Testimony Before the U.S.-China Economic and Security Review Commission

Hearing: "China's Domestic Energy Challenges and Its Growing Influence over International Energy Markets"

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FOREWORD

Members of the Commission and Commission staff, thank you for inviting me to testify on China's groundwork for the clean energy economy.

I was invited to present an overview of the Chinese energy and electricity landscapes, a review of energy consumption and energy efficiency policies, and an in-depth of decarbonization potential through industrial electrification in heavy industries. Recognizing the complexity of this topic, I have slightly expanded the scope beyond the initial parameters to provide more comprehensive coverage of China's energy ecosystem. While this broader approach risks appearing unfocused, it enables me to present a cohesive framework that may serve both current and future policy discussions. The urgency of China's dual carbon goals (peaking emissions by 2030 and achieving carbon neutrality by 2060) as well as the enormity of the topic itself, demands such thorough examination.

For the last decade, the Chinese tech sector has repeatedly embodied the narrative of: "*slowly, then suddenly all at once*". From solar panels, to EVs, to next-gen nuclear power, to artificial intelligence, Chinese tech stakeholders have repeatedly demonstrated the capacity to effectively funnel resources towards a strategic technology objective, rapidly make up for lost ground versus their global peers and then leap from relative obscurity into a world-leading position, often within the matter of just a few short years.

Much has been said already about topics like solar panels and EVs, and I don't intend to retrace such well-trodden earth here. Instead, the discussion will focus on China's current efforts to develop and master carbon-reducing technologies for heavy industry and process emissions, which still garner insufficient publicity, though they will be no less impactful over the long run. These include technology solutions like coal plant high-efficiency retrofits, electrification of petrochemical production, injection of green hydrogen into steelmaking, or deployment of carbon capture for decarbonized cement production, to name just a few.

While much discourse on the China energy sector has focused on short-term negative developments on the carbon emissions front, like China's thermal power expansion and coal-dependent chemical production processes, these framings critically overlook the pivotal question: are China's current approaches structurally aligned to fulfil its climate commitments to peak and eventually neutralize carbon emissions? Independent of short-term developments appearing this year or next, is the necessary groundwork being laid to actually achieve those long-term goals? I believe the answer to those questions is yes.

To put it bluntly, there's no way for China to continue to see heavy industry to continue to play such a dominant role in its overall economy, *and* simultaneously realize whole-of-economy emissions reduction, without developing, demonstrating, and deploying *en masse* practical substitutions for fossil-fuels use in industrial processes. As I will introduce in this piece, industrial decarbonization technology is now entering the take-off phase, crossing the tipping point from academic research to rapid commercial scaling. In many of these segments, Chinese companies are already quietly leapfrogging to the front of the development race. By assertively laying the foundation for their post-2030 industrial decarbonization blueprint, China is positioning itself to dominate the critical technologies bridging its carbon peaking and carbon neutrality milestones, reshaping global climate technology markets in the process. This blueprint will transform all energy-consuming sectors, with especially profound implications for the power generation and heavy industry segments, which must pioneer a number of emergent and often still unvalidated technologies to hit their goals. These technologies are seeing demonstration implementation now, and while they won't necessarily all be successful, the ones that *are* successful will come to define global best-practices.

That being said, immense challenges still remain, particularly regarding the cost of electrification, the cost of green hydrogen, and the immaturity of the carbon-capture technology that will be needed for the hardest-to-abate sectors with the most unavoidable emissions. These challenges should not be understated or underestimated. China indeed has quite a mountain to climb, but at least it has already begun ascending. As China and Europe pull out to a dual pole position in industrial cleantech research and commercial deployment, the United States is at critical risk of being left behind.

US policymakers are also suffering, in my estimation, from a severe and persistent gap in up-to-date market intelligence on Chinese technology progress and achievements, even for segments where the relevant information is readily published via public channels and platforms. It is impossible to engage effectively with a peer nation, regardless of whether you view them as collaborator, adversary, or any combination of the two, when decision-making is predicated on incomplete or outdated views of your counterparty's activities, efforts, intentions, and capabilities. This must be rectified.

In the interest of full transparency, my hope is, and always will be, for greater cooperation between the United States and China on all cleantech sectors, industrial decarbonization included. I believe such collaboration is an unadulterated net positive for all citizens of planet Earth, regardless of nationality. An adversarial relationship can only make this monumental task at hand – the task of decarbonizing the global economy – slower and more difficult, and the outcomes for the environment (not to mention global economies) that much more damaging.

1. CHINA ENERGY OVERVIEW

1.1. ENERGY:

China's total primary energy production reached a new high in 2024, hitting 4.9 billion tons (5.4 billion short tons) of standard coal equivalent (SCE), up 3.1% from 2023. Raw coal continued to dominate the energy mix, although its share of primary energy use has declined from 72% in 2015 to approximately 67% in 2024.

Despite the slow re-orientation of the primary energy mix away from coal and in favor of primary electricity[1], fossil fuels still comprise most of China's energy use. However, primary energy demand is expected to peak in the coming years and enter a gradual decline thereafter, with coal's role declining as well.

Figure 1: China Primary Energy Composition 2015-2024

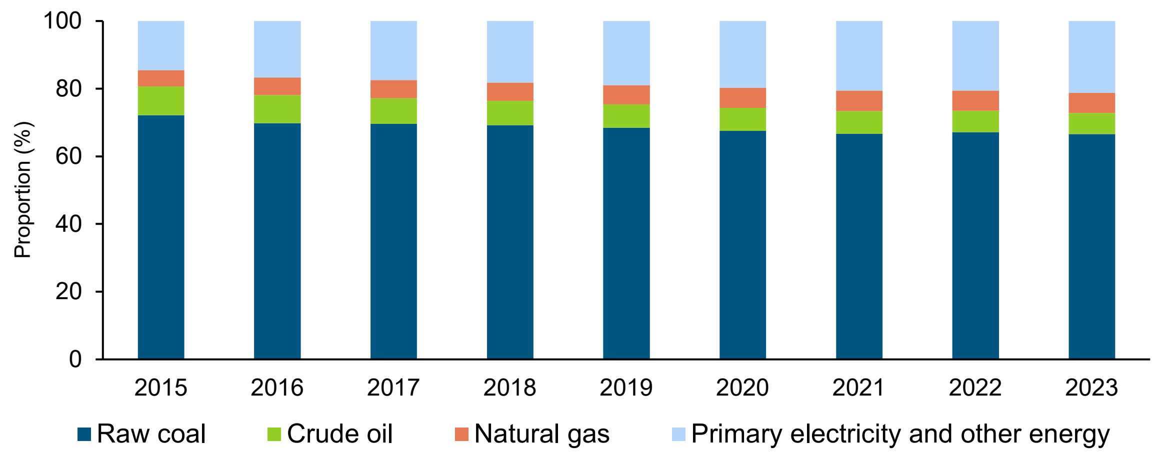
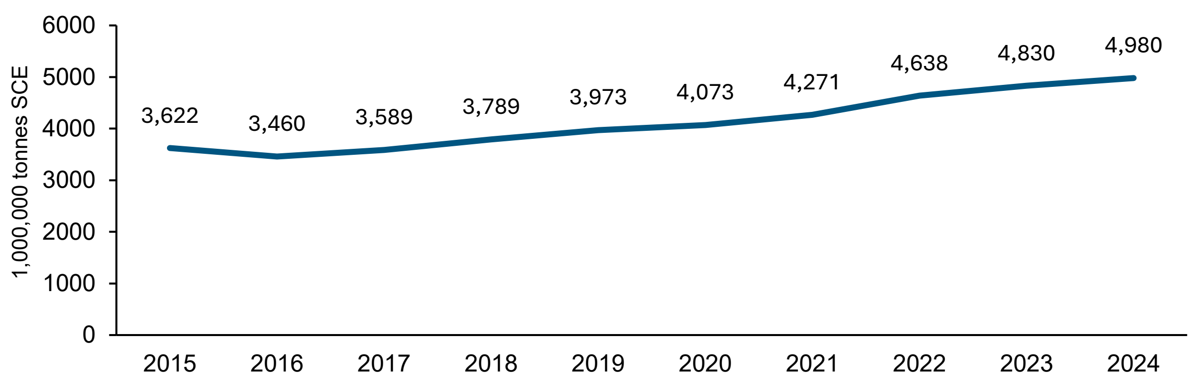


Figure 2: China Primary Energy Consumption Growth 2015-2024



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[1] Chinese statistics on primary energy employ report a metric not often used in the United States called "primary electricity." Electricity itself is *usually* defined as a secondary energy source. However, the category of 'primary electricity", when it is used, refers to electricity not produced from another primary energy source like coal or natural gas. Thus, "primary electricity" covers sources like hydropower, nuclear, solar PV, geothermal, and wind.

1.1.1. Petroleum

Chinese petroleum consumption hit 750 million tonnes (roughly 5.5 billion barrels) in 2024, declining 1.2% year-on-year. Whether this becomes a long-term petroleum consumption peak is still unclear, although the peak should certainly arrive before the end of the decade. Researchers at the state-owned China National Petroleum Corporation (CNPC) project Chinese total oil demand will peak at 770 million tonnes (5.6 billion barrels) in 2025 and decline thereafter,[2] while their state-owned competitor Sinopec projects Chinese oil consumption will peak in 2027 instead, at 800 million tonnes (5.8 billion barrels).[3] Meanwhile, financial services provider UBS Securities expects the petroleum peak will arrive as late as 2029 and start declining from 2030.[4] Notably, all these forecasts were performed *prior* to the current U.S. – China trade tensions of April 2025.

