects have to date been initiated by China Energy Engineering Corporation Limited (CEEC), a subsidiary of China Energy Corporation, one of the country's largest power equipment SOEs and a pioneer in overseas hydrogen investments.[261] Another leader in international projects is solar PV company LONGi, which is now also investing in electrolyzer development.[262]

In 2022, CEEC's international subsidiary signed an MOU with the Egyptian New Energy Authority, the Suez Canal Economic Zone Authority, a number of sovereign wealth funds, and power transmission companies to jointly develop a renewable hydrogen project in Egypt.[263] CEEC will export the equipment, services and technologies.[264] Its international arm also plans renewable hydrogen projects in Morocco and Brazil, relying on CEEC's renewable hydrogen production equipment.[265] For CEEC then, electrolyzer exports will be part of its overseas hydrogen projects.[266]

China's private equipment manufacturers, such as LONGi, have signed supply contracts for electrolyzers but also intend to export electrolyzers as part of SOE projects.[267] In July 2023, LONGi signed its first electrolyzer supply contract with India,[268] later expanding into the Australian market.[269] In January 2024, LONGi successfully won a bid to provide electrolyzers for a renewable hydrogen project led by Power China Co. Ltd., a subsidiary of another central SOE – Power Construction Corporation of China – in Uzbekistan.[270] Likewise, it is reported that the leadership of CEEC had regular meetings with the CEO of LONGi,[271] and that a research branch of CEEC signed a cooperation agreement with LONGi.[272] Moreover, in 2023, LONGi successfully bid to provide electrolyzers to the planned hydrogen projects invested in by CEEC in 2024.[273] It is very likely that LONGi will be eligible for providing electrolyzers for CEEC's foreign hydrogen projects.

Electrolysis exports are currently taking place as part of larger projects for the most part, given that alkaline electrolyzers made in China are cost competitive. For instance, in December 2023, CEEC launched a centralized procurement tender for electrolyzers to supply its renewable hydrogen projects in China and abroad in 2024. The successful bids in CEEC's tender averaged $210,000/MW, three to five times lower than the global average of $700,000 to $1,100,000/MW.[274]

8. Conclusion

The Chinese government's support for its renewable hydrogen industry and progress to date in lowering electrolyzer costs in China have led to hopes and concerns in the West. The hope is that Chinese companies' leadership in electrolyzer manufacturing will contribute to accelerating the clean energy transition worldwide. The challenge, however, is that competitors based in Europe and the US could lose market share, like they did when China scaled up the production of solar PV and came to dominate global markets.

But before assuming that China will achieve similar cost reductions in electrolysis, the comparison needs to be unpacked and questioned. The scale up and cost declines in solar PV in China, at its initial stages, were achieved through a combination of private sector innovation in a manufacturing-intensive technology, local government support, and an enabling external environment. Indeed, solar PV began as an export-oriented industry, which, when faced with trade defence measures globally, expanded with central government support to become a domestic-market serving industry. Given the size of production – and in light of domestic overcapacity – costs decreased rapidly, allowing exports to remain high even as a number of manufacturers went bankrupt. Unlike many common perceptions, the solar industry gained recognition as a 'strategic emerging industry' only later on in its development.

Meanwhile, even though hydrogen development in China started as far back as the mid-1980s, it has yielded limited results, largely related to the policy focus on FCVs. This changed markedly in 2016 when Beijing recognised renewable hydrogen and electrolyzer manufacturing as strategic emerging industries. There is now considerable government support for electrolysis manufacturing in China which has enabled significant cost reductions for alkaline electrolyzers and made it possible for Chinese manufacturers to catch up in proton exchange membrane (PEM) electrolyzers.

But as this paper argues, PEM electrolyzers are less likely to achieve the same significant cost declines and global market share as solar PV did for a number of reasons. First, the complexity of electrolysis systems can make it harder to achieve similar cost reductions to solar PV because it limits learning rates and potential cost declines. The components in electrolysis systems each have their own distinct learning rates and cost declines, making the overall assessment of cost declines more complicated.

Government support can help manufacturers to mitigate risks at the early stage of R&D and expand manufacturing. It has also enabled the creation of a manufacturing innovation system that enables Chinese companies to evolve from technology catch-up to taking leading positions in some clean energy technologies.[275] China's solar PV prices fell to global levels in 2007 and then continued to decline through 2023, extending and exceeding expected cost declines[276] in large part due to standardized equipment and economies of scale from mass production, but also due to efficiency enhancements and innovations in the manufacturing process. But as argued here, electrolysis is not just a manufacturing-intensive sector.

In addition, unlike in solar PV, the cost reductions in electrolyzers are only one factor in the final price of renewable hydrogen, which also depends on the cost of renewable electricity inputs. This implies that rapid cost reductions in electrolyzers may not be sufficient to bring renewable hydrogen to a price level enabling parity with fossil-fuel-based hydrogen or other energy sources, at least within the next decade.

Other factors distinguish the path of China's PV sector from the future path of China's hydrogen industry. China's solar PV sector benefitted from open markets, investments, and foreign technology transfers. Chinese manufacturers imported turnkey production lines and relatively standardized equipment and subsequently innovated the manufacturing process. But innovation in electrolysis systems requires feedback from application and deployment, in addition to learning in the manufacturing process.

The shifting international landscape also presents challenges for technology transfers as well as for electrolyzer exports. At the early stage of solar PV development, global trade was more open to China, and European policies to promote renewables meant demand for PV exceeded supplies. Now, the energy transition has been recognized as a crucial strategy, but it has also become more politicized and securitized, intertwining with domestic industrial policies to ensure local competitiveness. While China's ambition for developing renewable hydrogen and electrolyzers provides business opportunities for foreign energy companies,[277] the securitization of existing economic relations can prevent foreign companies from investing in China's hydrogen sector or may extend protectionist measures on Chinese electrolyzers.[278] The securitization of China's engagement in global clean energy supply chains may increase the costs of adopting clean energy technologies and thus lead to cost inefficiencies of the global energy transition.[279] Furthermore, the global overcapacity for electrolyzers, possibly due to the slow deployment of planned renewable hydrogen investments hydrogen,[280] is an additional barrier to China's electrolyzer exports.

In sum, there exist major differences in the future path of renewable hydrogen in China as compared with the past trajectory of solar PV. Technology complexity, China’s relative weakness in PEM electrolyzers, and the domestic focus of the country’s renewable hydrogen strategy all differentiate this market from that of solar PV in past decades. While rapid cost reductions are possible, this appears unlikely to lead to the type of market dominance achieved by China in the solar PV space.

Endnotes

---

[1] Yuki (2021), 'China's Electrolysis Market: Would it Repeat Solar' Success Story?', *Energy Iceberg*, 22 September 2021, accessed on 4 April 2024 at https://energyiceberg.com/china-electrolysis-market/; Ouyang, A. (2023), 'Can China Make Hydrogen Electrolyzers Cheap as It Did for Solar?', *MarcoPolo*, 16 October 2023, accessed on 4 April 2024 at https://macropolo.org/china-hydrogen-electrolyzers-cheap-solar/?rp=e; Collins, L. (2022), 'Chance Is High That China Will Take Over Global Hydrogen Electrolyser Market In Similar Way To Solar Sector', *RECHARGE*, 2 June 2022, accessed on 28 April 2024 at https://www.rechargenews.com/energy-transition/exclusive-chance-is-high-that-china-will-take-over-global-hydrogen-electrolyser-market-in-similar-way-to-solar-sector-bnef/2-1-1230106. For Chinese subsidies, see Oleksandra Mamchii, O. (2023), 'The Rise of China in the Solar Industry: A Global Revolution', *Best Diplomats*, 2 October 2023, accessed on 28 March 2024 at https://bestdiplomats.org/why-china-is-dominating-the-solar-industry/; Allison, G. (2023) 'China's Dominance of Solar Poses Difficult Choices for the West', *Financial Times*, 22 June 2023, accessed on 1 February 2024 at https://www.ft.com/content/fd8e7175-9423-4042-a6f7-c404afdfcda4.

[2] See Dodwell, D. (2024), 'Someday Soon China Might Dominate the Hydrogen Supply Chain Too', *South China Morning Post*, 28 April 2024, accessed on 15 January 2024 at https://www.scmp.com/opinion/china-opinion/article/3260668/someday-soon-china-might-dominate-hydrogen-supply-chain-too.

[3] Yang, Y., Hui Gao, H. (2020), '中国氢能产业发展的认识与建议 [Viewpoints and Suggestions on the Hydrogen Energy Industry Development in China]', 27 (6) *World Petroleum Industry* 13. '氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', National Development and Reform Commission (NDRC), 23 March 2022.

[4] '盘点中国氢能 20 年发展历程 [The Review of 20-Year Hydrogen Development in China]', *China Buses*, 15 December 2021, accessed on 15 June 2024 at https://m.chinabuses.com/news/14/article_100433.html.

[5] Yang, Y., Hui Gao, H. (2020), '中国氢能产业发展的认识与建议 [Viewpoints and Suggestions on the Hydrogen Energy Industry Development in China]', 27 (6) *World Petroleum Industry* 13; '氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', NDRC, 23 March 2022.

[6] '探索光伏利润变化及未来发展空间 [Exploring its Profit Change and Future Development]', *iResearch*, 2023, accessed on 10 January 2024 at https://report.iresearch.cn/report/202303/4160.shtml; Sun, H. et al. (2014), 'China's Solar Photovoltaic Industry Development: The Status Quo, Problems and Approaches', 18 *Applied Energy* 221, pp. 222-225; Jackson, M. M., Lewis, J. I., and Zhang, X. (2021), 'A Green Expansion: China's Role in The Global Deployment and Transfer of Solar Photovoltaic Technology', 60 *Energy for Sustainable Development* 90.

[7] Quitzow, R. (2015), 'Dynamics of A Policy-Driven Market: The Co-Evolution of Technological Innovation Systems for Solar Photovoltaics in China and Germany', 17 *Environmental Innovation and Societal Transitions* 126, p. 139; de la Tour, A., Glachant, M., and Ménière, Y. (2011), 'Innovation and International Technology Transfer: The Case of The Chinese Photovoltaic Industry', 39 *Energy Policy* 761, pp. 763-5.

[8] Chen, G. (2015), 'China's Solar PV Manufacturing and Subsidies from the Perspective of State Capitalism', 33 (1) *The Copenhagen Journal of Asian Studies* 90, p. 94; Brandt, L., Wang, L. (2019)

‘China’s Development of Wind and Solar Power’ in Loren Brandt and Thomas G. Rawski (eds) *Policy, Regulation and Innovation in China’s Electricity and Telecom Industries*, Cambridge University Press, 2019, pp. 373-418, p. 378.

[9] ‘新能源基本建设项目管理的暂行规定 [Interim Regulations on Managing Basic Construction Projects for New Energy]’, State Planning Commission, 1997.

[10] Chen, T. (2016), ‘The Development of China’s Solar Photovoltaic Industry: Why Industrial Policy Failed’, 40 (3) *Cambridge Journal of Economics* 755, p. 760.

[11] ‘关于印发可再生能源发展’十一五’规划的通知:送电到乡 [The Notice on Adopting the 11th Five-Year Plan for Renewable Energy Development: Transmitting Electricity to Countryside]’, NDRC, 2008.

[12] Sun, H. et al. (2014), ‘China’s Solar Photovoltaic Industry Development: The Status Quo, Problems and Approaches’, 118 *Applied Energy* 221, p. 222.

