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

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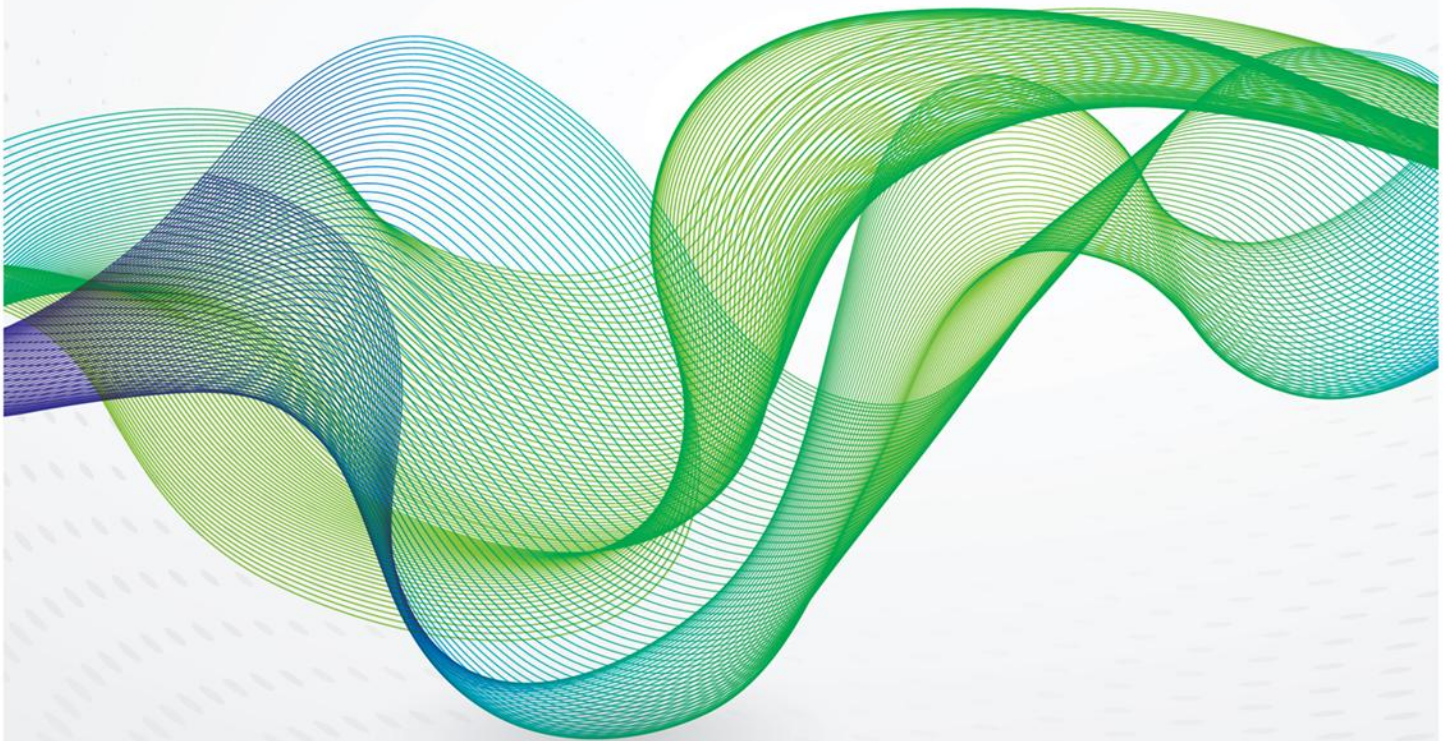
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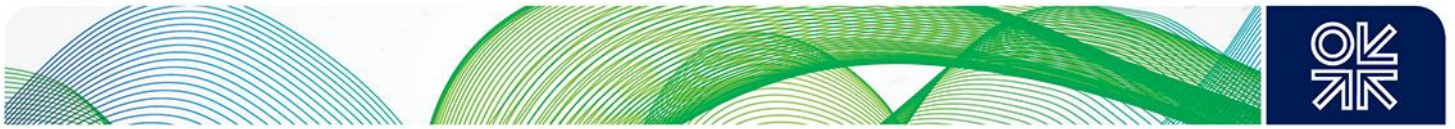
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February 2025

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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.