Among petroleum-consuming segments, demand in the transportation sector is widely agreed to have *already* peaked, driven by growth in alternative transportation sources, including high-speed rail, LNG trucking, and electric passenger vehicles (which accounted for 50% of new Chinese car sales in 2024). The International Energy Agency expects Chinese oil demand for transportation fuels will continue declining at an accelerating pace going forward.[5] Currently, the main segment driving petroleum demand growth in China is the petrochemicals sector, which added more than 250,000 barrels/day of demand in 2024 and is expected to continue growing at a modest pace, balancing the decline in transportation demand.

Chinese domestic petroleum reserves are limited, and expansion opportunities are limited. China imported about 73% of its petroleum in 2024, a number widely expected to fall as petroleum demand falls.

1.1.2. Natural Gas

Chinese natural gas consumption in 2024 reached 428 bcm (15.11 tcf), rising 8.4% over the previous year.[6] Industrial fuel gas was the largest consumption subsector, accounting for over 40% of total gas consumption. However, city gas has been the fastest-growing subsector, driven by the rapid expansion of the LNG-powered heavy duty trucking fleet. Power-to-gas remains a relatively small segment in China, accounting for just 67 bcm (2.37 tcf) of demand in 2023.[7]

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[2] “中石油经研院：中国石油需求将于 2025 年左右达峰,” December 11, 2024. https://companies.caixin.com/2024-12-11/102267051.html.

[3] Cao, Ella. “China’s Oil Consumption to Peak by 2027, Says Top Refiner Sinopec | Reuters.” Reuters, December 19, 2024. https://www.reuters.com/world/china/sinopec-forecasts-chinas-petroleum-consumption-peak-by-2027-2024-12-19/.

[4] Liu Yukun. “Petroleum Demand Forecast to Peak by 2029.” Chinadaily.com.cn. November 21, 2024. https://www.chinadaily.com.cn/a/202411/21/WS673e8e56a310f1265a1cec40.html.

[5] IEA. “Oil Demand for Fuels in China Has Reached a Plateau – Analysis - IEA,” March 11, 2025. https://www.iea.org/commentaries/oil-demand-for-fuels-in-china-has-reached-a-plateau.

[6] “2024 年 12 月份全国天然气运行快报.” 国家发展和改革委员会 January 23, 2025. https://www.ndrc.gov.cn/fggz/jjyxtj/202501/t20250123_1395858.html.

[7] Center on Global Energy Policy at Columbia University SIPA, CGEP. “Rising Production, Consumption Show China Is Gaining Ground in Its Natural Gas Goals - Center on Global Energy Policy at Columbia University SIPA | CGEP %,” April 7, 2025. https://www.energypolicy.columbia.edu/rising-production-consumption-show-china-is-gaining-ground-in-its-natural-gas-goals/.

Chinese gas demand will continue to grow beyond 2030 and potentially not peak until the end of the next decade, according to the state-owned China National Offshore Oil Corporation (CNOOC).[8] CNOOC predicts Chinese annual gas consumption will reach 700 bcm (24.72 tcf) when it peaks in 2040, while the International Gas Union expects Chinese gas consumption will reach 650 bcm (22.95 tcf) by that time.

China produced about 250 bcm (8.83 tcf) of gas domestically in 2024, meeting about 60% of its gas needs.

1.1.3. Coal

Coal meets the majority of China's primary energy demand, with raw coal consumption rising 2.3% YoY in 2024 to 4.59 billion tonnes (5.06 billion short tons). Major coal consumption segments include power generation (estimated to comprise about 60% of Chinese coal consumption), production of steel (15%), production of coal chemicals (8-10%) and production of building materials like cement and glass (about 6-10%). The last few percentage points go to smaller industrial applications, production of non-ferrous metals, and heating buildings (particularly in northern China, where small-scale coal boilers may still be found, despite official policy discouraging their use).

While coal consumption for power generation has seen slow growth and is close to peaking as renewable deployments ramp, the outlook for consumption of coal in other industry sectors is less clear as it depends on those sectors' performance. Demand for building materials has been sluggish following the contraction of the Chinese real estate market, and this sector is not expected to contribute much growth to coal demand going forward, but demand in the steel and chemicals segments could still rise. After coal consumption for power generation peaks, consumption in industrial segments could continue to prop up coal demand, even beyond the overall emissions peaking deadline of 2030. The likelihood of this happening is likely highest in the coal chemicals segment. However, the China National Coal Association currently forecasts overall Chinese raw coal use will peak by 2028.[9]

China is particularly notable for its heavy reliance on its abundant domestic coal to produce chemicals like ammonia, methanol, and even olefins, which in other countries are often produced using petroleum or natural gas as feedstock instead. Producing these chemicals with coal in China is rational, considering the distribution of China's fossil fuel resources; However, the coal-based pathway to production of these chemicals is usually much more carbon-intensive than using natural gas; for instance, ammonia produced from coal instead of gas releases 4x more carbon emissions.

More than 90% of Chinese coal consumption is met by domestic production. While Chinese domestic coal production capacity is sufficient to meet 100% of domestic needs, domestic mines are mostly located in the north of the country, which opens the door for competitively priced imports in the south.

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[8] Argus Media. "China's Natural Gas Consumption to Peak in 2040: CNOOC." *Latest Market News*, May 23, 2024. https://www.argusmedia.com/en/news-and-insights/latest-market-news/2571046-china-s-natural-gas-consumption-to-peak-in-2040-cnooc.

[9] Liu Yukun. "Association: Coal use forecast to peak by 2028." Chinadaily.com.cn. April 10, 2025. http://chinadailyglobal.com/a/202504/10/WS67f71da0a3104d9fd381e7f9.html

1.2. ELECTRICITY

1.2.1. Power Generation

The Chinese power sector is the largest in the world, with total power generation from all sources in 2024 reaching 10,087 terawatt-hours (or over 10 petawatt-hours).[10] After accounting for line losses, this allowed for 9,846 terawatt-hours of electricity consumption across all segments.

Table 1: China Electricity Generation Mix 2024

Power Source	Generation Volume	Percentage of Total *(with rounding)*	Comments
Coal	5528 TWh	54.8%	
Wind and Solar	1836 TWh	18.2%	
Hydropower	1426 TWh	13.4%	*Recovered partially, but not fully, from drought conditions in 2022/23*
Nuclear	451 TWh	4.5%	
Gas	241 TWh	2.4%	
Other	606 TWh	6.0%	*Includes biomass, waste-to-power, geothermal, wave energy, etc.*

In 2024, Chinese power generation rose 6.8% year-on-year, adding 631 TWh of new generation. For context, this is roughly equal to the entire power consumption of South Korea in 2023 (618 TWh). Of this growth, 522 TWh was provided by low-carbon sources (wind, hydro, solar PV, and nuclear). Again, to place this in context, this is slightly more than the entire power consumption of Germany in 2023 (506 TWh). Low-carbon power generation met roughly 83% of China's 2024 growth in power generation, with the remaining 17% met by rises in coal, gas, and other thermal generation.

Coal-fired power generation grew 1.7% year-on-year to 5528 TWh, however its overall role in the generation mix continued to decline, as other generation sources grew at a faster pace, causing it to end the year at roughly 55% of the total mix. Looking ahead, coal's share of the overall power generation mix will continue to decline, driven by tightening climate targets, slowing power consumption growth rates, and continued high levels of investment in clean energy. The portion of power provided by burning coal should drop to ~50% by 2030.

Once clean energy generation growth is able to consistently meet or exceed 100% of power consumption growth, coal-fired power generation will peak and begin to decline. This is likely to happen sometime in the next 2-3 years, depending on renewable capacity additions, hydropower performance, and economic conditions in the industrial sector. Long-term, power consumption will continue to grow well past China's carbon emissions peaking deadline, as industrial sectors, transportation, and buildings continue to substitute fossil fuels for electricity. Thus, while Chinese *energy* consumption is expected to peak in the

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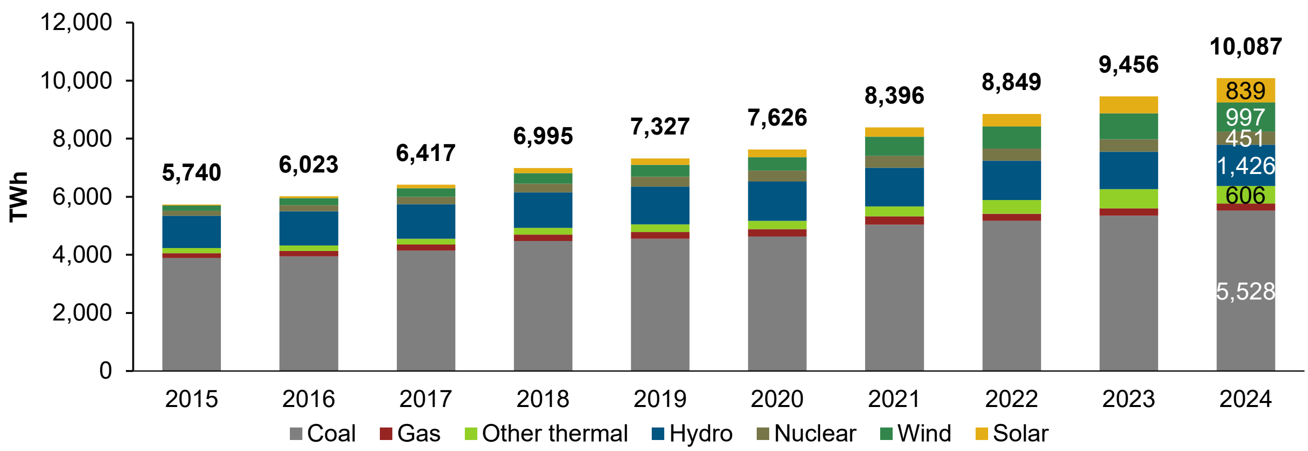
[10] "国家数据." National Bureau of Statistics. https://data.stats.gov.cn/search.htm?s=%E5%8F%91%E7%94%B5%E9%87%8F;

early 2030s, *electricity* consumption could continue growing for many decades thereafter. Consistent high rates of renewables additions plus industrial transformation to be needed to decrease reliance on coal as consumption continues to rise.