[13] Chen, G., Lees, C. (2016), ‘Growing China’s Renewables Sector: A Developmental State Approach’, *New Political Economy* 1, p. 8; Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, 74.

[14] Zhang, F., Gallagher, F. S. (2016), ‘Innovation and Technology Transfer Through Global Value Chains: Evidence from China’s PV Industry’, 94 *Energy Policy* 191, p. 195.

[15] Yu, J., Wang, Y., (2020), ‘中国光伏产业的发展与’一带一路’的新机遇 [Development of the PV Industry in China and New Opportunities from the Analysis from the Perspective of New Structural Economics]’, 40 (5) *Journal of Xi’an Jiaotong University* (Social Sciences) 87.

[16] Hu,Y. (2018), ‘光伏行业发展回顾及展望 [The Past and the Future of the Solar PV Industry]’, *Huachuang Securities*, 26 June 2018, accessed on 4 April 2024 at https://www.vzkoo.com/document/f1990b47255dbaa9363ec60044540644.html.

[17] Li, B., Ma, S., ‘关于加速开拓中国国内光伏市场的激励政策与措施的研究及建议 [Research and Recommendations on Incentive Policies and Measures to Accelerate the Development of China’s Domestic PV Market]’, *Energy Foundation China*, May 2009.

[18] Hopkins, M., Li, Y. (2016), ‘The Rise of the Chinese Solar Photovoltaic Industry: Firms, Governments, and Global Competition’ in Yu Zhou et al. (ed.) *China as an Innovation State*, Oxford University Press, pp. 306-32.

[19] Wang, Q. (2010), ‘Effective Policies for Renewable Energy—The Example of China's Wind Power—Lessons for China’s Photovoltaic Power’, 14 *Renewable and Sustainable Energy Reviews* 702, p. 709.

[20] Wang, Q. (2010), ‘Effective Policies for Renewable Energy—The Example of China's Wind Power—Lessons for China’s Photovoltaic Power’, 14 *Renewable and Sustainable Energy Reviews* 702; Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 75.

[21] Chen, T. (2016), ‘The Development of China’s Solar Photovoltaic Industry: Why Industrial Policy Failed’, 40 (3) *Cambridge Journal of Economics* 755; Chen, G. (2015), ‘China’s Solar PV Manufacturing and Subsidies from the Perspective of State Capitalism’, 33 (1) *The Copenhagen Journal of Asian Studies* 90, p. 94.

[22] Y, Jon. (2022), ‘How China Won the Solar Industry (& Why Germany Lost)’, *The Asianometry Newsletter*, 10 June 2022, accessed on 30 August 2024 at https://www.asianometry.com/p/how-china-won-the-solar-industry.

[23] Puttaswamy, N., Sahil Ali, M. S. (2015), ‘How Did China become the largest Solar PV Manufacturing Country?’, CSTEP, 6 September 2015, accessed on 30 August 2024 at https://cstep.in/drupal/sites/default/files/2019-07/CSTEP_WS_china_largest_solar_PV_2015.pdf.

[24] He, N., Fabio Couto, F. Jr., (2017), ‘Can Brazil Replicate China’s Success in Solar?’, *Dialogchino*, 17 June 2017, accessed on 7 May 2024 at https://dialogue.earth/content/uploads/2017/06/Can-Brazil-replicate-Chinas-successful-solar-industry-EN.pdf.

[25] Zhi, Q. et al. (2014), ‘China’s Solar Photovoltaic Policy: An Analysis Based on Policy Instruments’, 129 *Applied Energy* 308, pp. 311-2.

[26] ‘中华人民共和国国民经济和社会发展第十一个五年规划纲要 [The 11th Five-Year Plan for Economic and Social Development]’, State Council, 2006.

[27] ‘国家中长期科学和技术发展规划纲要（2006–2020 年）[National Mid-and-Long Term Plan for Science and Technology Development]’, State Council, 2005.

[28] ‘国家发展改革委关于印发高技术产业化’十一五’规划的通知 [The Notice on Adopting the 11th Five-Year Plan for Industrializing High Technologies]’, NDRC, 2007.

[29] Zhi, Q. et al. (2014), ‘China’s Solar Photovoltaic Policy: An Analysis Based on Policy Instruments’, 129 *Applied Energy* 308, p. 314.

[30] ‘中华人民共和国可再生能源法 [The PRC Renewable Energy Law], 2006; ‘可再生能源中长期发展规划 [The Mid-and-Long Term Plan for Renewable Energy Development]’, NDRC, 2007.

[31] Yu, J., Wang, Y., (2020), ‘中国光伏产业的发展与’一带一路’的新机遇 [Development of the PV Industry in China and New Opportunities from the Analysis from the Perspective of New Structural Economics]’, 40 (5) *Journal of Xi’an Jiaotong University* (Social Sciences) 87.

[32] Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 74.

[33] Chen, T. (2016), ‘The Development of China’s Solar Photovoltaic Industry: Why Industrial Policy Failed’, 40 (3) *Cambridge Journal of Economics* 755.

[34] ‘国务院关于加快培育和发展战略性新兴产业的决定 [The Decision on Accelerating the Foster and Development of Strategic Emerging Industries]’, State Council, 2010.

[35] ‘太阳能发电发展’十二五’规划 [The 12th Five-Year Plan for Solar Power Development]’, National Energy Administration (NEA), 2013.

[36] ‘探索光伏利润变化及未来发展空间 [Exploring its Profit Change and Future Development]’, *iResearch*, 2023, accessed on 10 January 2024 at https://report.iresearch.cn/report/202303/4160.shtml; He, N., Fabio Couto, F. Jr., (2017), ‘Can Brazil Replicate China’s Success in Solar?’, *Dialogchino,* 17 June 2017, accessed on 7 May 2024 at https://dialogue.earth/content/uploads/2017/06/Can-Brazil-replicate-Chinas-successful-solar-industry-EN.pdf.

[37] ‘关于开展大型并网光伏示范电站建设有关要求的通知 [The Notice on the Requirements for Developing Large-Scale Grid-Connected PV Demonstration Power Stations]’, NDRC, 2007.

[38] ‘关于实施金太阳示范工程的通知 [The Notice on Implementing the Golden Sun Projects]’, Ministry of Finance (MOF), Ministry of Science and Technology (MOST) and NEA, 2009.

[39] ‘国家发展改革委关于完善太阳能光伏发电上网电价政策的通知 [Notice on Perfecting Feed-in Tariff

Policy of Solar PV Power Generation], NDRC, 2011.

[40] ‘China to Set Solar Feed-In Tariff by Year-End’, *REVE*, 24 August 2009, accessed on 15 June 2024 at https://www.evwind.es/2009/08/24/china-to-set-solar-feed-in-tariff-by-year-end/942. See however, Lin. B., Wesseh, P. K. Jr, (2013), ‘Valuing Chinese Feed-In Tariffs Program For Solar Power Generation: A Real Options Analysis’, 28 *Renewable and Sustainable Energy Reviews* 474 (2013); ‘Renewable Energy Feed-In Tariffs’, *OECD Statistics*, Data extracted on 15 Jun 2024 at https://stats.oecd.org/Index.aspx?DataSetCode=RE_FIT.

[41] ‘关于 2018 年光伏发电有关事项的通知 [Notice on Matters Related to Photovoltaic Power Generation in 2018]’, NEA, 2018.

[42] ‘关于积极推进风电、光伏发电无补贴平价上网有关工作的通知 [The Notice on Actively Promoting the Work Concerning Subsidy-free Grid Parity for Wind Power and Solar Power Generation], NDRC and NEA, 2019.

[43] ‘探索光伏利润变化及未来发展空间 [Exploring its Profit Change and Future Development]’, *iResearch*, 2023, accessed on 10 January 2024 at https://report.iresearch.cn/report/202303/4160.shtml

[44] ‘长三角兴起’新能源革命 [New Energy Revolution in Yangtze River Delta]’, *the Central Government of People’s Public of China*, 21 October 2005, accessed on 6 May at https://www.gov.cn/ztzl/2005-10/21/content_81245.htm; Pearce, J.M. (2008), ‘Industrial Symbiosis of Very Large-Scale Photovoltaic Manufacturing’, 33(5) *Renewable Energy* 1101.

[45] Brandt, L., Wang, L. (2019) ‘China’s Development of Wind and Solar Power’ in Loren Brandt and Thomas G. Rawski (eds) *Policy, Regulation and Innovation in China’s Electricity and Telecom Industries*, Cambridge University Press, 2019, pp. 373-418, p. 393.

[46] ‘国内外提高光伏发电效率最新成果 [The Latest Achievements In Improving Photovoltaic Power Generation Efficiency At Home And Abroad]’, *Sohu News*, 7 February 2024, accessed on 15 June 2024 at https://www.sohu.com/a/756933425_121123895.

[47] ‘太阳能电池板的转化率 [The Conversion Efficiency for Solar Cells], *Guang Fu Fa Dian*, 18 August 2023, accessed on 6 May 2024 at https://www.75xn.com/27160.html.

[48] Liang, X. et al. (2023), ‘周期、成长共振，光伏 20 年回顾及展望 [Twenty-Year Development of the Solar PV Industry]’, *Orient Securities*, 10 February 2023, accessed on 5 June 2024 at https://pdf.dfcfw.com/pdf/H3_AP202302131583073061_1.pdf.

[49] Wu, M. (2023), ‘我国氢能产业商业化探索前景及挑战 [Prospects and Challenges for Hydrogen Industry Development in China]’, *China Energy News*, 12 May 2023, accessed on 28 March 2024 at https://www.cpnn.com.cn/news/baogao2023/202305/t20230531_1605570.html.

[50] ‘从纯电动走过 12 年看燃料电池发展阶段 [Examining the Development Stages of Fuel Cells Through 12 Years of Pure Electric Vehicles]’, *Pearl Hydrogen*, 25 September 2021, accessed on 8 June 2024 at http://www.pearlhydrogen.com/html/zh-detail-143.html; Zhang, X. (2023), ‘中国新能源汽车的跨越式发展之路 [China’s Leapfrog Development Path of New Energy Vehicles]’, *Economic Herald*, 18 May 2023, accessed on 8 June 2024 at www.jingjidaokan.com/icms/null/null/ns:LHQ6LGY6LGM6MmM5ZTg0ZWI4NDM3MjI1MjAxODgyY2RiNTIwMDAwYWIscDosYTosbTo=/show.vsml.

[51] ‘盘点中国氢能 20 年发展历程 [The Review of 20-Year Hydrogen Development in China]’, *China*

Buses, 15 December 2021, accessed on 15 June 2024 at https://m.chinabuses.com/news/14/article_100433.html.

52 '氢能在我国能源转型中的地位和作用任重道远 [The Crucial Role of Hydrogen in China's Energy Transition]', *Sina Finance*, 26 October 2021, accessed on 22 June 2024 at https://finance.sina.cn/esg/2021-10-27/detail-iktzqtyu3662150.d.html?from=wap.

53 '国家中长期科学和技术发展规划纲要（2006–2020 年）[National Mid-and-Long Term Plan for Science and Technology Development]', State Council, 2005.; Yang, Y., Hui Gao, H. (2020), '中国氢能产业发展的认识与建议 [Viewpoints and Suggestions on the Hydrogen Energy Industry Development in China]', 27 (6) *World Petroleum Industry* 13.

54 Tu, K. (2020), 'Prospects of A Hydrogen Economy with Chinese Characteristics', études de l'Ifri, October 2020, accessed on 15 June 2024 at chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ifri.org/sites/default/files/migrated_files/documents/atoms/files/tu_china_hydrogen_economy_2020_1.pdf.