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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 electrolyzers. 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

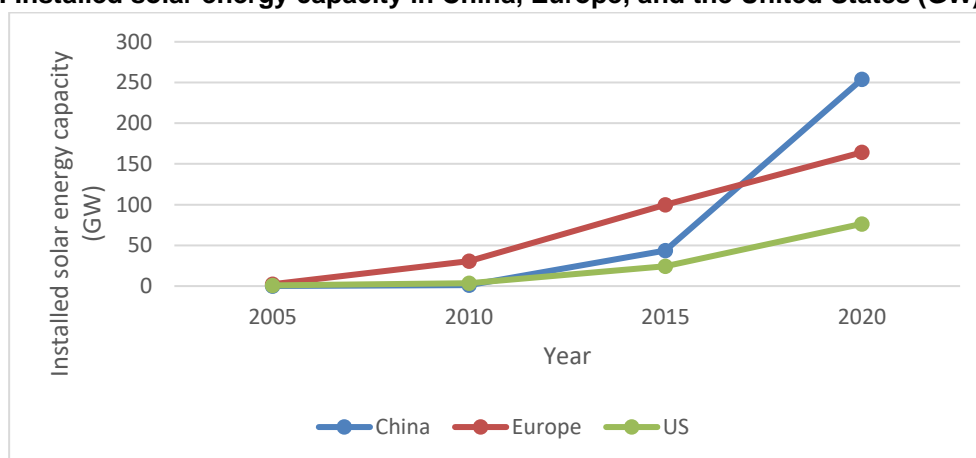
However, it was the huge export markets for solar PV, such as Spain and Germany, that stimulated the development of China's solar PV industry.¹⁶ From 2004 to 2008, the manufacturing of solar cell



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 labour²², 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

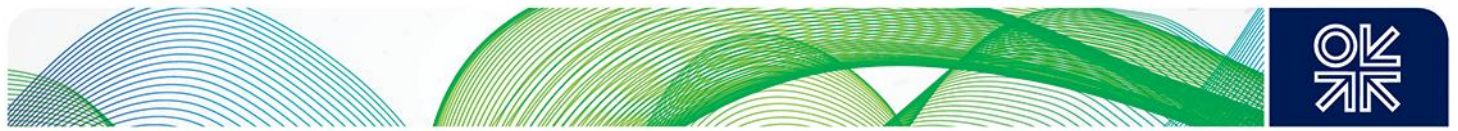
The conversion efficiency refers to the efficiency of transforming solar energy into electricity. For every 1 per cent increase in photovoltaic power conversion efficiency, the cost per kilowatt-hour decreases by 5 per cent to 7 per cent.⁴⁶ The conversion rate of monocrystalline silicon solar cells has 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 cells⁴⁹ 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 manufacturing⁶⁶, 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).