Figure 3: China Power Generation 2015-2024



1.2.2. Power Consumption

China divides its power consumption segments thusly:

- Primary industry (agriculture, aquaculture, and animal husbandry)
- Secondary industry (manufacturing and mining[11])
- Tertiary industry (commerce and services)
- Residential (commonly also called households or domestic consumption in international reporting)

Traditionally, secondary industry has been the largest power-consuming segment, driven mostly by manufacturing (which accounts for 95% of power consumed in the segment). The tertiary industry and residential sector have only started to play a larger role in the consumption mix in the last decade, following the growth of the consumption economy and continuing expansion of household wealth. However, power consumption in tertiary industry and households together still only account for about half as much as secondary industry.

Table 2: 2024 China Power Consumption by Segment[12]

Segment	2024 Total Consumption	% of Total
Primary Industry	136 TWh	1.4%

[11] Mining is classically considered to be part of primary industry in economics theory; however, within China's national accounting system is it counted within secondary industry.

[12] "2024 年全社会用电量同比增长 6.8%." 国家能源局. January 20, 2025. https://www.nea.gov.cn/20250120/4f7f249bac714e7693adecac996d742f/c.html.

Secondary Industry	6390 TWh	64.8%
Tertiary Industry	1830 TWh	18.6%
Residential	1490 TWh	15.2%
Total	9846 TWh	100%

1.2.3. Drivers of Power Consumption Growth

- **Secondary industry power consumption** trends are strongly correlated with economic activity in the manufacturing segment. In other words, when industrial value-added portion of GDP rises, industrial power consumption also rises.
- On the other hand, **tertiary industry power consumption** is driven by two things: economic activity (i.e., services consumption) AND the weather (severe hot or cool weather drives cooling and heating demand in, e.g. shopping malls and hotels). Regression analysis can help isolate out the effects.
- Finally, **residential power consumption** growth in developing countries is typically driven by the household electrification rate. However, since China's household electrification rate is already 100%, Chinese residential power consumption growth is now mostly driven by the rising penetration rate of electrical appliances (especially air conditioners) and the weather (hot or cold weather drives cooling or heating demand, just like in the services segment).

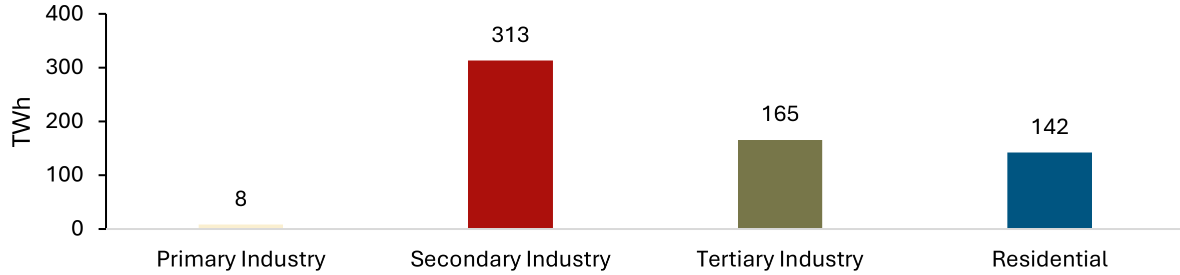
Table 3: 2024 China Power Consumption Growth Drivers

Segment	2024 YoY Consumption Growth Rate	% of 2024 Consumption Growth
Primary Industry	6.3%	1.3%
Secondary Industry	5.1%	49.7%
Tertiary Industry	9.9%	26.3%
Residential	10.6%	22.7%

While secondary industry remains the largest consumption segment in China by far, its growth rate in 2024 was considerably lower than that of the tertiary industry and residential segments, reflecting both a much higher base and persistent economic headwinds for the industrial sector.

In 2024, the tertiary industry and residential segments together added nearly as much new power consumption as the secondary industry segment, reflecting their higher rates of growth from a lower base. This trend will likely continue and even accelerate into the coming years, as manufacturing portion of GDP continues to shrink, services portion of GDP continues to grow, and household incomes continue to rise.

Figure 4: Comparison of China 2024 Power Consumption Growth Drivers by Segment



Despite its high total power consumption levels, China's annual power consumption *per capita* is still relatively modest, reaching roughly 7,000 kWh in 2024. This is now roughly on par with developed economies like Germany and Japan, and about 70% of the power consumption level per capita in countries like the United States, Canada, or Australia.

Furthermore, Chinese households still consume much less power per capita than their counterparts in developed countries. In 2024, Chinese residential power consumption per capita was approximately 1,000 kWh, around one-fourth of the average residential consumption level per capita in the USA.[13]

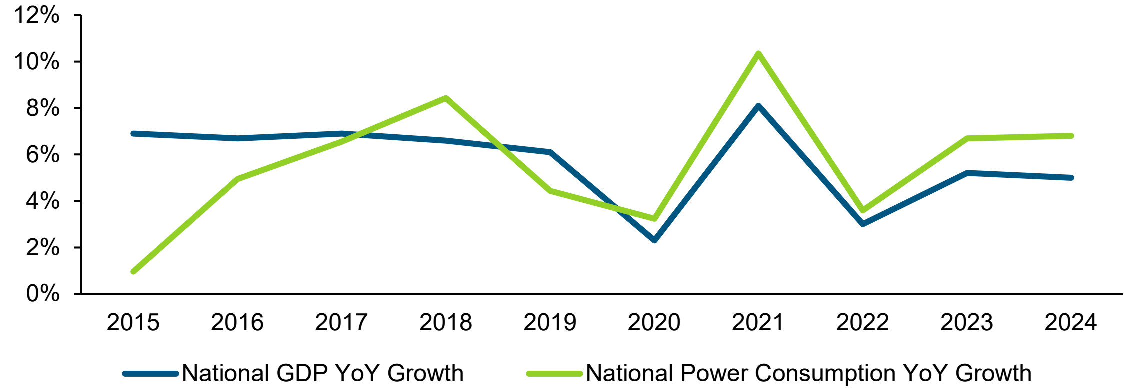
1.3. GDP Growth vs. Power Consumption Growth

Chinese GDP growth and power consumption growth have historically been well correlated, exhibiting a strong and predictable elastic ratio. In recent years, this relationship has changed slightly, with the correlation remaining, but elasticity ratio changing, with power consumption growth rate now consistently surpassing the GDP growth rate. This can be attributed to a combination of several factors:

- The ongoing electrification of industrial processes that traditionally use fossil fuels, such as steel, cement, and machinery production. This drives up electricity consumption while leaving GDP unchanged. This driver will continue to be relevant while there are still industrial processes to electrify.
- Extreme weather patterns, particularly hotter summers, have increased the use of air conditioning in residential, commercial, and industrial settings. This drives up electricity consumption but contributes little to GDP growth. This driver will continue to be relevant as extreme weather and hotter summers become more common.
- Stronger post-pandemic growth in energy-intensive industrial sectors like coal chemicals and aluminum manufacturing. Heavy industries tend to use more electricity to generate GDP activities than light industry or services like finance or healthcare.
- Intensive competition among industrial producers, causing them to focus on cutting costs and expanding output, rather than improving profit margins. This leads to increased power consumption sans a proportional rise in GDP, as lower-margin goods contribute less value in an accounting sense.

[13] Francis, Mickey. "Per Capita U.S. Residential Electricity Use Was Flat in 2020, but Varied by State ." U.S. Energy Information Administration, August 6, 2021. https://www.eia.gov/todayinenergy/detail.php?id=49036#:~:text=Per%20capita%20U.S.%20residential%20electricity%20use%20varied%20widely%20across%20the,Missouri%20(%2D3%25%20each.

Figure 5: China 2015-2024 Power Consumption Growth versus GDP Growth



However, this gap between GDP growth and power consumption growth is unlikely to persist in the mid/long term. As China accelerates its transition toward a more service-oriented and high-value economy, electricity consumption growth rates will slow again, re-aligning with GDP growth, and shrinking the gap between the two, which could happen by around 2030. In the long run, especially under a new economic model centered around services and innovation, electricity consumption could even grow more slowly than GDP.

1.4. The Role of AI and Data Centers in Driving Power Consumption Growth

Chinese power industry association the China Electricity Council (CEC) predicts total power consumption for computing infrastructure will hit 360 TWh in 2025, comprising 3-3.5% of total power consumption.[14] Of this, some smaller fraction represents the capacity needed to support artificial intelligence (AI) computing, representing a small but rapidly growing portion of services power consumption growth.