55 '盘点中国氢能 20 年发展历程 [The Review of 20-Year Hydrogen Development in China]', *China Buses*, 15 December 2021, accessed on 15 June 2024 at https://m.chinabuses.com/news/14/article_100433.html.

56 '关于加快发展湖北省氢能产业的建议 [Suggestions on Accelerating the Development of Hydrogen Industry in Hubei]', Hubei DRC, 8 May 2021; '燃料电池汽车相关政策标准形势分析 [Analysis on the Status, Policies and Standards for FCVs]', *China Association of Automobile Manufacturers*, 23 April 2021, accessed on 15 June 2024 at http://www.caam.org.cn/chn/38/cate_417/con_5233668.html.

57 Nakono, J. (2022), 'China Unveils its First Long-Term Hydrogen Plan', *Center for Strategic and International Studies*, 28 March 2022, accessed on 8 June 2024 at https://www.csis.org/analysis/china-unveils-its-first-long-term-hydrogen-plan.

58 '十三五'国家战略性新兴产业发展规划 [The 13th Industrial Development Plan of Strategic Emerging Industries]', State Council, 2016.

59 '十三五'国家战略性新兴产业发展规划 [The 13th Industrial Development Plan of Strategic Emerging Industries]', State Council, 2016.

60 '能源技术革命创新行动计划 (2016–2030) [the Action Plans of Energy Technological Revolution and Innovation (2016-2030)]', NDRC and NEA, 2016.

61 '能源技术革命创新行动计划 (2016–2030) [the Action Plans of Energy Technological Revolution and Innovation (2016-2030)]', NDRC and NEA, 2016.

62 '十四五能源领域科技创新规划 [The 14th Five-Year Plan of Energy Technology Innovation]', NEA and MOST, 2022.

63 Wu, M. (2023), '我国氢能产业商业化探索前景及挑战 [Prospects and Challenges for Hydrogen Industry Development in China]', *China Energy News*, 12 May 2023, accessed on 28 March 2024 at https://www.cpnn.com.cn/news/baogao2023/202305/t20230531_1605570.html.

64 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', NDRC, 23 March 2022.

65 '十四五能源领域科技创新规划 [The 14th Five-Year Plan of Energy Technology Innovation]', NEA and MOST, 2022.

[66] ‘北京市氢能产业发展实施方案(2021–2025 年) [The Implementation Plans of the Hydrogen Development Plan in Beijing (2021–2025)]’, Beijing Municipal Bureau of Economy and Information Technology, 2021; ‘深圳市氢能产业发展规划 (2021-2025 年) [Shenzhen Hydrogen Industrial Development Plan 2021–2025], Shenzhen DRC, 2021.

[67] ‘常熟市氢燃料电池产业发展规划 (2021-2030 年) [Industrial Development Plans of Hydrogen Fuel Cells 2021-2030]’, Changshu Municipal People’s Government, 2021.

[68] ‘常熟市氢燃料电池产业发展规划 (2021-2030 年) [Industrial Development Plans of Hydrogen Fuel Cells 2021-2030]’, Changshu Municipal People’s Government, 2021; ‘北京市氢能产业发展实施方案 (2021–2025 年) [The Implementation Plans of the Hydrogen Development Plan in Beijing (2021–2025)]’, Beijing Municipal Bureau of Economy and Information Technology, 2021.

[69] ‘宁波市人民政府办公厅关于加快氢能产业发展的若干意见 [Several Opinions on Accelerating Hydrogen Industrial Development]’, Ningbo Municipal People’s Government, 2021.

[70] ‘Water Electrolysis and Hydrogen: Growing Deployment Prospects in Europe And Beyond’, *EU Commission,* 24 November 2023, accessed on 7 April 2024 at https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/water-electrolysis-and-hydrogen-growing-deployment-prospects-europe-and-beyond-2023-11-24_en; Martin, P. (2023), ‘Which Type of Electrolyzer Should You Use? Alkaline, PEM, Solid Oxide or The Latest Tech?’, *Hydrogen Insight*, 5 July 2023, accessed on 7 April 2024 at www.hydrogeninsight.com/electrolysers/green-hydrogen-which-type-of-electrolyser-should-you-use-alkaline-pem-solid-oxide-or-the-latest-tech-/2-1-1480577.

[71] ‘氢能源：痛点和机会 [Hydrogen Energy: Challenges and Opportunities]’, *Haitong Securities*, 28 December 2021.

[72] ‘中华人民共和国能源法草案征求意见稿 [The Energy Law of the People’s Republic of China (Draft for Opinions)]’, National People’s Congress, 2020.

[73] ‘危险化学品安全管理条例 [Regulations on the Safety Management of Hazardous Chemicals]’, National People’s Congress, 2002, amended in 2011.

[74] ‘危险化学品安全管理条例 [Regulations on the Safety Management of Hazardous Chemicals]’, National People’s Congress, Articles 6 (1) and (3).

[75] ‘传统危化品管理的’氢’规戒律待破 [To Break the Perception of Hydrogen by Law as A Dangerous Chemical]’, *China Association of Automobile Manufacturers*, July 2019, accessed on 8 June 2024 at http://www.caam.org.cn/chn/8/cate_82/con_5224986.html.

[76] Meidan, M. (2021), ‘China’s Emerging Hydrogen Strategy and the 2060 Net Zero Commitment’, 127 *Oxford Energy Forum* 56.

[77] ‘《危险化学品目录》 (2022 调整版) [Catalogue of Hazardous Chemicals (2022)]’, Ministry of Emergency Management, 2022.

[78] ‘十四五现代能源体系规划 [The 14th Five-Year Plan of Modern Energy System]’, NDRC and NEA, 2022; 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]’, NDRC, 23 March 2022.

[79] 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]’, NDRC, 23 March 2022; ‘Green Hydrogen in China: A Roadmap for Progress’, *The World Economic Forum*, 2023, accessed on 8 June 2024 at https://www.weforum.org/publications/green-hydrogen-in-china-a-

roadmap-for-progress/.

80 Wang, A. M. (2023), ‘China’s Hydrogen Development: A Tale of Three Cities’, OIES, March 2023; Gong, X., Quitzow, R., and Boute, A. (2023), ‘China’s Emerging Hydrogen Economy: Policies, Institutions and Actors’, *Research Institute for Sustainability Studies*, January 2023.

81 *国际氢能技术与产业发展研究报告 2023 [International Hydrogen Technology and Industry Development Research Report 2023]*, China Industry Promotion Association – Hydrogen Association, 2023.

82 ‘十四五可再生能源规划 [The 14th Five-Year Plan of Renewable Energy Development]’, NEA, 2021.

83 ‘中国绿色氢项目分布地图 [The Map of the Layout of Renewable Hydrogen Projects in China]’, *OFWEEK*, 8 April 2024, accessed on 19 June 2024 at https://m.ofweek.com/hydrogen/2024-04/ART-180826-8440-30631071.html.

84 ‘河北省推进氢能产业发展实施意见 [Implementation Opinions on Promoting Hydrogen Industry Development in Hebei]’, Hebei DRC, 2019; ‘内蒙古自治区十四五氢能发展规划 [The 14th Five-Year Hydrogen Energy Development Plan]’, Inner Mongolia Energy Bureau, 2022.

85 Note: Different institutions have different calculation methods. See e.g., ‘Green Hydrogen in China: A Roadmap for Progress’, *The World Economic Forum*, 2023. Currently, the production costs of coal-based hydrogen and gas-based hydrogen respectively are 10.1 - 13.4 yuan/kg and 13.4 - 16.8 yuan/kg. ‘我国不同制氢技术成本有多高？[How High Are the Costs of Different Hydrogen Production Technologies in China?]’, *West Securities*, 4 July 2023, accessed on 22 March 2024 at http://www.tanpaifang.com/xinnengyuan/2023/0704/98357.html.

86 ‘山东省人民政府印发关于促进实体经济高质量发展的实施意见政策清单（第二批）的通知 [The Notice on the Second List of Support Policies for Making Steady Progress and Achieving High-Quality Development in 2022]’, The Provincial Government of Shandong, 2022; ‘河北省氢能产业安全管理办法(试行) [Safety Management Measures of the Hydrogen Industry in Hebei Province (Trial Implementation)]’, Provincial Government of Hebei, 2023, Article 9.

87 ‘新疆石河子首个绿氢制加一体站和氢能重卡投运 [Xinjiang Shihezi's First Green Hydrogen Production and Refueling Station and Hydrogen-Powered Heavy Trucks Put into Operation]’, *BJX Hydrogen*, 15 January 2024, accessed on 6 May 2024 at https://m.bjx.com.cn/mnews/20240115/1355887.shtml; Zhang, S. (2023), ‘安徽首个制氢加氢一体站经营许可证发放 [Anhui's First Hydrogen Production and Refueling Station Operating License Issued]’, *People’s News*, 27 November 2023, accessed on 6 May 2024 at http://paper.people.com.cn/zgnyb/html/2023-11/27/content_26029846.htm; Yu, H. (2024), ‘全国最大绿电制氢加氢一体站建成 [The Nation's Largest Green Power Hydrogen Production and Refueling Station Completed]’, *People’s Finance*, 26 March 2024, accessed on 6 May 2024 at http://finance.people.com.cn/n1/2024/0326/c1004-40203386.html.

88 ‘中国石化质子交换膜电解水制氢示范项目平稳运行 [The Smooth Operation of the Demonstration Project for PEM Electrolyzer – Renewable Hydrogen Production]’, *Sinopec*, 13 March 2023, accessed on 15 February 2024 at http://www.sinopecgroup.com/group/000/000/060/60406.shtml.

89 ‘中国制氢行业短报告 [The Short Report on China's Hydrogen Production Industry]’, *Yidu Data*, 2023, accessed 1 January 2024 at https://pdf.dfcfw.com/pdf/H3_AP202211281580628635_1.pdf. The Alliance of the ‘Going Out’ of Petro-Chemical Industry, ‘中国排名前十的制氢企业 [Top Ten Hydrogen

Production Enterprises in China]', *Sohu News*, 26 January 2020, accessed 1 January 2024 at https://www.sohu.com/a/376080171_825950. State Energy Corporation and Sinopec are two major hydrogen producers in China. Although both of them are engaging in cost reduction of renewable hydrogen production, currently State Energy Corporation produces most coal-based hydrogen and Sinopec produces most by-product hydrogen.

90 '2022 年中国电解槽出货排名出炉 [The 2022 Ranking Of Electrolyzer Shipments In China Has Been Released.]', *Sohu News*, 15 December 2022, accessed 19 June 2024 at https://www.sohu.com/a/617571397_121081747.

91 '中国制氢行业短报告 [The Short Report on China's Hydrogen Production Industry]', *Yidu Data*, 2023, accessed 1 January 2024 at https://pdf.dfcfw.com/pdf/H3_AP202211281580628635_1.pdf.

92 '国家电投的氢能征途 [SPIC's Hydrogen Journey]', *Sohu News*, 6 July 2022, accessed on 25 June 2024 at https://www.sohu.com/a/564557441_257552.

93 '中国氢能企业排行榜 2023 [China Hydrogen Energy Enterprises Ranking 2023]', *China Power*, 19 September 2021, accessed 24 June 2024 at http://mm.chinapower.com.cn/qingneng/dongtai/20230919/217715.html.