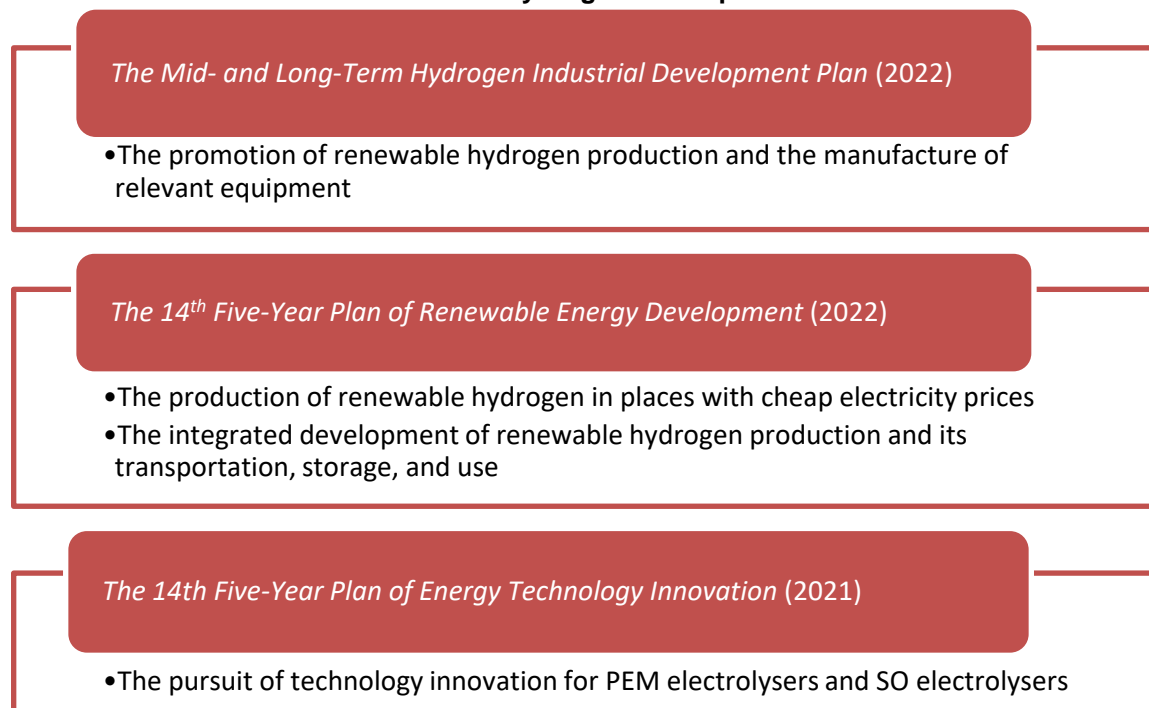


3.2 Strategies for hydrogen have shifted from a niche industry towards a key contributor to industrial decarbonization

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 licenses⁷⁴ 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



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		Hydrogen production based on wind power
	Jinfeng Science and Technology Corporation		

Source: Author, based on reports produced by securities companies⁹¹ and media⁹²

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 electrolyzers	205-230 MW	2000Nm3/h	1.5 GW
2	LONGi	POE	Alkaline electrolyzers	180-205 MW	1000Nm3/h	1.5 GW
3	John Cockerill	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 survey⁹³

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 equipment¹⁰⁰ 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 sectors¹⁰⁶ 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 infrastructure¹¹⁴ and are better equipped to deal with the bureaucratic approval procedures required for hydrogen projects¹¹⁵, 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
<i>Central support</i>		
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)
<i>Local Support</i>		
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

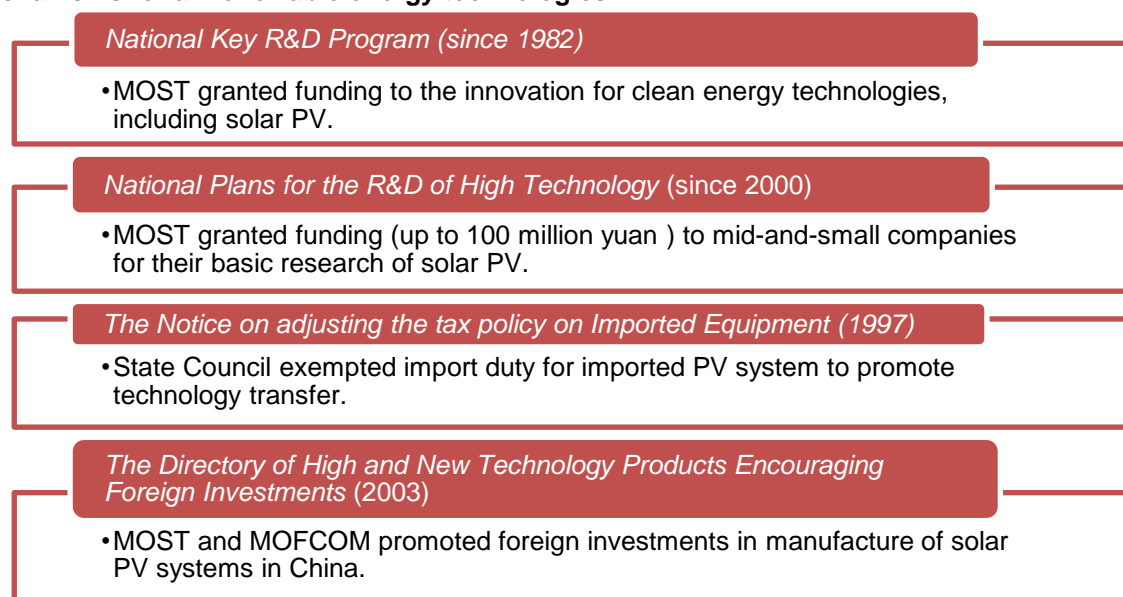
5.1 Instruments for the Early Development of Solar PV