According to CEC estimates, as recently as 2019, data centers in China consumed just 60-70 TWh of electricity, accounting for only 0.8% to 1% of the country's total electricity consumption. According to calculations by China's computing power platform, in 2023, data center consumption had grown to approximately 150 TWh, or about 1.6% of total electricity consumption nationwide, with an average annual growth rate of around 21%. [15] According to 2024 comments from the Vice GM of the China Energy Engineering Corporation (CEEC) power consumption for computing infrastructure will expand very rapidly in the next five years reaching as much as 1,100 TWh by 2030.[16]

[14]"电力消费新增长点 今年用电量将达 3600 亿千瓦时." 北极星电力新闻网, April 2025. https://m.bjx.com.cn/mnews/20250401/1434821.shtml#:~:text=%E4%B8%AD%E7%94%B5%E8%81%94%E9%A2%84%E8%AE%A1%EF%BC%8C2025,%E9%87%8F%E5%8D%A0%E6%AF%94%E6%8E%A5%E8%BF%916%25%E3%80%82.

[15]Chen, Yu. "算力的尽头是支撑性电源." 中国电力企业管理, February 27, 2025.

[16] As reported in Southern Energy Observer by reporter He Nuoshu on 11 July, 2024. Article retrieved at https://mp.weixin.qq.com/s/COfGh1l_254hNaYMIRPn4Q

2. ENERGY POLICY AND DECARBONIZATION

2.1. THE 2030/2060 "DUAL CARBON" TARGETS

China has set an official target of 2030 to peak its carbon emissions, followed by a 2060 target for carbon neutrality. The 2030 peak is likely to be reached early, and perhaps already arrived last year, according to analysis from the Helsinki-based Centre for Research on Energy and Clean Air[17], suggesting an "early peak". However, this early peak is likely to be more of a plateau from 2025-2030, before declining from 2030 onward, based on the continued high rate of electricity consumption growth. The Chinese government has made no official acknowledgement of the flat emissions growth in 2024 and maintains the official peaking target to be 2030.

2.2. ENERGY CONSUMPTION CONTROL AND DECARBONIZATION POLICIES

2.2.1. China's High Energy-Consuming Industries

Chinese energy policymakers have promoted many targeted policies in recent years to control/reduce energy and carbon emissions, across the economy and in heavy industry especially. These policies usually specify actions for China's 8 High Energy-Consuming Industries (HECI). The 8 HECIs are:

- Power generation
- Petrochemicals (ethylene, propylene, benzene, xylene, etc.)
- Other basic and fine chemicals (methanol, ammonia,[18] caustic soda, soda ash, sulfuric acid, etc.)
- Building materials (mostly cement and glass)
- Steelmaking
- Non-ferrous metals (production of aluminum, copper, zinc, nickel etc.)
- Papermaking
- Aviation (particularly fuel)

Decarbonization policies enacted at the highest level to control energy consumption and carbon emissions across the 8 HECIs include:

- The "Dual Controls" mandates, which impose performance benchmarks for energy consumption and energy intensity for high energy-consuming industries. Dual-controls policies have been amended to focus on carbon consumption and carbon intensity, rather than energy consumption and intensity.
- Minimum renewable power consumption mandates, called a renewable portfolio standard (RPS) which have already been rolled out for the power sector and some HECIs, with all HECIs to be folded into the RPS system by 2030.

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[17] Myllyvirta, Lauri. "Analysis: Record Surge of Clean Energy in 2024 Halts China's CO2 Rise ." Centre for Research on Energy and Clean Air, January 27, 2025. https://energyandcleanair.org/analysis-record-surge-of-clean-energy-in-2024-halts-chinas-co2-rise/.

[18] Methanol and ammonia are typically classified as petrochemicals, however they are primarily produced via coal gasification in China, thus they are considered coal chemicals here, not petrochemicals.

- A carbon emissions cap and trade system, which has only been rolled out for the power industry, but will soon include cement, steel, and aluminum, along with the rest of the HECIs by 2030.

Other policies, for example enforcement of energy efficiency benchmarks for certain sectors, are generally driven by these national objectives. Energy efficiency initiatives specifically support the Dual Controls mandates by reducing both energy consumption and intensity.

2.2.2. Energy Dual Controls and Carbon Dual Controls

The Energy Consumption Dual Controls: Introduced in 2015 during the 13th Five-Year Plan, the first iteration of this scheme aimed to **cap total energy consumption** at 5 billion tons of SCE and **reduce energy intensity** (defined as energy use per unit of GDP) by 15% by 2020 (energy consumption and energy intensity are the dual indicators to be controlled). This initial intensity goal was met by 2020.[19]

In 2021, the Chinese government proposed the "energy dual controls" evolve into "carbon dual controls" instead, targeting total carbon emissions and carbon intensity. Key goals for 2025 included another 18% reduction in carbon intensity and another 13.5% reduction in energy intensity. Provinces are evaluated individually and scored on their progress like a "report card". Provincial governments, in turn, promote implementing policies to the heavy industries operating within their jurisdiction.

To meet the dual controls objectives, provinces have pushed heavy industries to align themselves with industry best practice equipment and production standards, with manufacturers who are unable to meet the industry benchmarks forced to retrofit or shut down. However, some HECIs are just naturally high in carbon intensity or energy intensity, even when they are meeting industry best practice benchmarks. The post-pandemic economic development strategic in China has seen considerable growth in energy intensive industries, making adherence to the Dual Control targets a challenge.

By 2024, China had made some progress towards these goals but was **behind pace** to meet its 2025 targets. According to analysis published in Carbon Brief in early 2024, China would need to reduce carbon intensity by 7% in each of 2024 and 2025 to hit its 2025 carbon intensity goal, which it did *not* accomplish. Carbon intensity ended up falling just 3.4% in 2024, which missed the official target of 3.9%.[20] and the energy intensity goals for 2025 are likely to be missed as well.[21] This doesn't necessarily endanger the 2030 carbon peaking target, which is still five years away, but is a concerning sign worth monitoring.

2.2.3. Renewable Portfolio Standard (RPS)

China enforces a Renewable Portfolio Standard (RPS) policy, mandating certain sector entities to meet minimum renewable power consumption levels. Obligated entities may comply with RPS by buying green power or green energy certificates. The RPS level is differentiated by province, according to their renewable energy resources, and rises each year (usually +1% per year). Thus, a province like Sichuan with its

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[19] To be precise, Chinese official sources state *carbon intensity* decreased by 18.8% from 2015-2020, which is an imperfect proxy for energy intensity, which unfortunately was not reported following the re-focus from energy controls to carbon controls.

[20] Hale, Erin. "China's Missed Emissions Target Poses Challenge to Global Climate Efforts." Al Jazeera, March 25, 2025. https://www.aljazeera.com/news/2025/3/25/chinas-missed-emissions-target-poses-challenge-to-global-climate-efforts.

[21] Myllyvirta, Lauri. "Analysis: Record Drop in China's CO2 Emissions Needed to Meet 2025 Target." Carbon Brief, May 10, 2024. https://www.carbonbrief.org/analysis-record-drop-in-chinas-co2-emissions-needed-to-meet-2025-target/.

abundant hydropower has a relatively high RPS level (70%) while a coastal province with no hydropower resources and limited available land to build local renewables will have a lower RPS level (e.g., 20%).

The NEA and NDRC have called for the nationwide total share of renewables generation currently at 32%, to reach 40% by 2030.[22]

Until recently, only power sector entities, including grid companies, retailers, and wholesale power buyers, were mandated to meet the RPS at the national level. However, HECIs are now starting to be added into the RPS scheme as well, including aluminum since 2024. All HECIs will be included in the RPS scheme before 2030. Additionally, power consumption for data center operations is now subject to national mandates for renewable power consumption too, although data centers were not traditionally included in the list of HECIs.

Policies in some provinces have already moved faster than the national mandates. Inner Mongolia, for instance, has already announced *all* HECIs will be folded into its RPS by the end of 2025.

2.2.4. Emissions Trading Scheme

China launched a national carbon trading scheme in 2021, which initially covered just power generators. However, in March 2025, the carbon trading market was expanded to cover steel, cement, and aluminum, covering 60% of China’s total emissions, according to the Ministry of Ecology and Environment.

Under the national carbon trading scheme, firms are allocated a quota of free emission allowances according to national benchmarks. If their emissions exceed the quota, they must purchase additional carbon emission allowances via the carbon market. So far, the quotas have been quite generous, leading to low demand for allowances and depressed carbon prices. Carbon trading will become a more effective tool for decarbonization when more firms are pulled into the scheme, free quotas drop, and higher carbon prices become an effective motivator to promote changes in behavior. This should all happen before 2030, but for now the national carbon market is currently still more of a pilot/demonstration effort, teaching obligated entities the mechanics of carbon trading while limiting the real burden imposed.

2.2.5. Coal Plant Efficiency Standards and Retrofits

While Chinese power generation is still highly reliant on coal-fired power, policy stakeholders have also set very aggressive policies for coal plant efficiency and performance standards, ensuring Chinese coal plants are among the most efficient and “cleanest” in the world (as least, as clean as coal can get). This has been reported previously by other international research institutions for nearly a decade, for instance, the DC-based Center for American Progress, in their provocatively-titled 2017 report: “*Everything You Know about Coal in China is Wrong*”:[23] Their findings included:

- China’s new coal-fired power plants are more efficient than anything operating in the United States.
- China’s emissions standards for pollutants from coal-fired power plants are stricter than comparable standards in the United States.

