EQUITY RESEARCH | January 20, 2021 | 8:43 PM GMT

The following is a redacted version of the original report. See inside for details.

Goldman Sachs

Carbonomics

China Net Zero: The clean tech revolution

China's pledge to achieve net zero carbon by 2060 represents two-thirds of the c.48% of global emissions from countries that have pledged net zero, and could transform China's economy, starting with the 14th Five-Year Plan. **We model the country's potential path to net zero** by sector and technology, laying out **US$16 tn of clean tech infrastructure investments** by 2060 that could create **40 mn net new jobs** and drive economic growth. Our China Carbonomics cost curve highlights three **key interconnected scalable technologies** for net zero: 1) **Electrification** through renewable power dominates the lower part of the cost curve and has potential to de-carbonize around half of Chinese CO_2 emissions, with **power generation tripling by 2060** – dominated by wind and solar, driving **increased demand for base metals such as copper (+15%)** and a complete overhaul of the country's power networks; 2) **Clean Hydrogen** is the second most important technology, potentially driving 20% of the de-carbonization, mostly in industry and heating; and 3) **Carbon Capture** could address 15% of China's emissions, mostly in industrial processes. **Exports contribute c.20% of Chinese CO_2 emissions** (gross): growing global consumer awareness of the carbon footprint of goods and the prospect of a **border adjustment on carbon prices** add urgency to China's net zero policy and highlight the importance of carbon markets.

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The Goldman Sachs Group, Inc.

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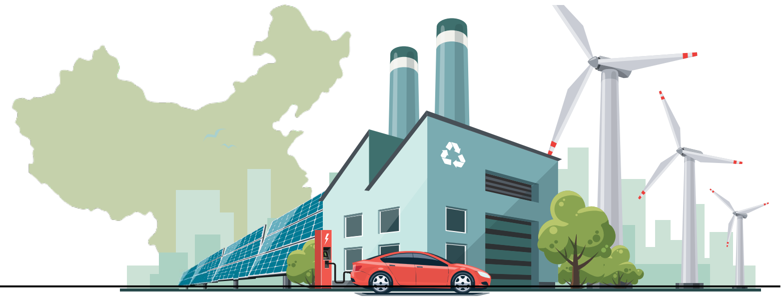
The following is a redacted version of Goldman Sachs Research's report ***"Carbonomics: China net zero: The clean tech revolution"*** *originally published Jan. 21, 2021 (86pgs). All company references in this note are for illustrative purposes only and should not be interpreted as investment recommendations.*

China Net Zero

Story in numbers



China's pledge to achieve net zero carbon by 2060 represents two-thirds of the c.48% of global emissions from countries that have pledged net zero…

...as the country accounts for c.30% of global CO_2 emissions (2019), and c.64% of the increase in global CO_2 emissions since 2000...

...despite a substantial reduction of c.40% in the CO_2 intensity of its economic output (CO_2 emissions per GDP) since 2000.

China's net zero path leads, on our estimates, to a US$16 tn clean tech infrastructure investment opportunity by 2060 and c.40 mn net new jobs.

Renewable power is the most important technology, potentially aiding the de-carbonization of c.50% of Chinese CO_2 emissions...

…and we expect China's power generation to triple to 2060, driven mostly by solar, wind, nuclear and hydro generation.

Electrification transforms road transportation, with almost 100% penetration of new energy vehicles (NEVs) by 2060 requiring a > US$1 tn investment opportunity in charging infrastructure...

...and a c.15% rise in annual copper demand, with notable increases in aluminium, lithium and nickel too.

Clean hydrogen drives c. 20% of the de-carbonization, mostly in industry, heating and long-haul transport…

…and we estimate that the market for hydrogen could increase 7x by 2060, from c.25 Mtpa to c.170 Mtpa.

Carbon capture is another critical technology with a wide range of industrial applications, critical to decarbonize c.15% of the country's emissions.