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 production¹²⁶ (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



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 electrolyzers, 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 electrolyzers.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 electrolyzers. 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 vehicles¹⁵² sets a carbon emission standard for hydrogen of less than 15 kg CO₂ for every 1 kg of



hydrogen¹⁵³ 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 CO₂ per kg of hydrogen¹⁵⁴. 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 CO₂ 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

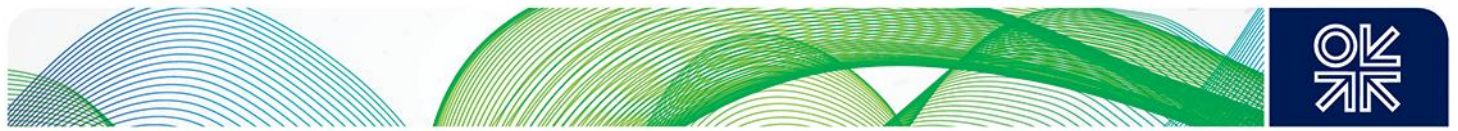
Provinces/Cities	Issuing dates	Local governments' efforts to relax the regulatory requirements governing hazardous chemicals
Wuhan	2022	Projects for hydrogen production are allowed to be operated outside chemical industrial parks. ¹⁵⁷
Shandong province	2022	Projects for renewable hydrogen production are allowed to be operated outside chemical industrial parks. ¹⁵⁸
The district of Dadong in Shenyang	2023	
Hebei province	2023	Projects for renewable hydrogen production are allowed to be operated outside chemical industrial parks. ¹⁵⁹
Jilin province	2023	
Xinjiang	2024	No safety production permit for renewable hydrogen production; ¹⁶⁰
Inner Mongolia	2024	

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 upgrading¹⁶³ and the need for China to catch up with global hydrogen technology development¹⁶⁴ 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 electrolyzers. While the government is still experimenting with hydrogen regulations and support mechanisms¹⁶⁷ 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