[22] 北极星储能网. “能源局可再生能源消纳目标征意见！2030 年全国统一消纳责任权重 40%.” February 10, 2021. https://news.bjx.com.cn/html/20210210/1135946.shtml.

[23] Center for American Progress. “Everything You Think You Know About Coal in China Is Wrong,” May 15, 2017. https://www.americanprogress.org/article/everything-think-know-coal-china-wrong/.

- Despite rapid growth in generation capacity, Chinese coal-fired power plants continue to see lower annual operating hours as they are displaced by low-carbon alternatives.

These trends have only deepened since 2017, as power sector reform and aggressive policy mandates for coal-power have ensured Chinese coal plants continuously operate at the frontier of what is technologically possible for the technology. Using coal efficiently, in new ultra-supercritical coal plants, with high-efficiency boilers that maximize the energy extracted from the coal, makes just as much of a contribution to trimming emissions as replacing coal with renewable power, especially considering the long-term backup/peak smoothing role China's coal plants are expected to play in the grid mix.

In 2022, the NDRC mandated the coal-fired fleet reduce its coal consumption rate from 305.5 grams (10.78 oz) of standard coal per kWh to 300 grams (10.58 oz) by 2025. Back in 2005, this number stood as high as 370 grams (13.05 oz), making the 2025 target a 23% reduction. Meanwhile, no new plants can be approved that consume more than 285 grams/kWh (10.05 oz). Retrofits applied to already-existing plants ensure they can operate as efficiently or even more efficiently than newbuilds. A 2023 POWER magazine article described a newly retrofit Chinese coal plant as "The World's Most Efficient Coal Plant"[24] with the Phase 2 unit consuming as few as 251 grams/kWh (8.85 oz).[25]

Beyond this, newly-built coal plants are mandated to be able to ramp from 80% power output to as low as 30% output, and back up to 80%, in a matter of just hours, an uncommon and technically challenging operating regime for any coal plant in the world, but increasingly typical for Chinese coal plants forced to operate as load followers, like gas plants in the USA. Meanwhile, power market reforms have forced coal plants into the merchant market, competing against other generation types, where they now see annual fleet-wide capacity factors lower than 50%, necessitating capacity payment to maintain their solvency.

Such actions are necessary for China's long-term energy transition planning; China simply does not have the natural gas reserves countries like the United States are able to leverage to support the integration of variable renewable generation like wind and solar. Instead, coal will fill this role. Coal will remain integral to China's power generation mix for a long time, and while they are, it's in both China's and the world's interest that those coal plants operate as efficiently as possible. While early and more proactive steps to reform power markets could have resulted in fewer coal plants being added over the long-term, the new coal plants built in China these days are as superlatively efficient and "clean" as they possibly can be.

2.3. National Low-Carbon Demonstration Projects

Far from being just an empty title, National Demonstration Project is a powerful designation with many practical benefits to project owners, including direct financial and fiscal support, policy and approval advantages, increased access to technology and talent resources, prioritization in government procurement events, and long-term institutional backing from local authorities (for example, being written into the province's five-year plan). China uses the official designation of National Demonstration Project to identify projects with high strategic or symbolic value for technological breakthrough application.

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24 Patel, Sonal. "China's Pingshan Phase II Sets New Bar as World's Most Efficient Coal Power Plant." POWER Magazine, October 4, 2023. https://www.powermag.com/chinas-pingshan-phase-ii-sets-new-bar-as-worlds-most-efficient-coal-power-plant/.

25 NS Energy. "Pingshan Thermal Power Plant Phase Two, Anhui Province, China," November 5, 2020. https://www.nsenergybusiness.com/projects/pingshan-thermal-power-plant-phase-two/.

In 2025, China added 101 projects[26] to its national low carbon demonstration project list, building on the 47 projects named in 2024. These projects are a direct proxy for what Chinese energy stakeholders think are the most important cutting-edge items in furthering the national low-carbon energy agenda. Some notable energy efficiency items are mentioned below (heavy industry is excluded, as it will be covered in the next section).

2.3.1. High-Efficiency Motors

China has focused heavily on improving the efficiency of electric motors. As of 2020, the efficiency level of domestic industrial motors remained below international standards, with unit efficiencies averaging approximately 75%—about 10 percentage points lower than their overseas counterparts—and system operational efficiency ranging from 30- 40% lower than the international benchmark by 20 to 30 percentage points. High-efficiency motors accounted for only 32% of total production that year. [27]

In response, Chinese authorities have adopted increasingly stringent energy efficiency standards and introduced industrial upgrading policies. The 2022 "Action Plan for Industrial Energy Efficiency Improvement," issued by the Ministry of Industry and Information Technology, aims to transform motor manufacturing through performance optimization, high-efficiency core design, and lightweight motor casings. The plan also promotes high-efficiency motor remanufacturing, targeting a 70% share of high-efficiency motors in new installations by 2025.

2.3.2. Building Retrofits

Public building retrofits are a core pillar of China's commercial sector decarbonization strategy. One notable demonstration project is the Beijing Future Building Innovation Center, designed as a near-zero energy and near-zero carbon structure. The building integrates multiple novel technologies, including high-efficiency motor systems, building-integrated photovoltaics (BIPV), hybrid photovoltaic-storage-direct current systems, and a comprehensive smart energy-carbon management platform. Upon completion, the Center achieved a 38% reduction in building-level energy use and an overall 70% improvement in energy efficiency, lowering energy intensity to below 26 kWh/sqm/year.

A second example, the Xi'an Taikoo Li Complex, similarly advances sustainable commercial architecture using shallow and mid-depth geothermal heat pump systems, multi-energy coupling heating technologies, and prefabricated construction with low-carbon materials. The facility incorporates solar panels with adjustable angles and an integrated energy storage system. Upon completion, it achieved a 70% overall reduction in energy use and a renewable energy utilization rate of 25%, serving as a model for zero-carbon commercial infrastructure. [28]

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[26] List of Advanced Green and Low-Carbon Technology Demonstration Projects (Second Batch). NDRC. https://yyglxxbs.ndrc.gov.cn/file-submission/20250402115327890451.pdf

[27] "电机能效标准严苛及降低能耗背景下 我国节能电机行业发展潜力充足." 观研报告网. May 3, 2024. https://www.chinabaogao.com/detail/706141.html.

[28] Ibid.

2.3.3. High-Efficiency Data Centers

China has also prioritized improving the energy efficiency of data centers, which are a rapidly growing source of new electricity demand.

In Zhejiang, the Jiaxing Advanced Intelligent Computing Center was developed as a near-zero carbon data center. It employs energy-efficient servers, variable-frequency centrifugal chillers, and cold-plate liquid cooling, resulting in a PUE below 1.2 and 100 percent reliance on green electricity.

In Shanghai, an underwater data center project integrates offshore wind power with ocean-based cooling systems. The 2.3 MW computing module, completely submerged underwater and powered by offshore turbines, achieved a PUE below 1.15 and 95 percent wind energy utilization, while avoiding freshwater consumption and reducing land use by 90 percent.

In Inner Mongolia, the Flexible Cooling Green Computing Center combines air and liquid cooling technologies, indirect evaporative cooling, and fluorine-pump HVAC systems. This facility maintains an average PUE of 1.14 and consumes approximately 90% green electricity. A parallel initiative in Ulanqab City further scaled this approach: the Smart Power-Computing Coordinated Data Center incorporating a 200 MW wind farm, 100 MW of solar capacity, and 180 MWh of storage, enabling direct green electricity supply. The facility's PUE remains below 1.2, with annual green electricity use exceeding 600 GWh, equivalent to an annual reduction of approximately 320,000 tons of CO2.

2.3.4. Residential Sector Applications

Energy-Efficient Appliance Innovation

One notable example is the High-Efficiency Refrigerator Green and Low-Carbon Technology Demonstration Project in Qingdao, led by Haier. This initiative integrates industrial internet systems with green manufacturing technologies, including inner-liner adsorption materials and low-cost, energy-saving insulation. The demonstration factory includes a high-efficiency refrigerator assembly line and three modular production lines, enabling the manufacture of one million energy-saving units per year and establishing a potential model for intelligent, low-carbon appliance production.

Clean Heating

Clean residential heating has also been prioritized as part of China's broader air pollution control and rural revitalization strategies. As outlined in the 2023 central government budget report, 33 billion yuan (approximately USD 4.8 billion) was allocated to promote clean winter heating in northern regions. By the end of that year, over 39 million rural households were reported to have transitioned to cleaner heating systems. These efforts have collectively reduced annual coal consumption by more than 70 million tonnes and carbon dioxide emissions by over 100 million tonnes, representing one of the world's largest energy-use transitions in rural housing. This transformation was described by Chinese authorities as both an environmental and a public welfare project, "revolutionizing" rural energy use.

Among the most prominent examples is the Phase II Geothermal Heating Demonstration Project in Xixian New Area, Shaanxi. The project employs mid-depth geothermal wells without centralized heating stations, instead utilizing distributed underground pipe arrays. With a seasonal coefficient of performance (COP) exceeding 4.5, the system serves 1.13 million sqm (12.2 million sqf) of building area and displaces nearly 20,000 tonnes of standard coal annually, corresponding to a 50,000-tonne reduction in carbon emissions.