94 Wu, M. (2023), '我国氢能产业商业化探索前景及挑战 [Prospects and Challenges for Hydrogen Industry Development in China]', *China Energy News*, 12 May 2023, accessed on 28 March 2024 at https://www.cpnn.com.cn/news/baogao2023/202305/t20230531_1605570.html.

95 *Global Hydrogen Review 2023*, IEA, 2023, p. 71.

96 Quan, X. (2023), '碱性电解槽：绿氢核心设备订单不断放量 [Alkaline Electrolyzer: Core Equipment for Green Hydrogen Sees Increasing Orders]', *Securities Times China News*, 8 June 2023, accessed on 15 February 2024 at https://stcn.com/article/detail/886776.html.

97 '绿氢项目饱满，电解槽放量可期 [Green Hydrogen Projects Are Abundant, And A Significant Increase In Electrolyzer Production Is Anticipated]', *Guo Tai Jun An Securities*, January 2024, accessed on 15 February 2024 at http://www.zg-kg.com/news-2147.html; '电解槽行业即将过剩? [Is The Electrolyser Industry About to Face Overcapacity]', *Energy Magazine*, 11 April 2024, accessed on 15 June 2024 at https://www.inengyuan.com/h2/12449.html.

98 Xu, S., Yu, B. (2021), '中国氢能技术发展现状与未来展望 [Development Status and Prospect of Hydrogen Energy Technology in China]', 23 (6) *Journal of Beijing Institute of Technology* (Social Sciences Edition) 1.

99 '绿氢放量在即，电解槽有望率先受益 [With Green Hydrogen Production Set To Expand, Electrolyzers Are Expected To Be The First To Benefit]', *HWABAO Securities*, 27 April 2024, accessed on 15 February 2024 at https://pdf.dfcfw.com/pdf/H3_AP202304281586021109_1.pdf; Gaogong Hydrogen Fuel Cell (2023), 'PEM 电解槽商用进展探秘 [Exploring the Progress of Commercializing PEM electrolysers]', *Sohu News*, 1 August 2023, accessed on 15 February 2024 at https://www.sohu.com/a/707885224_120717004#google_vignette.

100 'U.S. Expands Ban on Tech Sales to China', *The National Association of Manufacturers*, 20 December 2022, accessed on 15 February 2024 at https://nam.org/u-s-expands-ban-on-tech-sales-to-china-2-24453/; Vela, J. H., Moens, B. (2023), 'EU Looks to Ban Companies From Making Sensitive Tech in China', *POLITICO*, 20 June 2023, accessed on 15 February 2024 at https://www.politico.eu/article/eu-ban-companies-make-sensitive-tech-china/.

[101] ‘外商投资产业指导目录 [the Directory of Encouraging Foreign Investments]’, NDRC and MOFCOM, 2019.

[102] Dokso, A. (2023), ‘Cummins and Sinopec Put Jointly-Owned Hydrogen Equipment Factory Into Production’, *Hydrogen Energy News*, 8 May 2023, accessed 30 August 2024 https://energynews.biz/cummins-and-sinopec-put-jointly-owned-hydrogen-equipment-factory-into-production/.

[103] 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]’, NDRC, 23 March 2022.

[104] ‘国务院关于加快培育和发展战略性新兴产业的决定 [The Decision on Accelerating the Foster and Development of Strategic Emerging Industries]’, State Council, 2010.

[105] Chen, X. (2023), ‘战略性新兴产业发展态势探究 [Exploring the Development Trends of Strategic Emerging Industries]’, *People Forum*, 17 November 2023, accessed 1 January 2024 at http://www.rmlt.com.cn/2023/1117/687839.shtml.

[106] ‘困境突围——光伏领域企业在危机中育先机 [Breaking Through Difficulties: Opportunities Arising for Photovoltaic Enterprises Amid Crisis]’, *King & Wood Mallesons*, 21 May 2021, accessed 1 January 2024 at https://www.lexology.com/library/detail.aspx?g=e4d95735-7f82-4f41-807d-66d2fc924b86; Yingli New Energy, ‘一文看懂国家为什么大力发展光伏发电 [Understanding Why the Country is Vigorously Developing Photovoltaic Power Generation in One Article]’, *Sohu News*, 9 September 2022, accessed 1 January 2024 at https://www.sohu.com/a/523931375_120215979.

[107] ‘《绿色产业指导目录（2023 年版）》[The Directory for Green Industries]’, NDRC, 2023.

[108] ‘《新质生产力发展：氢能与储能新业态新领域》[New Productivity Development: Hydrogen and Energy Storage]’, *Energy Administration of Jilin Province*, 28 June 2024, accessed 19 December 2024 at < http://nyj.jl.gov.cn/xwdt/nyyw/202406/t20240628_3250801.html.

[109] ‘中华人民共和国能源法 [The Energy Law of the PRC]’, National People’s Congress, November 2024, Article 33.

[110] Gong, X., Quitzow, R., and Boute, A. (2023), ‘China’s Emerging Hydrogen Economy: Policies, Institutions and Actors’, *Research Institute for Sustainability Studies*, January 2023; Wang, A. M. (2023), ‘China’s Hydrogen Development: A Tale of Three Cities’, OIES, March 2023.

[111] Bian, L. et al., (2024), ‘China’s Role in Accelerating the Global Energy Transition Through Green Supply Chains and Trade’, *Grantham Research Institute on Climate Change and the Environment*, February 2024, accessed on 1 March 2024 at https://www.lse.ac.uk/granthaminstitute/wp-content/uploads/2024/02/Chinas-role-in-accelerating-the-global-energy-transition-through-green-supply-chains-and-trade.pdf.

[112] Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 75.

[113] ‘Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal’, *International Renewable Energy Agency*, 2020, executive summary.

[114] Gong, X., Quitzow, R., and Boute, A. (2023), ‘China’s Emerging Hydrogen Economy: Policies, Institutions and Actors’, *Research Institute for Sustainability Studies*, January 2023.

[115] Regarding SOEs’ capacity to deal with bureaucracy, see Gong, X. and Boute, A. (2021) ‘For Profit or Strategic Purpose? Chinese Outbound Energy Investments and the International Economic

Regime', 14 (5) *Journal of World Energy Law & Business* 345.

[116] Zhi, Q. et al. (2014), 'China's Solar Photovoltaic Policy: An Analysis Based on Policy Instruments', 129 *Applied Energy* 308, p. 310; Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 74.

[117] 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', NDRC, 23 March 2022.

[118] Schmidt, T., Huenteler, J. (2016), 'Anticipating Industry Localization Effects of Clean Technology Deployment Policies in Developing Countries', 38 *Global Environmental Change* 8, p. 13.

[119] '国家科技攻关计划 [Introduction of National Key R&D Program]', MOST, 2006, accessed on 19 May 2024 at https://www.most.gov.cn/ztzl/swkjjh/kjjhjj/200610/t20061021_36374.html.

[120] 'National High-Tech Research and Development Program [国家高技术研究发展计划]', MOST, 2006.

[121] '中国光伏产业发展战略报告 2004-2005 [The Report on Solar PV Development in China 2004–2005]', *Office for China Renewable Energy Development Project*, NDRC/GEF/WB China Renewable Energy Development Project, 1 August 2006, accessed on 6 February 2024 at https://cnecc.org.cn/UploadFile/2005.pdf.

[122] Zhang, Z., Li, J. (2006), '《中国风电技术商业化促进政策评价与设计》 [The Assessment of Design of Policies for Commercializing China's Wind Power]', *Energy Foundation*, 26 October 2006, accessed on 19 May 2024 at https://www.efchina.org/Reports-zh/reports-efchina-20061026-50-zh.

[123] '新能源基本建设项目管理的暂行规定 [Interim Regulations on Managing Basic Construction Projects for New Energy]', State Planning Commission, 1997; '关于调整进口设备税收政策的通知 [Notice on Adjusting the Tax Policy for Imported Equipment]', State Council, 1997; 'How Solar Developed from the Bottom-Up in China', *Institute on Global Conflict and Cooperation*, 14 March 2023, accessed on 19 May 2024 at https://ucigcc.org/blog/how-solar-developed-from-the-bottom-up-in-china/.

[124] '高新产品外商投资指导目录 [Guidance Catalogue for Foreign Investment in High-Tech Products]', MOST and Ministry of Commerce (MOFCOM), 2003.

[125] '关于进一步支持可再生能源发展有关问题的通知 [The Notice on Issues Related to Further Supporting the Development of Renewable Energy]', State Planning Commission and MOST, 1999; 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', NDRC, 23 March 2022.

[126] '新能源和可再生能源产业发展'十五'规划 [The 10th Five-Year Plan for the Development of the New and Renewable Energy Industry]', State Economic and Trade Commission, 2001. This Plan just generally stated that solar PV development should benefit from preferential tax treatment, cheap loans, investment promotion measures, and direct subsidies.

[127] '2000 年政府工作报告 [Government Report 2000]', State Council, 2000.

[128] Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 74; Zhang, S. et al. (2013), 'The Development Trajectories of Wind Power and Solar PV Power In China: A Comparison and Policy Recommendations', 26 *Renewables and Sustainable Energy Reviews* 322 (2013), p. 329; Chen, G. (2015), 'China's Solar PV Manufacturing and Subsidies from the Perspective of State Capitalism', 33 (1) *The Copenhagen Journal of Asian Studies* 90, p. 97. Local governments designed high-tech support regimes to develop high-tech industries, an objective initiated by the central

government. They viewed solar PV as one of these high-tech industries.

129 See however, the government of Dandong, Liaoning province once discouraged the use of solar energy at this early stage by banning the installation of solar water heaters. '可再生能源法明年 1 月 1 日正式施行 [The Renewable Energy Law Will Come Into Effect On January 1 Next Year]', *Sina Finance*, 30 November 2005, accessed on 9 June 2024 at https://finance.sina.cn/sa/2005-11-30/detail-ikkntiak9747037.d.html?from=wap.

130 '关于运用价格杠杆促进可持续发展的实施意见 [Implementation Opinions on Using Price Leverage to Promote Sustainable Development], Jiangsu Provincial Price Bureau, 2005.

131 '关于运用价格杠杆促进可持续发展的实施意见 [Implementation Opinions on Using Price Leverage to Promote Sustainable Development], Jiangsu Provincial Price Bureau, 2005.

132 '大扩张下的无锡光伏产业 [The Wuxi Solar PV Industry Under Major Expansion]', *Sina Finance*, 14 July 2023, accessed on 18 October 2023 at https://finance.sina.cn/chanjing/gdxw/2023-07-14/detail-imzaqnyf8906327.d.html?from=wap.

133 '中华人民共和国海关法 [Customs Law of the People's Republic of China]', National People's Congress, 2017 Amendment, Article 53; Chen, T. (2016), 'The Development of China's Solar Photovoltaic Industry: Why Industrial Policy Failed', 40 (3) *Cambridge Journal of Economics* 755; Chen, G., Lees, C. (2016), 'Growing China's Renewables Sector: A Developmental State Approach', *New Political Economy* 1, p. 8. However, the full texts of relevant policies issued at the early stage are not available. Corwin, S., Johnson, T. L. (2019), 'The Role of Local Governments in The Development of China's Solar PV Industry', 130 *Energy Policy* 283, p. 287.

134 '江苏省'十一五'太阳能光伏产业发展规划 [The 11th Five-Year Plan for Developing the Solar PV Industry in Jiangsu]', Provincial Government of Jiangsu, 2009.

135 Regarding the objective of developing renewable hydrogen, see Section 3.

136 '国家重点研发计划'氢能技术'重点专项-2021 年度拟立项项目公示清单 [The List of Projects of The Key Program of 'Hydrogen Technology in 2021 for Public Review]', MOST, 2021.