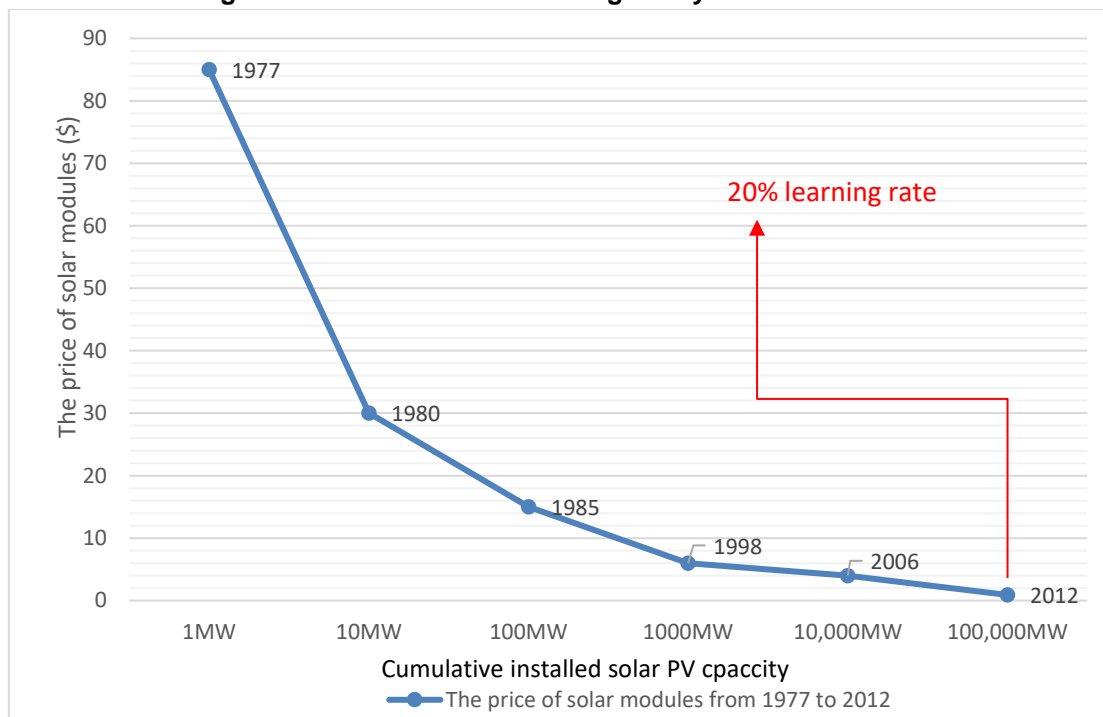
6.1 Learning rates in solar PV

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 Data¹⁹⁹

6.2 Learning rates in electrolysis

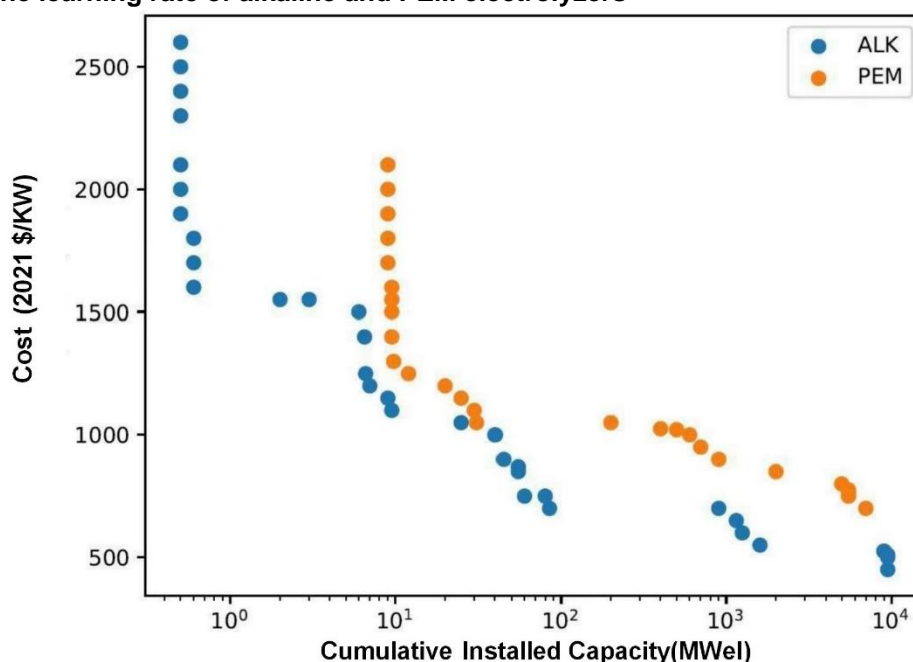
In contrast, electrolyzers are a technology with complex products and systems, including stacks design, stack manufacturing, and compressor manufacturing, all of which have their own learning rates.²⁰⁰ Consequently, the estimated learning rates for different types of electrolyzers globally vary. The 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 estimation²⁰⁹