In Jilin, the China-Korea International Cooperation Demonstration Zone established a hybrid geothermal heating and cooling system that combines shallow and mid-depth geothermal wells with multi-energy smart control systems. The project includes 11,345 shallow wells and six mid-depth wells, along with a centralized energy station and a smart supply network. Upon completion, the system will serve 1.33 million sqm (14.3 million sqf) meters of residential and commercial space.

3. HEAVY INDUSTRIAL DECARBONIZATION

3.1. HIGH ENERGY CONSUMING INDUSTRY (HECI) DECARBONIZATION LOGIC AND PATHWAYS

Before examining Chinese efforts in this space, it's important to first broadly describe the underlying chemical and physical principles of fossil fuel use and CO2 emissions in these industrial processes. At a high level, consumption of fossil fuels in HECIs can be split into two broad buckets:

Usage of fossil fuels as an **energy carrier**, usually combusting them to produce the high temperatures necessary for some step of the industrial process.

Usage of fossil fuels as a **chemical feedstock**, where the fossil fuels are chemically inseparable from the process, often via a chemical reduction process (which usually means the carbon molecule in the fossil fuel is part of the final product).

> **Important Nuance:** Some other industrial processes, such as the production of cement, release carbon via the processing of a carbon-containing mineral (for instance, in cement, the decomposition of limestone during the production of clinker releases CO2). Strictly speaking, this is a mineral-based process, not fossil fuel-derived, and cannot be addressed with electrification or substitution of fuels. However, emergent technologies to replace limestone calcination exist and are under research now.

For the purposes of this summary, industrial electrification is treated as a discrete pathway from the use of green hydrogen, although they are often performing the same function (i.e., serving as an alternative source of heat). Green hydrogen is produced via electrolysis of water with green electricity, and so it is a second-order product of electricity, not electrification itself.

As a rule of thumb, it is generally technologically feasible to replace **energy carrier applications** for fossil fuels with electrification, although cost competitiveness may remain a barrier. Similarly, combustion of green hydrogen produced via electrolysis is often a technically viable (but costly) substitute for combustion of fossil fuels.

On the other hand, when fossil hydrocarbons are **chemically integral** to the final product (e.g., petroleum-based feedstocks in plastics or chemicals) decarbonization via electrification is unviable. However, green hydrogen often also finds potential applications here as a substitute for fossil fuels, particularly as a reducing agent in chemicals production.

For scenarios where fossil fuels are chemically inseparable from the production process, the typical alternative options to consider are:

1. **Carbon Capture and Utilization/Storage (CCUS):** Capture the emitted CO2 and sequester it, or use it as a feedstock for industrial production (like synthetic fuels).

2. **Material Substitution:** Replace fuel-based products with bio-based alternatives (like algae-based bioplastics).

In some cases, decarbonization of the industry can be achieved in phased steps, where electrification allows for some gains, introduction of green hydrogen improves those gains, and carbon capture accounts for the last few percentage points. In other cases, the most reasonable approach is to commit entirely to carbon capture from the outset, because the gains possible via electrification or green hydrogen aren't impressive enough to warrant the cost.

In many or even most cases, China pursues an "all of the above" approach to decarbonization and cleantech innovation. Thus, it would not be surprising to see multiple pathways to decarbonizing the same industrial process under research or even piloting commercially at the same time, advanced by different companies and all enjoying the benefit of state funding and resource support. The most successful and economic options will see mass deployment in the end, but not until all the potentially viable pathways have been explored.

Table 4: Fossil Fuel Applications and Substitutability of Electricity or Hydrogen Across China's 8 HECIs

Industrial Segment	Fossil Fuels Application	Opportunities for Substitution with Electricity	Opportunities for Substitution with Green Hydrogen	Comments
Power Generation	Combustion of coal or natural gas to produce heat, boil water, and spin a turbine	Yes – with power produced from wind, solar, hydropower, nuclear, geothermal, etc.	Hydrogen may find some limited application in the power sector as an alternative storage medium but is likely better used in other sectors.	
Petrochemicals	Fossil fuels are used both as feedstock and as energy carriers for heat via combustion.	High-temperature applications using fossil fuels can be substituted with electric steam crackers, but the technology is very new and relatively unproven. The medium/low-temperature operations can be substituted with electric boilers and infrared heating.	Gret hydrogen can be replaced with green hydrogen in many processes, including hydrotreating, hydrocracking, catalytic reforming. Hydrogen can also provide heat for production of aromatics and alkenes.	Hydrocarbons used as feedstock are irreplaceable in the current production processes of petrochemicals. In the long term, CCUS and/or alternative materials like bioplastics may be the only way to fully decarbonize petrochemicals.
Other Basic and Fine Chemicals	Fossil fuels are used both as feedstock and as energy carriers for heat via combustion.	Depends on product. Energy carrier applications for fossil fuels can be substituted with electrified heat and/or hydrogen. Products with no carbon molecules in the final product like ammonia often have alternative production processes using hydrogen. However, products with a carbon molecule in the final product like methanol are currently chemically inseparable from the use of carbon-bearing inputs (most commonly fossil fuels) as a feedstock.		Long-term, carbon produced via CCUS can be used as a feedstock for alternative production of carbon-containing chemicals like methanol.
Building Materials	Fossil fuels are used primarily as energy carriers for heat via combustion	High-temperature applications for glass manufacturing can substitute fossil fuels in glass furnaces with electricity or hydrogen, which account for most of the fossil fuel use in glass manufacturing. High-temperature applications for cement manufacturing can substitute fossil fuels for electricity or hydrogen, but emissions from limestone calcination remain.		Cement's production also relies on a process called limestone calcination, which leads to unavoidable emissions via the decomposition of $CaCO_3$. This process must either be substituted for an alternative process, or CCUS implemented, to decarbonize cement production.
Steelmaking	Fossil fuels are used both as energy carries for heat, and as a reducing agent for iron ore processing.	Electric Arc Furnaces (EAF) can enable steel producers to utilize a different production process called direct reduced iron (DRI) instead of reliance on the traditional blast furnace – basic oxygen furnace (BF-BOF) process. This eliminates the use of coking coal but introduces the use of natural gas as a reducing agent at a later stage in the process. EAFs can also be used to produce secondary steel from scrap, offsetting demand for primary steel, but this pathway is limited by the supply of scrap.	If the steel plant is using the DRI process instead of the BF-BOF process, the natural gas typically used for reduction in this process can be almost entirely replaced with hydrogen with only trace emissions remaining. However, the cost and requirements for the grade of iron ore are higher. Hydrogen can also be cofired with coking coal in the BF-BOF process, reducing the demand for coke, but the reduction of demand is limited.	Steel plants must convert fully to 100% DRI and substitute hydrogen in the reduction process to realize decarbonized steel. If the BF-BOF process is still used, implementation of CCUS will be needed to achieve higher decarbonization levels for steel production.

Non-ferrous metals	Fossil fuels are primarily energy carriers in the production of non-ferrous metals, but some processes also rely on fossil-fuel based reduction.	Partially yes. Electricity already dominates production of these metals, particularly aluminum, but some chemically inseparable fossil fuels remain (carbon anodes for aluminum; coke for zinc or copper).	The use of coke as a reducing agent in pyrometallurgical production of zinc, and the use of coke or gas in pyrometallurgical smelting of copper could substitute hydrogen instead, but the technological and cost barriers are still very large.	Aluminum production uses carbon anodes (made from petroleum coke). Producers are exploring substitution of carbon anodes for inert anodes, which eliminate process-related emissions, but cost is a barrier.
Papermaking	Fossil fuels are energy carriers in the papermaking process, but most energy use is electricity.	Most energy use in paper production is used for drying, which can be met by electrified heating.	Combustion of hydrogen can be considered as an alternative heat source, but cost is a barrier.	Unlike many other industries, papermaking has a relatively high penetration of biomass combustion for its energy use, which creates biogenic carbon emissions and would necessitate use of CCUS to mitigate.
Aviation	Fossil fuels are chemically integral to the production of aviation fuel	Electric aircraft are a potential pathway, but battery energy density limits the application of electric-battery aircraft to short ranges only.	Hydrogen-powered aircraft are a potential pathway, but the cost of hydrogen limits their application.	Sustainable Aviation Fuels (SAF) are an emergent alternative pathway to production of jet fuel with lower emissions, although the release of CO2 is still part of their production process and would require CCUS to fully decarbonize.

Note: Some recent Chinese planning documents have started to include data centers/digital computing as a new/unofficial HECI, although it is categorized as being part of the tertiary industry sector, rather than the secondary industry sector. Data center operation can be virtually 100% decarbonized with electricity if green power is used, so while it IS a HECI, it is not a particularly problematic one to decarbonize from a technological perspective.

3.1.1. Chinese HECI Decarbonization Potential and Progress Assessment

A detailed assessment of electrification potential for ALL major carbon-emitting segments is worthy of extensive and detailed research but is outside of the scope of this exercise. Here, only an estimate of decarbonization potential via electrification for selected segments is provided, along with the additional incremental benefits of using green hydrogen or CCUS. Often these numbers represent very speculative numbers from academia or the results of just a single demo/pilot project. If a demonstration project exists somewhere in the world that can be referred to, it is usually deployed in Europe, China, or Japan.