137 '国家自然科学基金委发布氢能专项申报指南 [NSFC Issued Guidelines on Application for Specific Funding Regime for Hydrogen Research]', *BJX*, 2022, accessed on 15 December 2022 at https://news.bjx.com.cn/html/20221017/1261332.shtml.

138 '鼓励外商投资产业目录 [Catalogue of Industries for Encouraging Foreign Investment]', NDRC and MOFCOM (three versions respectively published in 2019, 2020 and 2022).

139 'Perception of the Implementation of a Hydrogen Economy in Asia-Pacific: An Expert Survey', *KAS*, 2022, accessed on 1 June 2024 at https://www.kas.de/en/web/recap/single-title/-/content/perception-of-the-implementation-of-a-hydrogen-economy-in-asia-pacific.

140 '山西首支氢能产业基金在综改示范区设立 [The Establishment of First Government-Led Hydrogen Industrial Fund in Shanxi Province]', *Shanxi Daily News*, 7 February 2021, accessed on 1 June 2024 at http://sx.people.com.cn/n2/2021/0207/c189130-34568328.html; '成都市人民政府办公厅关于促进氢能产业高质量发展的若干意见 [Guidance on Promoting the High-Quality Development of the Hydrogen Industry in Chengdu]', Office of Chengdu Municipal People's Government, 2020; '深圳市氢能产业发展规划（2021–2025 年）[Shenzhen Hydrogen Industrial Development Plan 2021-2025]', Shenzhen DRC, 2021.

[141] 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]', NDRC, 23 March 2022.

[142] '绿色低碳转型产业指导目录（2024 年版） [Guidance Catalogue for Green and Low-Carbon Transformation Industries (2024 Edition)]', NDRC, 2024.

[143] '成都市人民政府办公厅关于促进氢能产业高质量发展的若干意见 [Guidance on Promoting the High-Quality Development of the Hydrogen Industry in Chengdu]', Office of Chengdu Municipal People's Government, 2020; '嘉兴市关于加快氢能产业发展的工作意见 [Guidance on Hydrogen Development in Jiaxing]', Office of Jiaxing Municipal People's Government, 2021; '促进氢能产业高质量发展的若干措施（2024 修订）[Several Measures to Promote High-Quality Development of the Hydrogen Energy Industry (Revised 2024)]', the Managing Committee for the Ningdong Energy and Chemical Base, 2024.

[144] '嘉兴港区：东方氢港乘氢而起 [Jiaxing Port Area: Rising as the 'Eastern Hydrogen Port' on the Tide of Hydrogen]', *Xinhua News*, 28 September 2023, accessed on 1 June 2024 at http://zj.news.cn/20230928/737f36dd066d414d9658c56603bb2766/c.html.

[145] '天津市新能源产业发展三年行动计划（2018–2020 年） [The Three-Year Action Plan of Tianjin New Energy Industrial Development (2018–2020)]', Office of Tianjin Municipal People's Government, 2018; '宁东能源化工基地'十四五'发展规划的通知 [The 14th Development Plan of Ningdong Energy and Chemical Base]', The Government of Autonomous Region of Ningxia, 2021.

[146] Andrews-Speed, P., Zhang, S. (2019), '*China as a Global Clean Energy Champion*, Springer, p. 145; Chen, W. (2021), '地方政府押注氢能背后：重复建设、地方保护、骗补等弯路还会再走一次吗 [Behind Local Governments' Bet on Hydrogen Energy: Will the Pitfalls of Redundant Construction, Local Protectionism, and Subsidy Fraud Be Repeated?]', *China News*, 1 March 2021, accessed on 1 May 2023 at https://www.chinanews.com.cn/gn/2021/03-01/9421280.shtml.

[147] '河北省推进氢能产业发展实施意见 [Implementation Opinions on Promoting Hydrogen Industry Development in Hebei]', Hebei DRC, 2019.

[148] '佛山市南海区氢能产业发展规划 2020–2035 [Hydrogen Industrial Development Plan in the Nanhai District of Foshan 2020–2035]', Foshan DRC, 2020.

[149] '成都市人民政府办公厅关于促进氢能产业高质量发展的若干意见 [Guidance on Promoting the High-Quality Development of the Hydrogen Industry in Chengdu]', Office of Chengdu Municipal People's Government, 2020.

[150] '张家口市支持氢能产业发展的十条措施 [Zhangjiakou's Ten Measures of Supporting the Development of Hydrogen Industry]', Zhangjiakou DRC, 2019.

[151] According to the Legislation Law of PRC [立法法], local regulations are not allowed to conflict with Chinese constitutional law or national laws and administrative regulations.

[152] '关于开展燃料电池汽车示范应用的通知 [Notice of the Pilot Application of Fuel Cell Vehicles], MOF et al., 2020. The central government has established the national pilot regime for FCV in 2020 to test new technologies associated with value chains for FCVs, while continuing incentivizing stable demand for hydrogen.

[153] '燃料电池汽车城市群示范目标和积分评价体系 [The Demonstration Objectives and Credits Evaluation System for Pilot City Clusters of Fuel Cell Vehicles]', MOF et al., 2020.

[154] ‘低碳氢、清洁氢与可再生能源氢的标准与评价 [Standard and Evaluation of Low-carbon Hydrogen, Clean Hydrogen and Renewable Hydrogen]’, China Hydrogen Alliance, 2020.

[155] ‘促进氢能产业高质量发展的若干措施（2024 修订）[Several Measures to Promote High-Quality Development of the Hydrogen Energy Industry (Revised 2024)]’, the Managing Committee for the Ningdong Energy and Chemical Base, 2024.

[156] ‘绿氢:发展机遇与挑战并存 [Green Hydrogen: Development Opportunities and Challenges Coexist]’, *CNPC News*, 16 May 2023, accessed on 11 June 2024 at http://news.cnpc.com.cn/system/2023/05/16/030101582.shtml.

[157] ‘市人民政府关于支持氢能产业发展的意见 [Opinions on Supporting Hydrogen Industry Development]’, Municipal Government of Wuhan, 2022.

[158] ‘稳中求进高质量发展政策清单（第二批）的通知 [Notice on the List of Policies for High-Quality Development with the Approach of Seeking Progress while Maintaining Stability (Second Batch)]’, Provincial Government of Shandong, 2022; ‘沈阳市大东区人民政府关于印发《大东区支持氢能暨氢燃料电池汽车产业高质量发展的若干政策措施》的通知 [Notice on Several Policy Measures of Dadong District to Support High-Quality Development of the Hydrogen Energy and Hydrogen Fuel Cell Vehicle Industry]’, The Government of Dadong District of Shenyang, 2023.

[159] ‘河北省氢能产业安全管理办法（试行）[Hebei Province Hydrogen Energy Industry Safety Management Measures (Trial Implementation)]’, Provincial Government of Hebei, 2023; ‘吉林省氢能产业安全管理办法（试行）[Jilin Province Hydrogen Energy Industry Safety Management Measures (Trial Implementation)]’, Provincial Government of Jinlin, 2023; ‘新疆发展改革委联合自治区应急管理厅、工业和信息化厅印发关于加快推进氢能产业发展的通知 [The Notice on Accelerating Hydrogen Industry Development]’, Xinjiang DRC et al., 2024; ‘内蒙古自治区能源局、内蒙古自治区应急管理厅、内蒙古自治区工业和信息化厅联合发布关于加快推进氢能产业发展的通知 [The Notice on Accelerating Hydrogen Industry Development]’, The Energy Administration of Inner Mongolia et al., 2024.

[160] ‘河北省氢能产业安全管理办法（试行）[Hebei Province Hydrogen Energy Industry Safety Management Measures (Trial Implementation)]’, Provincial Government of Hebei, 2023; ‘吉林省氢能产业安全管理办法（试行）[Jilin Province Hydrogen Energy Industry Safety Management Measures (Trial Implementation)]’, Provincial Government of Jinlin, 2023; ‘新疆发展改革委联合自治区应急管理厅、工业和信息化厅印发关于加快推进氢能产业发展的通知 [The Notice on Accelerating Hydrogen Industry Development]’, Xinjiang DRC et al., 2024; ‘内蒙古自治区能源局、内蒙古自治区应急管理厅、内蒙古自治区工业和信息化厅联合发布关于加快推进氢能产业发展的通知 [The Notice on Accelerating Hydrogen Industry Development]’, The Energy Administration of Inner Mongolia et al., 2024.

[161] Haas, R. et al. (2022), ‘Technological Learning: Lessons Learned on Energy Technologies’, 12 *WIREs Energy and Environment* 1, p. 15.

[162] Zhi, Q. et al. (2014), ‘China’s Solar Photovoltaic Policy: An Analysis Based on Policy Instruments’, 129 *Applied Energy* 308, p. 310; Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 74.

[163] Gong, X., Quitzow, R., and Boute, A. (2023), ‘China’s Emerging Hydrogen Economy: Policies, Institutions and Actors’, *Research Institute for Sustainability Studies*, January 2023; Wang, A. M. (2023), ‘China’s Hydrogen Development: A Tale of Three Cities’, OIES, March 2023.

[164] 氢能中长期规划 [The Mid- and Long-Term Hydrogen Industrial Development Plan]’, NDRC, 23

March 2022.

165 Wang, K. ‘Hydrogen Electrolyzers Latest Star Export Item’, *China Daily*, 22 August 2024, accessed 20 December 2024 at https://www.chinadailyhk.com/hk/article/591204.

166 Zhao, T., van Dorsten, B. (2024), ‘The Competitive Edge of China's Electrolysers’, *Wood Mackenzie*, 5 September 2024, accessed 20 December 2024 at https://www.woodmac.com/news/opinion/the-competitive-edge-of-chinas-electrolysers.

167 Gong, X., Rainer Quitzow, R., and Boute, A. (2024), ‘Developing China’s Hydrogen Economy: National Regulation through Local Experimentation’, 13 (2) *Transnational Environmental Law* 337.

168 Laube, S. (2023), ‘China’s Hydrogen Energy Industry: State Policy, Investment Opportunities’, *China Briefing*, December 2023, accessed on 22 February 2024 at https://www.china-briefing.com/doing-business-guide/china/sector-insights/china-s-hydrogen-energy-industry-state-policy-investment-opportunities; Dellatte, J. (2023), ‘Global Green Hydrogen Policy: China, A Giant Biding Its Time’, *Montaigne Institute*, 28 April 2023, accessed on 22 February 2024 at https://www.institutmontaigne.org/en/expressions/global-green-hydrogen-policy-china-giant-biding-its-time.

169 Shamdasani, A. (2024), ‘China: Foreign Direct Investment Hits 30-Year Low’, *Global Finance*, 2 April 2024, accessed on 22 May 2024 at https://gfmag.com/economics-policy-regulation/china-foreign-direct-investment-hits-30-year-low/ .

170 Kalwasiński, M. (2024), ‘Paradise Lost? Falling Foreign Investments in China’, *Center for Eastern Studies*, 10 January 2024, accessed on 19 June 2024 at https://www.osw.waw.pl/en/publikacje/osw-commentary/2024-01-10/paradise-lost-falling-foreign-investments-china.