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

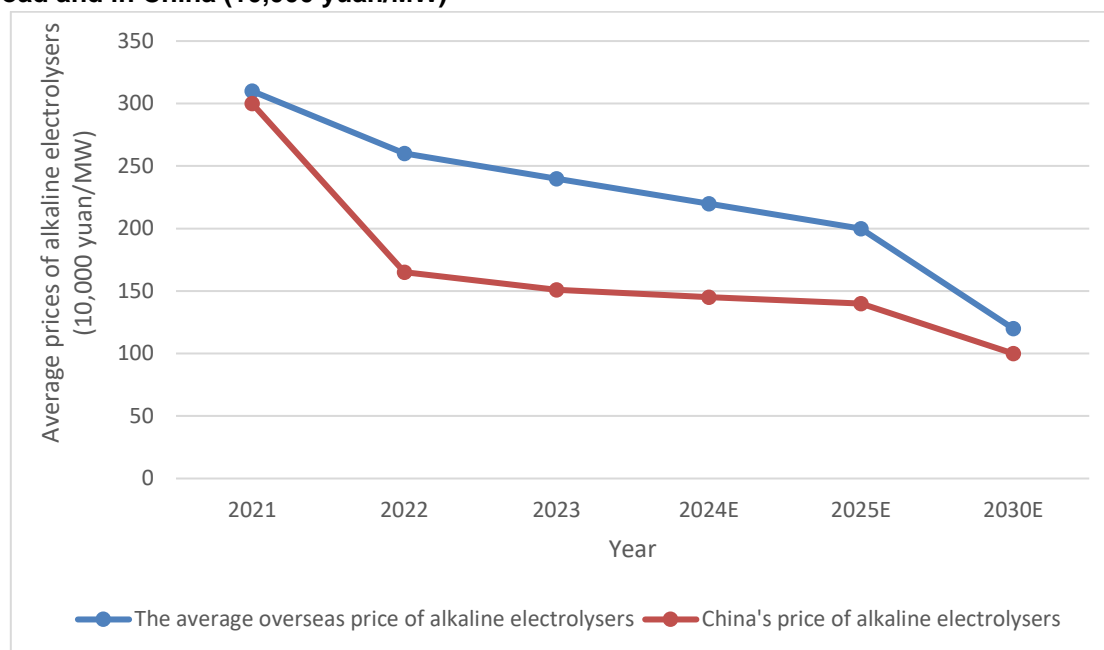
The OECD also notes that 'cost reductions [of electrolyzers] are expected to be largest during the early phase of demonstration which is starting now'.²¹⁰ As such, continuous large-scale manufacturing may contribute less to the cost reduction of electrolyzers as they mature. Significantly, because electrolyzers 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 electrolyzers. 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 electrolyzers 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 electrolyzers made both abroad and in China (10,000 yuan/MW)