For most industrial segments, Chinese research institutions and academic bodies are already at the forefront of decarbonization research (using electrification, green hydrogen, efficiency advancements, and/or CCUS) and have been for several years. The Chinese Academy of Sciences (CAS) has been particularly prolific in furthering industrial low-carbon research, supported by the full resource backing of the Chinese state. The role and ambition of the CAS is well summarized by a 2022 bulletin which established **CAS Strategic Action Plan for Science and Technological Support to Achieve Carbon Peak and Carbon Neutrality.** This action plan highlights eight Major Initiatives and 18 Priority Tasks, all revolving around research and deployment for industrial decarbonization.[29]

The academic and research efforts of the CAS, SOEs, private companies, universities, and various research institutes across both the public and private sector have yielded obvious fruit in the last decade. According to analysis from Nikkei, by 2024, Chinese companies held nearly half of the global total of patents related to CCUS, with issuance of patents in the cleantech and decarbonization space rising by 4x vs. 2015.[30] In a separate analysis, Nikkei reviewed research papers on Elsevier published between 2015 and 2020 across 18 cleantech-related sectors and found Chinese institutions led all other countries in 16/18 technical areas (for the last two, the United States led in paper count, barely, for research into geothermal and energy-efficient semiconductors).[31] Additionally, while not all these papers were necessarily categorized as high-quality papers, it is telling that China has also consistently led for energy research output in the Nature Index (a ranking system weighted for high-quality academic research in credible journals, and which also considers how often the research is cited by other papers).[32] By most available metrics, Chinese cleantech research, including for industrial decarbonization, is dominating in the world.

However, the commercial deployment of these technologies in China has lagged theoretical research a bit more and has only started to pick up in the last 2-3 years. While nearly every major energy-consuming industrial segment in China has at least a few demonstration low-carbon projects (either recently completed, or under construction now) their technological success or failure remains to be seen — and economic

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[29] He, Jingdong, Daquan Cao, Duan Xiaonan, et al., “Give Full Play to National Strategic S&T Force to Provide Vigorous Support for Carbon Peak and Carbon Neutrality Goals.” *Bulletin of the Chinese Academy of Sciences*, April 6, 2022. http://bulletin.cas.cn/BCAS_CH/doi/10.16418/j.issn.1000-3045.20220324004

[30] “中国脱碳技术崛起，碳捕集专利数居首.” Nikkei.com. June 18, 2024. https://cn.nikkei.com/industry/scienceatechnology/55675-2024-06-18-05-00-40.html.

[31] Misumi, Yuki. “China Hot on Heels of US in Cutting-edge Green Tech Research.” *Nikkei Asia*, June 11, 2021. https://asia.nikkei.com/Spotlight/Environment/Climate-Change/China-hot-on-heels-of-US-in-cutting-edge-green-tech-research.

[32] “Asia Leads Rise in Clean-energy Research.” *Nature* 639, no. 8055 (March 19, 2025): S24. https://doi.org/10.1038/d41586-025-00744-6.

viability is likely still years or decades away. When it comes to commercial deployment of low-carbon or zero-carbon industrial process technology (not just theoretical research) the closest peers to Chinese companies are typically European.

From a timing perspective, targeting completion of these demo projects in the late 2020s is reasonable. Even if they are successful, batch deployment of these technologies will not be strictly necessary for hitting decarbonization goals until post-2030, after the carbon peaking deadline is hit. Industrial decarbonization at scale is not necessary to peak carbon in China, but it will certainly be necessary to decrease emissions after 2030 and achieve carbon neutrality by 2060.

3.1.2. Decarbonization Potential in China for Selected Industrial Segments

Note these estimates for decarbonization potential focus entirely on technological feasibility, not economic feasibility. The percentage refers to the extent to which fossil fuels can be replaced via the indicated decarbonization pathway.

Petrochemicals

- **Electrification:** 30-40%

Electric motors can replace steam turbines and are more energy efficient as well. High-temperature cracking still relies on fossil fuels for now, but electrification can meet low-temperature heat applications and partial steam cracking via electric boilers. Electric steam cracking technologies are piloting at a BASF demonstration plant in Germany but are still very early-stage. BASF's electric steam cracking pilot in Germany targets 90% CO2 reduction, but this has not been demonstrated yet.

- **+ Green hydrogen:** 50-60%

Green hydrogen replaces fossil-based hydrogen in steam methane reforming (SMR) and feedstock production. Pilot projects show 23% emission reductions in ethylene cracking with incorporation of green hydrogen. Green hydrogen can replace grey hydrogen in production of various other alkenes and aromatics.

- **+ CCUS:** 80-90%

CCUS captures any remaining process emissions from cracking and SMR.

Situation in China: Chinese petrochemical firms and research universities are close to the technological frontier of petrochemical electrification and innovation, and lag only a few European companies in the whole world when it comes to track record for commercial deployment.

Electric steam cracking technology has been under research at the State Key Laboratory of Heavy Oil Processing at the China University of Petroleum for several years already.[33] In January 2025, The Tarim Phase II Ethylene Project announced it would be powering its triple ethylene units (cracked gas compressor, ethylene refrigeration compressor, and propylene refrigeration compressor) with electric motor drives, instead of steam turbines powered by fossil fuels. Additionally, the power for the site would be sourced from

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[33] Gao, Jinsen, Xiaogang Shi, Xingying Lan, and Chunming Xu. "A Technical Roadmap for China's Petrochemical Industry Upgrading to Achieve Carbon Neutrality." *Engineering* 29 (August 25, 2023): 55–58. https://doi.org/10.1016/j.eng.2023.05.021.

renewable energy, and the site's remaining carbon emissions would be captured via CCUS and used as feedstock for the integrated production of synthetic urea and ammonia.[34] This is a first-of-a-kind project in China.

Steel

- **Electrification:** 25-50%

Swapping the Blast Furnace-Basic Oxygen Furnace (BF-BOF) production process for Direct Reduction Iron DRI with an Electric Arc Furnace (EAFs) can cut emissions associated with steel production by 25-50%. Use of coking coal in the blast furnace is eliminated, but natural gas is introduced as a reduction agent.

- **+ Green hydrogen:** 75-95%

Hydrogen DRI replaces natural gas as a reduction agent in the DRI process, eliminating the associated emissions. ArcelorMittal's Sestao facility in Spain claims ~75% decarbonized steel using hydrogen DRI and EAF.[35] Up to 95% is theoretically possible.

Alternatively, green hydrogen may be injected into the BF-BOF process as a substitute for coking coal.

- **+ CCUS:** 90-100%

If using hydrogen DRI with EAFs, there should be very few emissions left to capture, perhaps only some process emissions associated with additives. However, carbon capture can help to eliminate any remaining unabated emissions.

Situation in China: Multiple Chinese steel producers are establishing production of low-carbon or zero-carbon steel. For instance, Baowu Group has announced plans to invest 730M USD at its Zhanjiang site, using a hydrogen-fed shaft furnace in place of fossil fuels, with an annual capacity of 1.8 metric tons of "green steel".[36] This site will produce steel sheets for automobiles as well as electrical steel and was recently named a National Demonstration Project.

Cement

- **Electrification:** 30–40%

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34 中国石油网. "国内首套全电气化驱动的百万吨乙烯机组将应用于独山子石化项目." January 28, 2025. https://mp.weixin.qq.com/s/ig3cxucGiREkkYgft669cg.

35 Ricardo, and Ricardo. "Policies to Accelerate Steel Decarbonization in Europe 'Critical' in 2025: ArcelorMittal CEO - EUROMETAL." *EUROMETAL - The Voice of European Steel, Tubes and Metal Distribution Representing All Types of Steel Intermediation.* (blog), February 7, 2025. https://eurometal.net/policies-to-accelerate-steel-decarbonization-in-europe-critical-in-2025-arcelormittal-ceo/.

36 "Baosteel Zhanjiang Steel to Invest RMB 5.2046 Billion in Zero-carbon High-grade Sheet Plant," Steelorbis. March 20, 2024. https://www.steelorbis.com/steel-news/latest-news/baosteel-zhanjiang-steel-to-invest-rmb-52046-billion-in-zero-carbon-high-grade-sheet-plant-1332837.htm.

Electric kilns and plasma torches can replace fuel combustion (albeit very cost-ineffectively). Process emissions from limestone calcination remain.

- **+ Green Hydrogen**: 60–70%

Hydrogen combustion in kilns can reduce fossil fuel use but would also be very cost ineffective.

- **+ CCUS:** 85–90%

CCUS is needed to address unavoidable process emissions (60% of sector emissions) and is more promising as a pathway compared to the electrification or hydrogen routes. Demo projects like Heidelberg Materials' net-zero cement project in Norway validate the potential of this pathway.[37]

Situation in China: Several Chinese cement producers have targeted CCUS as the decarbonization pathway of choice for cement and launched pilot/demonstration projects.

The Baima Cement Plant of Conch Group launched its carbon capture project at the cement kiln flue gas outlet in 2018. At the time, it was the world's first demonstration project in the cement industry for flue gas capture and purification using chemical absorption technology. It was designed with an annual output of 50,000 tons of liquid CO2 for use in other industrial applications. In 2021, Conch Group developed a new generation of low-energy, high-efficiency chemical absorbents for cement kilns, further reducing capture energy consumption to 2.1 GJ per ton of CO_2.[38]

In 2024, Qingzhou Zhonglian Cement launched a CO2 oxy-fuel combustion enrichment and purification demonstration project. It is currently the largest CCUS project in China's cement industry, producing 150,000 tons of industrial-grade CO2, 45,000 tons of food-grade CO2, and 5,000 tons of dry ice annually. The project adopts several technological innovations to significantly increase CO2 concentration in flue gas and reduce overall capture energy consumption to below 1.6 GJ per ton of CO2, substantially lowering operating costs.[39]

Due to the limited number of large-scale operational CCUS projects in China's cement industry and the early stage of development and application, operational models are still under exploration and optimization. As a result, carbon utilization by cement enterprises remains relatively limited, and the construction of CCUS industry clusters (to use the captured CO2 onsite) has not yet been prioritized.