171 Lindman, A., Söderholm, P. (2012), ‘Wind Power Learning Rates: A Conceptual Review and Meta-Analysis’, 34 (3) *Energy Economics* 754; Nordhaus, W. D. (2014), ‘The Perils of the Learning Model for Modeling Endogeous Technological Change’, 35 (1) *The Energy Journal* 1 (2014). Saba, S. M. et al. (2018), ‘The Investment Costs of Electrolysis E A Comparison of Cost Studies from The Past 30 Years’, 43 (3) *International Journal of Hydrogen Energy* 1209; Glenk, G., Meier, R. and Reichelstein, R. (2021), ‘Cost Dynamics of Clean Energy Technologies’, 73 *Schmalenbach Journal of Business Research* 179.

172 Neij, L. (1997), ‘Use of Experience Curves to Analyse the Prospects for Diffusion and Adoption of Renewable Energy Technology’, 25 (13) *Energy policy* 1099; Lindman, A., Söderholm, P. (2012), ‘Wind Power Learning Rates: A Conceptual Review and Meta-Analysis’, 34 (3) *Energy Economics* 754.

173 Grafström, J., Poudineh, R. (2021), ‘A Review of Problems Associated with Learning Curves for Solar and Wind Power Technologies’, OIES; Rubin, E. (2015), ‘A Review of Learning Rates for Electricity Supply Technologies’, 86 *Energy Policy* 198.

174 Grafström, J., Poudineh, R. (2021), ‘A Review of Problems Associated with Learning Curves for Solar and Wind Power Technologies’, OIES; Elshurafa, A. et al. (2017), ‘Estimating the Learning Curve of Solar PV Balance-of Systems for Over 20 Countries’, K*ing Abdullah Petroleum Studies and Research Center*, June 2017; Ibenholt K. (2002), ‘Explaining Learning Curves for Wind Power’, 30 *Energy Policy* 1181.

175 McDonald, A., Schrattenholze, L. (2001), ‘Learning Rates for Energy Technologies’, 29 *Energy Policy* 255; Roser, M. (2023), ‘Learning Curves: What Does It Mean for A Technology To Follow Wright’s Law?’, *Our World in Data*, 18 April 2023, accessed on 6 February 2024 at

https://ourworldindata.org/learning-curve.

176 Dai, Y., Shu, Y., and Zeng, Y. (2024), 'Use of Learning Curve to Explore the Competition Between Renewables and Conventional Fossil Fuel Power Technologies in China', 52 *Energy Strategy Reviews* 101352.

177 Schmidt, T., Huenteler, J. (2016), 'Anticipating Industry Localization Effects of Clean Technology Deployment Policies in Developing Countries', 38 *Global Environmental Change* 8, p. 9.

178 Huenteler, J. et al. (2016), 'Technology Life Cycles in the Energy Sector — Technological Characteristics and the Role of Deployment for Innovation', 104 *Technological Forecasting and Social Change* 102.

179 Schmidt, T., Huenteler, J. (2016), 'Anticipating Industry Localization Effects of Clean Technology Deployment Policies in Developing Countries', 38 *Global Environmental Change* 8, p. 10.

180 Reinhard Haas, et al. (2022), 'Technological Learning: Lessons Learned on Energy Technologies', 12 *WIREs Energy and Environment* 1, p. 13

181 chmidt, T., Huenteler, J. (2016), 'Anticipating Industry Localization Effects of Clean Technology Deployment Policies in Developing Countries', 38 *Global Environmental Change* 8, p. 14.

182 Binz, C. et al. (2017), 'Toward Technology-Sensitive Catching-Up Policies: Insights from Renewable Energy in China', 96 *World Development* 418, p. 421.

183 Binz, C. et al. (2017), 'Toward Technology-Sensitive Catching-Up Policies: Insights from Renewable Energy in China', 96 *World Development* 418, p. 421; Huenteler, J. et al. (2016), 'Technology Life Cycles in the Energy Sector — Technological Characteristics and the Role of Deployment for Innovation', 104 *Technological Forecasting and Social Change* 102.

184 Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 75.

185 Binz, C. et al. (2017), 'Toward Technology-Sensitive Catching-Up Policies: Insights from Renewable Energy in China', 96 *World Development* 418.

186 Haas, R. et al. (2022), 'Technological Learning: Lessons Learned on Energy Technologies', 12 *WIREs Energy and Environment* 1, p. 13. See however, Bolinger, M., Wiser R., and O'Shaughnessy, E. (2022), 'Levelized Cost-Based Learning Analysis of Utility-Scale Wind and Solar in the United States', 25(6) *iScience* 1. The authors argue that the learning may not be slow after technology becomes mature.

187 Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 75.

188 '绿氢的成本下降能有多快? [How Quickly Can the Cost of Green Hydrogen Decrease?]', *China Energy Storage News*, 10 December 2023, accessed on 11 May 2024 at https://www.escn.com.cn/20231210/2b4fed77910f4ee5b81fd8066dfd3474/c.html.

189 Potter, B. (2023), 'How Did Solar Power Get Cheap?', *Construction Physics*, 20 April 2023, accessed on 6 February 2024 at https://www.construction-physics.com/p/how-did-solar-power-get-cheap-part-28a.

190 Gan, P. Y., Li, Z. (2015), 'Quantitative Study on Long Term Global Solar Photo Voltaic Market', 46 *Renewable and Sustainable Energy Reviews* 88. The author carried out the single-factor learning curve analysis. Keith, D. W., Moreno-Cruz, J. (2011), 'Is the Solar Photovoltaic Learning Curve Flattening?', *Technical Note*, 15 July 2011, accessed on 6 February 2024 at https://hds.harvard.edu/files/tkg/files/178.keith_and_moreno-

cruz.isthesolarphotovoltaiclearningcurveflattening.pdf.

[191] Roser, M. (2023), 'Learning Curves: What Does It Mean for A Technology To Follow Wright's Law?', *Our World in Data*, 18 April 2023, accessed on 6 February 2024 at https://ourworldindata.org/learning-curve.

[192] '中国光伏产业发展战略报告 2004-2005 [The Report on Solar PV Development in China 2004–2005]', *Office for China Renewable Energy Development Project*, NDRC/GEF/WB China Renewable Energy Development Project, 1 August 2006, accessed on 6 February 2024 at https://cnecc.org.cn/UploadFile/2005.pdf.

[193] '中国光伏产业发展战略报告 2004-2005 [The Report on Solar PV Development in China 2004–2005]', *Office for China Renewable Energy Development Project*, NDRC/GEF/WB China Renewable Energy Development Project, 1 August 2006, accessed on 6 February 2024 at https://cnecc.org.cn/UploadFile/2005.pdf.

[194] '光伏行业观察 [The Observation for the Solar PV Industry]', *People News*, 30 January 2024, http://paper.people.com.cn/rmrb/html/2024-01/30/nw.D110000renmrb_20240130_1-10.htm.

[195] '我国光伏发电成本变化分析 [Analysis of Changes in China's Photovoltaic Power Generation Costs]', *China Power*, 6 June 2016, accessed on 6 February 2024 at http://www.chinapower.com.cn/informationhyfx/20160606/30333.html.

[196] 'Solar PV Panels Prices', *Our World in Data*, last updated on 8 May 2024, accessed on 10 May 2024 at https://ourworldindata.org/grapher/solar-pv-prices.

[197] *Special Report on Solar PV Global Supply Chains*, IEA, 2022, p. 7.

[198] Dahlmeier, U. (2023), 'Empirical Approach Shows PV Is Getting Cheaper Than All the Forecasters Expect', *PV Magazine*, 5 December 2023, accessed on 10 May 2024 at https://www.pv-magazine.com/2023/12/05/empirical-approach-shows-pv-is-getting-cheaper-than-all-the-forecasters-expect/; Shetty, S. (2024), 'Utility PV Solar Leads Renewable Revolution', *Solar Quarter*, 1 March 2024, accessed on 10 May 2024 at https://solarquarter.com/2024/03/01/utility-pv-solar-leads-renewable-revolution-costs-hit-record-low-surpassing-coal-in-asia/. The hit-record low cost of solar power was also explained by China's manufacturers' urgent need to clear their inventories in a season lull. 'China Solar Panel Costs Plunge in 2023, 60% Cheaper Than US', *Asia Financial*, 14 December 2023, accessed on 1 September 2024 at https://www.asiafinancial.com/china-solar-panel-costs-plunge-in-2023-60-cheaper-than-us.

[199] Roser, M. (2023), 'Learning Curves: What Does It Mean for A Technology To Follow Wright's Law?', *Our World in Data*, 18 April 2023, accessed on 6 February 2024 at https://ourworldindata.org/learning-curve.

[200] Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, *IRENA*, 2020; Böhm, H., Goers, S., and Zauner, A. (2019), 'Estimating Future Costs of Power-To-Gas–A Component-Based Approach for Technological Learning', 44 (59) *International Journal of Hydrogen Energy* 30789.

[201] *Hydrogen Insights, A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness*, Hydrogen Council, 2021, p. 15; Detz, R., Weeda, M. (2022), 'Projections of Electrolyzer Investment Cost Reduction Through Learning Curve Analysis', TNO Netherlands, 20 January 2022, accessed on 9 January 2024 at https://energy.nl/wp-content/uploads/tno-2022-p10111_detzweeda_projections-of-electrolyzer-investment-cost-reduction-through-learning-curve-

analysis.pdf.

[202] Patonia, A., Poudineh, R. (2022), 'Cost-Competitive Green Hydrogen: How to Lower the Cost of Electrolysers?', OIES, p. 24. Böhm, H. et al. (2020), 'Projecting Cost Development for Future Large-Scale Power-To-Gas Implementations by Scaling Effects', 264 *Applied Energy* 114680; Böhm, H., Goers, S., and Zauner, A. (2019), 'Estimating Future Costs of Power-To-Gas – A Component-Based Approach For Technological Learning', 44 (59) *International Journal of Hydrogen Energy* 30789; Schmidt, O. et al. (2017), 'Future Cost and Performance Of Water Electrolysis: An Expert Elicitation Study', 42 (52) *International Journal of Hydrogen Energy* 30470.

[203] Schmidt, O. et al. (2017), 'Future Cost and Performance of Water Electrolysis: An Expert Elicitation Study', 42 (52) *International Journal of Hydrogen Energy* 30470.

[204] *Innovation and Industrial Policies for Green Hydrogen*, Organisation for Economic Co-operation and Development (OECD), 2022, p. 16.

[205] *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal*, IRENA, 2020, p. 73; P Patonia, A., Poudineh, R. (2022), 'Cost-Competitive Green Hydrogen: How to Lower the Cost of Electrolysers?', OIES, p. 25. The authors also argued that 'similar to solar PV, electrolysers are expected to initially benefit from module efficiency driven by government-funded and private R&D, and at a later stage from scale economies and, to some extent, from learning-by-doing.'

[206] Detz, R., Weeda, M. (2022), 'Projections of Electrolyzer Investment Cost Reduction Through Learning Curve Analysis', TNO Netherlands, 20 January 2022, accessed on 9 January 2024 at https://energy.nl/wp-content/uploads/tno-2022-p10111_detzweeda_projections-of-electrolyzer-investment-cost-reduction-through-learning-curve-analysis.pdf.

[207] IEA, 'Will Solar PV And Wind Costs Finally Begin to Fall Again in 2023 and 2024?', *Renewable Energy Market Update*, June 2023, accessed 20 December 2024 at https://www.iea.org/reports/renewable-energy-market-update-june-2023/will-solar-pv-and-wind-costs-finally-begin-to-fall-again-in-2023-and-2024. IEA explained that 'although global average levelised costs of energy (LCOEs) for onshore wind and solar PV are expected to remain 10-15% above 2020 levels in 2024, continued innovation is also expected to reduce costs further'.