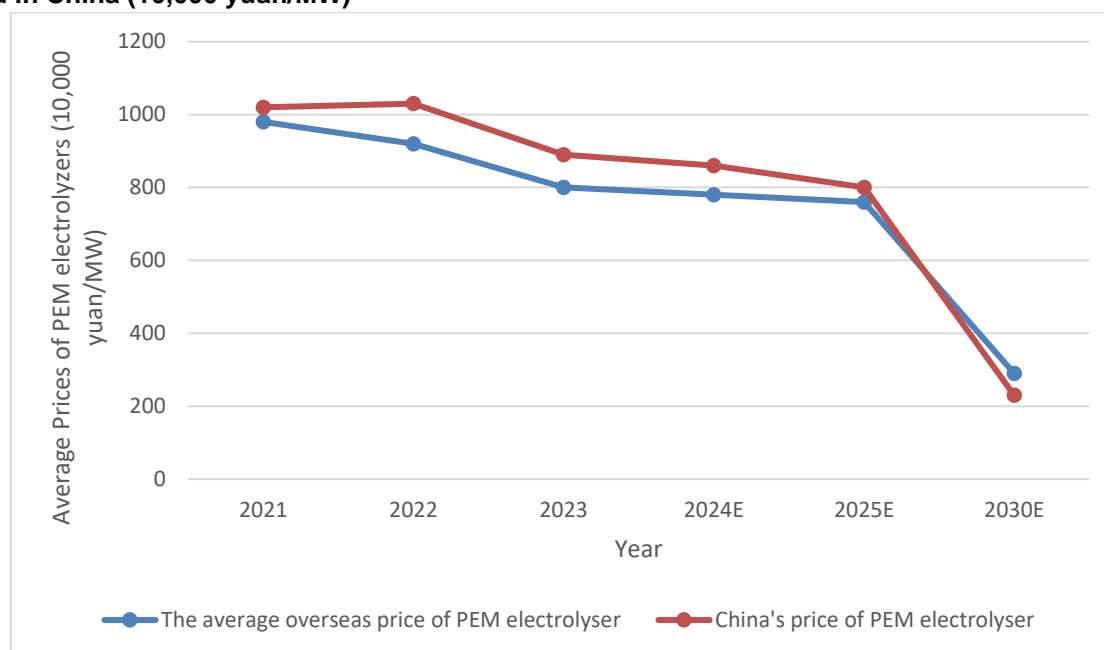
Source: Author's own, based on reports produced by consultancy or securities companies²¹⁸

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 electrolyzers (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 companies²²¹

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

Considering this, China's mature manufacturing-intensive innovation system²²² – 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 electrolyzers²³⁹ 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.

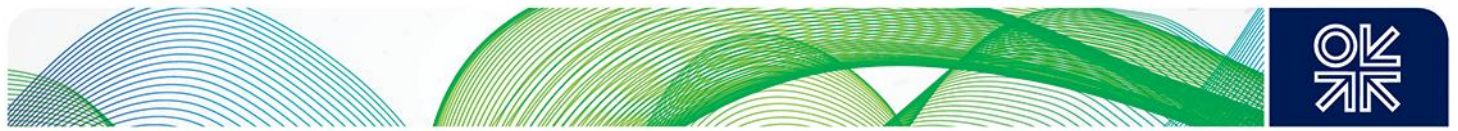
So, while tax rebates, overseas demand, and the availability of turnkey production lines from international manufacturers allowed the Chinese solar PV industry to catch up with global solar development and gradually begin to export solar cells, the outlook for electrolysis exports is more challenging. 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 development²⁴⁸) 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 states²⁵⁸ 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.

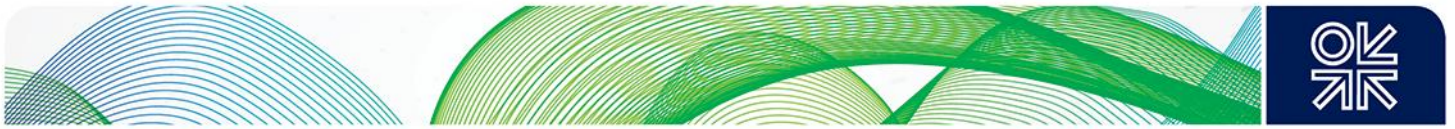
But as this paper argues, PEM electrolyzers are less likely to achieve the same significant cost declines and global market share as solar PV did for a number of reasons. First, the complexity of electrolysis systems can make it harder to achieve similar cost reductions to solar PV because it limits 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 declines²⁷⁶ 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.



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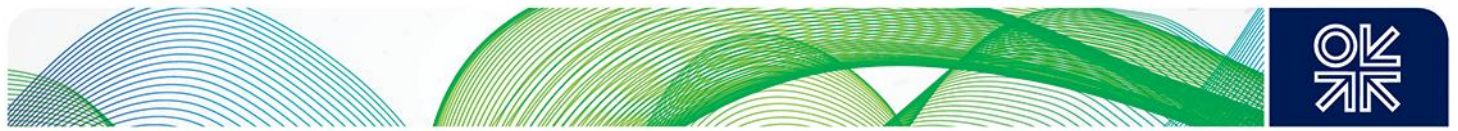
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