Aluminum

- **Electrification**: 65-70%

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[37] HM Group. "Pioneering the Transformation to Net Zero: Brevik CCS Project in Norway Reaches Mechanical Completion." Heidelberg Materials, December 2, 2024. https://www.heidelbergmaterials.com/en/pr-2024-12-02.

[38] Current Status and Outlook of CCUS Development in China's Cement Industry. China Building Materials Foundation. http://www.nrdc.cn/Public/uploads/2024-12-16/675f8b7c57920.pdf

[39] Ibid.

The Hall-Héroult aluminum smelting process itself is already fully electric, which means it can be abated by using green electricity. The remaining 30% of unaddressed emissions can be attributed to the use of carbon anodes, which are essential components of the Hall-Héroult process, and which are made from petroleum. Replacing carbon anodes with inert anodes can eliminate almost all process emissions.

- **Hydrogen:** N/A

There's little obvious role for green hydrogen in primary aluminum production; however, it can replace fossil fuels in the melting process of aluminum recycling to produce secondary aluminum. This has been trialled with some success at a demo project in Spain.

- **+ CCUS:** N/A

CCUS would not typically be applied for alumnium process decarbonization; however, it could be applied on a fossil-fuels power plant that is powering an aluminium smelter, in lieu of using green electricity.

Situation in China: The Action Plan for Carbon Peaking and Carbon Neutrality of Aluminum Corporation of China Limited calls for the sector to reach peak carbon emissions five years ahead of the national schedule (2025) and to reduce carbon emissions by 40% by 2035, aiming to become the first sub-sector in the non-ferrous metals industry to achieve carbon neutrality.[40] Besides hydropower-backed aluminum projects, there are several "green aluminum" demonstration projects using wind and solar, for instance the 350,000 ton capacity Zhahanuo'er Green Aluminum project in Inner Mongolia, which plans to obtain 80% of its power from wind and solar.

To date, there are not yet any instances of inert anode demonstration projects in China, but they are explicitly named as key research areas in the Electrolytic Aluminum Industry Energy Conservation and Carbon Reduction Special Action Plan released in July 2024.[41]

Ammonia

- **Electrification:** 20-30%

Traditional ammonia production involves the use of fossil-derived hydrogen in the Haber-Bosch process, so the direct gains achievable by electrification of ammonia production are relatively limited.

- **+ Green hydrogen:** 70-90%

Green hydrogen produced via electrolysis replaces fossil-based hydrogen. Pilot projects have shown up to 90% emissions reduction using this pathway and is the pathway currently showing the most commercial activity.

- **+ CCUS:** 90-95%

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40 "铝冶炼低碳清洁智能化创新发展研究丨中国工程科学." 中国工程科学. December 20, 2024. https://mp.weixin.qq.com/s/S08vZNZaLZoplKJbqsztNA.

41 "Electrolytic Aluminum Industry Energy Conservation and Carbon Reduction Special Action Plan", National Development and Reform Commission, July 2024. https://www.ndrc.gov.cn/xwdt/tzgg/202407/P020240723623280665889.pdf

In this scenario, CCUS would be applied to a traditional ammonia production facility (producing "blue ammonia" via steam methane reforming of natural gas) rather than as an additive measure to a green ammonia facility producing green ammonia from green hydrogen.

Situation in China: China has many green hydrogen and green ammonia projects under development nationwide, especially in the north and northwest of the country, where the cheap and abundant renewable resources can be found. A recent list of national low-carbon demonstration projects included an experimental carbon capture + green hydrogen + ammonia + oxamide production facility in the Xinjiang UAR with 200,000 tonnes of annual green ammonia production capacity.

Summary Comments

A comprehensive and detailed whole-of-industry assessment of the potential for electrification to abate fossil fuel usage would be well outside of the scope of this report. However, based on the typical figures for some of the highest energy-consuming segments shown above, a rough estimate of the percentage of fossil fuels in heavy industry that can be replaced by electrification alone (with no consideration of cost) might be somewhere in the 40% range, **leaving the hard-to-electrify portion at 60%.**

After accounting for the further introduction of green hydrogen, the percentage of fossil-fuels removed could be in the 60% range, **leaving a final 40% of hard-to-abate fossil fuel use**. For this final 40%, CCUS or alternative production processes may be considered.

4. OTHER KEY TRENDS

Chinese renewable energy integration into industrial supply chains has been supported by many different policy and economic features, but at least two major ones are worth closer evaluation:

1. **Ultra-High Voltage Network**: China employs world-leading UHVDC technology to transmit power thousands of miles from the resource-rich regions of north, northwest, and southwest China to industrial bases in central, eastern, and southern China. This allows industrial producers in those areas to enjoy low-cost hydropower, coal-power, and renewables generated on the other side of the country. Even after accounting for the transmission costs, the power is often cheaper and cleaner than the alternatives for local power generation.

2. **Industrial Clusters**: China has leveraged industrial clusters to great effect, reducing energy, raw materials, and logistics costs by constructing integrated heavy-industry hubs in one area. For instance, a green hydrogen producer might be co-located with a pre-existing coal-fired power plant and a wind farm in the Gobi Desert. Green hydrogen is produced from co-located wind power, while carbon capture is employed to secure carbon feedstock. The green hydrogen and carbon feedstock may then be combined onsite to produce green methanol or urea, along with green hydrogen and coal-fired power. With a single company or single joint venture entity financing the entire endeavor, the facility diversifies its revenue into multiple sectors, decarbonizes multiple industrial segments (urea is a critical component of fertilizers) and complies with national mandates, earning access to additional resources, funding, subsidies, and other forms of support from provincial or national bodies.

5. POLICY RECOMMENDATIONS

5.1. JUMP-START DOMESTIC INVESTMENT

Recommendation:

Accelerate U.S. Investment Support for Deployment of Next-Gen Industrial Cleantech

Rationale:

While China leads in industrial decarbonization and cleantech research output, the United States is still a strong contender in the research space and still performs very well when it comes to *high-quality* research. The gap, therefore, is not in quality of R&D output, but in support for commercial deployment of demonstration projects, particularly consistent and reliable federal support.

Actions:

- **Expand federal funding for R&D in hard-to-abate sectors** (e.g., cement, steel, aviation) with programs modelled on the Inflation Reduction Act's provisions supporting EVs and clean energy deployment.
- Create and/or enhance **incentive programs for pilot projects** employing U.S.-developed demonstration clean technology (green hydrogen, CCUS, electric steam cracking, etc.) to partially derisk the initial commercial deployment of demonstration/pilot facilities.
- Investigate establishment of public-private partnerships to establish power sources for green hydrogen production and smooth grid integration.

5.2. ENHANCE INTERNATIONAL COLLABORATION

Recommendation:

Strengthen U.S.-China Collaboration in Cleantech Deployment

Rationale:

China's industrial decarbonization achievements, particularly in scaling renewables, grid infrastructure, and piloting emerging technologies, offer lessons for global climate action. A partnership of equals, predicated on mutual respect and the leveraging of complementary strengths, can accelerate progress for both nations while advancing global climate goals.

Actions:

- Co-develop open-access platforms for industrial decarbonization R&D, perhaps a kind of "U.S.-China Clean Industrial Innovation Hub", focusing on the hardest-to-abate sectors. This would marry U.S. strengths in foundational research/AI-driven solutions with China's rapid prototyping and manufacturing scale.
- Launch reciprocal technology demonstration zones, allowing U.S. and Chinese firms to pilot industrial decarbonization technologies in each other's countries, or in a third country (see next item).
- Align incentives for joint ventures or joint investments in third countries, particularly in developing nations also seeking to decarbonize heavy industry.

- Harmonize carbon accounting methodologies through a bilateral working group, creating standards for tracking emissions across integrated industrial supply chains. This will help to prevent "green trade" fragmentation while respecting each nation's policy autonomy.

5.3. Improve Understanding of Cross-Border Clean Technology Innovation Progress

Recommendation:

Improved information-gathering on China's industrial advancements and other activities creates opportunities for mutual learning, accelerates climate progress, and helps align international decarbonization efforts. Real and actionable insights into technological developments benefit all nations pursuing sustainable growth, while ensuring that any remaining suggestions for improvement are accurate, sensible, and likely to be received as thoughtful and reasonable constructive critiques.

Actions:

- Establish a U.S.-China Clean Energy Research Coordination Initiative. This could be a congressional effort, or alternatively a multi-agency program (Energy, State, Commerce) to analyze publicly available technical developments, like peer-reviewed studies from the Chinese Academy of Sciences, corporate sustainability reports, lists of demonstration projects under deployment in China, etc., for use in congressional briefings. Special emphasis should be placed on technologies with cross-border or collaborative climate applications.
- Create technical exchange programs for low-carbon industries. Specialists with appropriate language and technical skills should be deployed to strengthen cross-cultural understanding of clean/low-carbon industrial transformation strategies and enhance understanding of progress, barriers, and intentions on both sides.
- Leverage the insights of U.S. firms already working in China (e.g., Tesla, GE, ExxonMobil) to share observations on industrial trends in the cleantech sector, like the uptake of electric arc furnaces or retirements of small-capacity coal-fired power plants.

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