[208] Revinova, S. et al. (2023), 'Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves', 16 *Energies* 4338; Reksten, A. et al. (2022), 'Projecting the Future Cost of PEM And Alkaline Water Electrolysers; A CAPEX Model Including Electrolyser Plant Size And Technology Development', 47 (90) *International Journal of Hydrogen Energy* 38206.

[209] Zun, M.T., McLellan, B.C. (2023), 'Cost Projection of Global Green Hydrogen Production Scenarios', 4 *Hydrogen* 932; Saba, S. M. et al. (2018), 'The Investment Costs of Electrolysis E A Comparison of Cost Studies from The Past 30 Years', 43 (3) *International Journal of Hydrogen Energy* 1209

[210] *Innovation and Industrial Policies for Green Hydrogen*, OECD, 2022, p. 17.

[211] *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal*, IRENA, 2020.

[212] '论制氢市场中的'内卷'之战 [the 'Involution' Battle in the Hydrogen Production Market]', *Hydrogen Observation*, 7 October 2023, accessed on 18 June 2024 at https://news.cnpowder.com.cn/73011.html.

[213] Lichner, C. (2024), 'Electrolyzer Prices – What to Expect', *PV Magazine*, 21 March 2024, accessed

on 18 June 2024 at https://www.pv-magazine.com/2024/03/21/electrolyzer-prices-what-to-expect/.

214 Lichner, C. (2024), 'Electrolyzer Prices – What to Expect', *PV Magazine*, 21 March 2024, accessed on 18 June 2024 at https://www.pv-magazine.com/2024/03/21/electrolyzer-prices-what-to-expect/.

215 '抢滩全球电解槽市场，中国成赢家？ [Can China Win in the Competition for Shares in the Global Electrolyser Market?]', *China Energy*, 1 March 2022, accessed on 18 June 2024 at http://www.cnenergynews.cn/zhuanti/2022/03/01/detail_20220301118460.html.

216 '国内首条！用于大功率碱性电解槽核心零部件自动化生产线正式揭牌 [The Country's First Automated Production Line For Key Components Of High-Power Alkaline Electrolyzers Has Been Officially Unveiled.]', *China Forge*, 1 September 2023, accessed 1 September 2024 at https://www.metalform.cn/news/show39939.html.

217 '掘金'电解水制氢产线设备 [Unlocking Opportunities' in Water Electrolysis Hydrogen Production Line Equipment]', *International Hydrogen*, 2 January 2024, accessed 1 September 2024 at https://h2.in-en.com/html/h2-2432557.shtml.

218 '2024 年国内碱性电解槽价格下降或将趋缓，PEM 电解槽或迎大幅市场降价 [In 2024, the decline in domestic alkaline electrolyzer prices may slow down, while PEM electrolyzers could see a significant market price reduction.]', *EnerScen*, 27 December 2023, accessed on 17 May 2024 at https://m.ofweek.com/hydrogen/2023-12/ART-180820-8420-30621349.html; '绿氢成本受多因素影响 [The Cost of Green Hydrogen Impacted by Multiple Factors]', *Goal Fore Advisory*, accessed on 1 June 2024 at https://www.goalfore.cn/a/4522.html; '氢能产业系列报告（四）：绿氢星辰大海，电解槽放量可期 [Hydrogen Industry Development Report (IV): A Significant Increase in Electrolyzer Production Is Anticipated.]', *Topsperity Securities*, 31 May 2023, accessed on 17 May 2024 at https://pdf.dfcfw.com/pdf/H3_AP202305311587387421_1.pdf#page=20.05.

219 '论制氢市场中的'内卷'之战 [the 'Involution' Battle in the Hydrogen Production Market]', *Hydrogen Observation*, 7 October 2023, accessed on 18 June 2024 at https://news.cnpowder.com.cn/73011.html.

220 '电解槽路径：碱式还是 PEM？ [Competing Electrolysers: Alkaline or PEM?]', *Science and Innovation*, 27 April 2023, accessed on 18 June 2024 at https://www.eet-china.com/mp/a215237.html.

221 '2024 年国内碱性电解槽价格下降或将趋缓，PEM 电解槽或迎大幅市场降价 [In 2024, the decline in domestic alkaline electrolyzer prices may slow down, while PEM electrolyzers could see a significant market price reduction.]', *EnerScen*, 27 December 2023, accessed on 17 May 2024 at https://m.ofweek.com/hydrogen/2023-12/ART-180820-8420-30621349.html; '氢能产业系列报告（四）：绿氢星辰大海，电解槽放量可期 [Hydrogen Industry Development Report (IV): A Significant Increase in Electrolyzer Production Is Anticipated.]', *Topsperity Securities*, 31 May 2023, accessed on 17 May 2024 at https://pdf.dfcfw.com/pdf/H3_AP202305311587387421_1.pdf#page=20.05.

222 Hove, A., Meidan, M., and Andrews-Speed, P. (2021), 'Software Versus Hardware: How China's Institutional Setting Helps and Hinders the Clean Energy Transition', OIES, 2021, p. 50; Hu, H. (2023), '绿氢放量在即，电解槽有望率先受益 [With Green Hydrogen Production Set To Expand, Electrolyzers Are Expected To Be The First To Benefit]', *Sina Finance*, 27 April 2023, accessed on 9 June 2024 at https://finance.sina.cn/2023-04-27/detail-imyrvsqp3143238.d.html.

223 Badgett, A. et al. (2021), 'Techno-economic Analysis (TEA) Methods Identifying Cost Reduction Potential for Water Electrolysis Systems', 33 *Current Opinion in Chemical Engineering* 100714.

[224] Hu, Y. (2018), '光伏行业发展回顾及展望 [The Past and the Future of the Solar PV Industry]', *Huachuang Securities*, 26 June 2018, accessed on 4 April 2024 at https://www.vzkoo.com/document/f1990b47255dbaa9363ec60044540644.html.

[225] Zhi, Q. et al. (2014), 'China's Solar Photovoltaic Policy: An Analysis Based on Policy Instruments', 129 *Applied Energy* 308, p. 312; Zhang, S. et al. (2013), 'Interactions Between Renewable Energy Policy and Renewable Energy Industrial Policy: A Critical Analysis of China's Policy Approach to Renewable Energies', 62 *Energy Policy* 342, p. 347.

[226] Andrews-Speed, P., Zhang, S. (2019), *China as a Global Clean Energy Champion*, Springer, p. 151; Liang, X. et al. (2023), '周期、成长共振，光伏 20 年回顾及展望 [Twenty-Year Development of the Solar PV Industry]', *Orient Securities*, 10 February 2023, accessed on 5 June 2024 at https://pdf.dfcfw.com/pdf/H3_AP202302131583073061_1.pdf.

[227] '中国光伏产业发展战略报告 2004-2005 [The Report on Solar PV Development in China 2004–2005]', *Office for China Renewable Energy Development Project*, NDRC/GEF/WB China Renewable Energy Development Project, 1 August 2006, accessed on 6 February 2024 at https://cnecc.org.cn/UploadFile/2005.pdf.

[228] Crowther, H. (2023), 'Three Years On: Assessing Power Sector and Renewable Energy Manufacturing Policy in China Since the Announcement of Dual Carbon Goals', OIES, October 2023, p. 3.

[229] '中华人民共和国国民经济和社会发展第十个五年计划纲要 [The 10th Five-Year Plan for National Economic Development and Social Development]', National People's Congress, 2001.

[230] Andrews-Speed, P., Zhang, S. (2019) *China as a Global Clean Energy Champion*, Springer.

[231] '中国高新技术产品出口目录 [China High-Tech Products Export Catalogue]', MOST, et al., 2003; '财政部、国家税务总局关于调整出口货物退税率的补充通知 [Supplementary Notice on Adjusting the Export Tax Rebate Rate for Exported Goods]', the Ministry of Finance and the State Administration of Taxation, 2003.

[232] '十四五可再生能源规划 [The 14th Five-Year Plan of Renewable Energy Development]', NEA, 2021; 'IRENA and National Energy Administration of China Signed an Mou To Advance The Transition And Cooperate On Market Development', *IRENA*, 2021, accessed on 8 June 2024 at https://www.irena.org/News/pressreleases/2021/Jun/China-and-IRENA-Boost-Ties-as-Leading-Renewables-Market-Eyes-Net-Zero-Goals

[233] Uchôa, V. (2021), 'Brazil Sets Its Sights On The Global Green Hydrogen Market', *Diálo Chio*, 18 November 2021, accessed on 8 June 2024 at https://dialogochino.net/en/climate-energy/brazil-sets-sights-green-hydrogen-market/

[234] 'SPIC Bets on Power Generation in Brazil', *Valor Business*, 31 August 2021, accessed on 8 June 2022 at https://valorinternational.globo.com/business/news/2021/08/31/spic-bets-on-power-generation-in-brazil.ghtml

[235] 'Declaration on China-Africa Cooperation on Combating Climate Change', *Ministry of Foreign Affairs*, 2 December 2021, accessed on 6 December 2023 at https://www.mfa.gov.cn/mfa_eng/wjdt_665385/2649_665393/202112/t20211203_10461772.html

[236] '能源生产和消费革命战略（2016–2030）[Energy Production and Consumption Transition Strategy (2016–2030)]', NDRC and NEA, 2016; '国务院关于推进国际产能和装备制造合作的指导意见 [Guiding

Opinions of the State Council on Promoting International Capacity and Equipment Manufacturing Cooperation]', State Council, 2015.

[237] '氢能行业深度研究：氢能源产业链企业梳理 [In-Depth Research on the Hydrogen Energy Industry: An Overview of Hydrogen Energy Industry Chain Enterprises]', *Huachuang Securities*, 3 July 2023, accessed on 2 January 2024 at https://www.sohu.com/a/694095763_121123901#google_vignette.

[238] *Hydrogen Insights, A Perspective on Hydrogen Investment, Market Development and Cost Competitiveness*, Hydrogen Council, 2021; Revinova, S. et al. (2023), 'Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves', 16 *Energies* 4338.

[239] '2023 年底中国电解槽厂商总产能激增至 38 GW [By The End Of 2023, The Total Production Capacity Of Chinese Electrolyzer Manufacturers Surged to 38 GW]', *BJX Hydrogen*, 10 January 2024, accessed on 28 January 2024 at https://m.bjx.com.cn/mnews/20240110/1355097.shtml.

[240] 'Current Electrolyzer Manufacturing Capacity Could Quadruple By 2025 As OEMs Scale Facilities in The Face of Rising Demand', *S&P Global Commodity Insights*, 16 August 2022, accessed on 28 January 2024 at https://www.spglobal.com/esg/s1/research-analysis/current-production-capacity-could-quadruple-by-2025-as-oems-sc.html; 'Electrolyser Manufacturing Capacity Could Be 2x Greater Than Demand in 2030', *Hydrogen Europe*, 8 February 2024, accessed on 28 May 2024 at https://hydrogeneurope.eu/electrolyser-manufacturing-capacity-could-be-2x-greater-than-demand-in-2030/.

[241] 'Electrolysers', IEA, 2024, accessed on 28 January 2024 at https://www.iea.org/energy-system/low-emission-fuels/electrolysers#tracking.

[242] *Global Hydrogen Review 2023*, IEA, 2023, p. 72.

[243] Tang, C. (2024), 'As World Erects Barriers Against Chinese Exports, What About Free Trade?', *South China Morning Post*, 10 April 2024, accessed on 16 May 2024 at https://www.scmp.com/opinion/china-opinion/article/3258241/world-erects-barriers-against-chinese-exports-what-about-free-trade; Hunnicutt, T., Mason, M., and Shepardson, D., (2024), 'New Biden Tariffs on China's EVs, Solar, Medical Supplies Due Tuesday – Sources', *Reuters*, 13 May 2024, accessed on 16 May 2024 at https://www.reuters.com/business/us-set-impose-tariffs-china-evs-certain-strategic-sectors-bloomberg-reports-2024-05-10/; Verhelst, K. (2024), 'Chinese EV Makers Risk Tougher Duties Over Failure To Cooperate With EU Probe', *POLITICO*, 2 May 2024, accessed on 16 May 2024, at https://www.politico.eu/article/china-electric-vehicle-uncooperative-probe-european-commission-letters/.

[244] Martin, P. (2024), 'European Commission Reveals How It Will Calculate 25% Limit on Chinese Electrolysers', *Hydrogen Insight*, 14 November 2024, accessed on 20 December 2024 <https://www.hydrogeninsight.com/policy/european-commission-reveals-how-it-will-calculate-25-limit-on-chinese-electrolysers/2-1-1739760>.

[245] Yu, J., Wang, Y., (2020), '中国光伏产业的发展与'一带一路'的新机遇 [Development of the PV Industry in China and New Opportunities from the Analysis from the Perspective of New Structural Economics]', 40 (5) *Journal of Xi'an Jiaotong University* (Social Sciences) 87.

[246] Chen, T. (2016), 'The Development of China's Solar Photovoltaic Industry: Why Industrial Policy Failed', 40 (3) *Cambridge Journal of Economics* 755.

[247] Chen, T. (2016), 'The Development of China's Solar Photovoltaic Industry: Why Industrial Policy

Failed', 40 (3) *Cambridge Journal of Economics* 755.

[248] Zhang, F. et al. (2021), 'The Role of The Local Government in China's Urban Sustainability Transition: A Case Study of Wuxi's Solar Development', 117 *Cities* 103294, p. 103298.

[249] Korsnes, M. (2020), *Wind and Solar Energy Transition in China*, Routledge, p. 75; Yang, K., Schot, J., Truffer, B. (2022), 'Shaping the Directionality of Sustainability Transitions: The Diverging Development Patterns Of Solar Photovoltaics In Two Chinese Provinces', 56 (5) *Regional Studies* 751, p. 762;

[250] Zhang, F. et al. (2021), 'The Role of The Local Government in China's Urban Sustainability Transition: A Case Study of Wuxi's Solar Development', 117 *Cities* 103294.

[251] "尚德兴衰背后的政府之手 [The Rise and Fall of Suntech: The Hand of the Government Behind It]", 3 April 2013, *New York Times Chinese*, accessed on 6 June 2024 at https://cn.nytimes.com/business/20130403/cc03suntech/.

[252] Yu, J., Wang, Y. (2020), '中国光伏产业的发展与'一带一路'的新机遇 [Development of the PV Industry in China and New Opportunities from the Analysis from the Perspective of New Structural Economics]', 40 (5) *Journal of Xi'an Jiaotong University* (Social Sciences) 87.

[253] Pearson, M. (2019), 'Local Government and Firm Innovation in China's Clean Energy Sector', in Loren Brandt and Thomas G. Rawski (eds.), *Policy, Regulation and Innovation in China's Electricity and Telecom Industries*, Cambridge University Press, 2019, pp. 96-133, p. 108.

[254] Zhang, F. et al. (2021), 'The Role of The Local Government in China's Urban Sustainability Transition: A Case Study of Wuxi's Solar Development', 117 *Cities* 103294.

[255] Zhou, J. (2018), '从无锡尚德破产重整案看政府与市场的关系 [Discussing the Relationship Between Governments and Markets Based on the Case of the Bankrupt of Suntech]', *People's News*, 2 August 2018, accessed on 10 January 2024 at http://theory.people.com.cn/n1/2016/0802/c401815-28604378.html; '无锡尚德溃败背后的故事与启示 [Implications of the Bankrupt of Suntech]', *BJX Solar*, 10 October 2019, accessed on 10 January 2024 at https://mguangfu.bjx.com.cn/mnews/20191014/1012893.shtml.

[256] Zhou, J. (2018), '从无锡尚德破产重整案看政府与市场的关系 [Discussing the Relationship Between Governments and Markets Based on the Case of the Bankrupt of Suntech]', *People's News*, 2 August 2018, accessed on 10 January 2024 at http://theory.people.com.cn/n1/2016/0802/c401815-28604378.html.

[257] "尚德施正荣与无锡政府矛盾公开化 [The Conflict Between Shi Zhengrong Of Suntech And The Wuxi Government Becomes Public.]", *Sina Finance*, 20 October 2012, accessed 19 June 2024 at https://finance.sina.com.cn/chanjing/gsnews/20121020/000413424294.shtml.

[258] Ahrens, N. (2013), 'Case Study: Suntech', in Aburaki, K. et al. (eds.), *China's Competitiveness: Myth, Reality, and Lessons for the United States and Japan*, Center for Strategic and International Business, 2013.

[259] Zhang, F. et al. (2021), 'The Role of The Local Government in China's Urban Sustainability Transition: A Case Study of Wuxi's Solar Development', 117 *Cities* 103294.

[260] Ahrens, N. (2013), 'Case Study: Suntech', in Aburaki, K. et al. (eds.), *China's Competitiveness: Myth, Reality, and Lessons for the United States and Japan*, Center for Strategic and International Business, 2013.

[261] ‘电力设备及新能源 [Electricity Equipment and New Energy]’, *Pingan Securities*, 8 December 2023, accessed on 8 June 2024 at https://pdf.dfcfw.com/pdf/H3_AP202312181614439659_1.pdf.

[262] Crowther, H. (2023), ‘Three Years On: Assessing Power Sector and Renewable Energy Manufacturing Policy in China Since the Announcement of Dual Carbon Goals’, OIES, October 2023, p. 20.

[263] ‘CEEC's Hydrogen Business Goes to Sea For The First Time’, *Seetao*, 9 December 2022, accessed on 8 June 2024 at https://www.seetao.com/details/194586.html.

[264] ‘中国能建氢能业务首次出海 [CEEC's Hydrogen Business Goes To Sea For The First Time]’, *China International Contractual Association*, 2022, accessed on 8 June 2024 at https://www.chinca.org/CICA/info/22120909450711.

[265] ‘央企不断进入绿氢项目，绿氢产业发展趋向规模化 [Central State-Owned Enterprises Continuously Enter Green Hydrogen Projects, Leading to the Scaling Up of the Green Hydrogen Industry]’, *Great Wall Securities*, 30 October 2023, accessed on 8 June 2024 at http://www.cgws.com/cczq/ggdt/ccyj/202311/P020231103310731801447.pdf.

[266] CEEC has already relied on this mode to export energy-related equipment. ‘全球能源建设龙头，风光火氢储多维发力、转型蝶变进行时: 中国能建 [China Energy Engineering Corporation: A Global Leader in Energy Construction, Making Multidimensional Efforts in Wind, Solar, Thermal, Hydrogen, and Storage for Transformative Change]’, *Zhongtai Securities*, 20 June 2023, accessed on 26 May 2024 at https://www.sgpjbg.com/baogao/130483.html.

[267] Whitlock, R. (2021), ‘Oracle Power Signs Cooperation Agreement for Green Hydrogen Facility in Pakistan’, *Renewable Energy Magazine*, 11 October 2021, accessed on 8 June 2024 at https://www.renewableenergymagazine.com/hydrogen/oracle-power-signs-cooperation-agreement-for-green-20211011.

[268] ‘隆基氢能与印度签署电解水制氢设备采购合同 [LONGi Hydrogen Signs Electrolyzer Equipment Procurement Contract with India]’, *BJX Hydrogen*, 4 July 2023, accessed on 8 June 2024 at https://m.bjx.com.cn/mnews/20230704/1317006.shtml.

[269] ‘隆基氢能走进澳洲 [LONGi Hydrogen Expands into Australia]’, *International Energy*, 13 July 2023, accessed on 8 June 2024 at https://xueqiu.com/5860059157/255571204.

[270] ‘氢能产业链双周评 [Biweekly Review of the Hydrogen Energy Industry Chain]’, *GUOSEN Securities*, 27 January 2024, accessed on 8 June 2024 at https://pdf.dfcfw.com/pdf/H3_AP202401281619241625_1.pdf?1706446576000.pdf.

[271] ‘中能建氢能源有限公司与隆基绿能集团座谈交流 [China Energy Engineering Corporation Hydrogen Energy Co., Ltd. Holds Talks with LONGi Green Energy Group]’, *BJX Hydrogen*, 20 November 2023, accessed on 8 June 2024 at https://m.bjx.com.cn/mnews/20231120/1344347.shtml.

[272] ‘隆基绿能与中国能建西北院达成合作 [LONGi Green Energy and China Energy Engineering Corporation's Northwest Institute Reach Cooperation Agreement]’, *Sohu News*, 6 September 2023, accessed on 8 June 2024 at https://h2.in-en.com/html/h2-2428044.shtml.

[273] ‘隆基氢能成为中国能建 2023 年制氢设备集中采购候选人 [LONGi Hydrogen Selected as Candidate for China Energy Engineering Corporation's Concentrated Procurement of Hydrogen Equipment in 2023]’, *Securities Times News*, 13 December 2023, accessed on 8 June 2024 at https://h2.in-en.com/html/h2-2431669.shtml.

[274] ‘中国能建项目竞标结果显示西方电解槽比中国贵 2 到 5 倍 [Auction results reveal that Chinese hydrogen electrolysers are two to five times cheaper to buy than Western machines]’, *China Auto*, 27 December 2023, accessed on 19 June 2024 at https://chinaautoms.com/a/new/2023/1227/24596.html.

[275] *Tracking Clean Energy Innovation: Focus on China*, IEA, 2022, pp. 87-89; Hove, A. (2021), ‘Renewable Energy: Is China’s Innovation System Adequate to Enable a Low-Carbon Transition?’, *Green*, September 2021, accessed on 9 June 2024 at https://geopolitique.eu/en/articles/renewable-energy-is-chinas-innovation-system-adequate-to-enable-a-low-carbon-transition/.

[276] Regarding when the solar PV technology became mature, Roser, M. (2023), ‘Learning Curves: What Does It Mean for A Technology To Follow Wright’s Law?’, *Our World in Data*, 18 April 2023, accessed on 6 February 2024 at https://ourworldindata.org/learning-curve.

[277] Fourcade, F. (2024), ‘China’s Energy Transition Inspiring European Investments’, *Modern Diplomacy*, 2 March 2024, accessed on 8 June 2024 at https://moderndiplomacy.eu/2024/03/02/chinas-energy-transition-inspiring-european-investments/.

[278] Nevertheless, it is possible for Chinese electrolyzer manufacturers to invest in renewable hydrogen projects and export electrolyzers in emerging markets that present less stringent trade barriers, for instance, China’s cooperation on renewable hydrogen production with the Middle East and Brazil.

[279] Regarding China’s contribution to global energy transition, see Alvik, S. (2024), ‘How Trade Friction Is Slowing Down the World’s Shift To Clean Energy’, *World Economic Forum*, 23 May 2024, accessed on 1 March 2024 at https://www.weforum.org/agenda/2024/05/clean-energy-transition-china-trade-friction/.

[280] *Global Hydrogen Review 2023*, IEA, 2023.