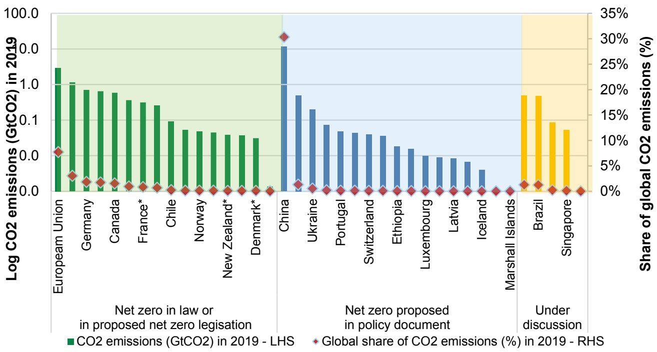
Net international trade contributes c.13% of China's CO_2 emissions through net exports (and c.20% for gross exports)…

…whose competitiveness could be affected by a border adjustment of carbon taxes that could cost China up to US$240 bn pa for a carbon tax of US$100/tnCO2 applied to the entire carbon footprint of gross exported emissions...

...highlighting the importance of a clear de-carbonization strategy and the implementation of carbon pricing schemes, with China's upcoming national ETS expected to be the largest globally and bring the total share of global GHG emissions covered by carbon schemes to c.23%.

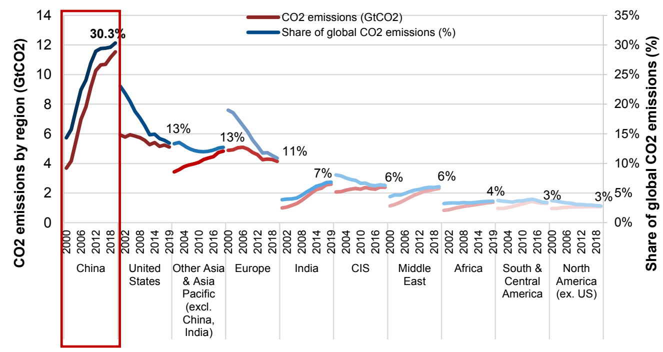
China net zero: Thesis in charts

Exhibit 1: China accounts for the majority of the c.48% of global emissions from countries that have pledged net zero carbon...
Countries that have pledged net zero (in law, in proposed legislation and in proposed policies)



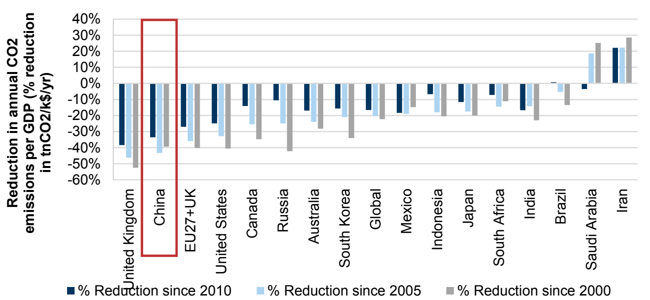
Source: Energy & Climate Intelligence Unit, Goldman Sachs Global Investment Research

Exhibit 2: ...and for 30% of global CO2 emissions, and c.64% of the increase in global CO2 emissions since 2000...
CO2 emissions (GtCO2, LHS) and share of global CO2 emissions by region (%, RHS)



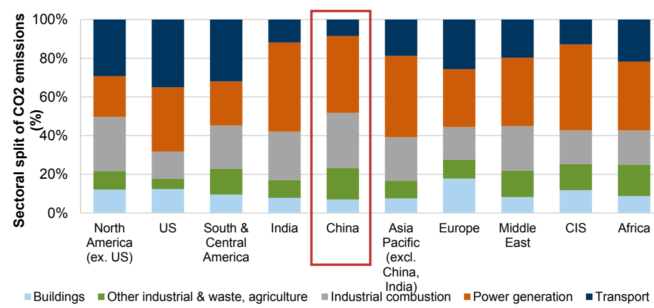
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 3: ...despite a substantial reduction in the CO2 intensity of its economic output.
Reduction in annual CO2 emissions per unit of annual GDP (%)



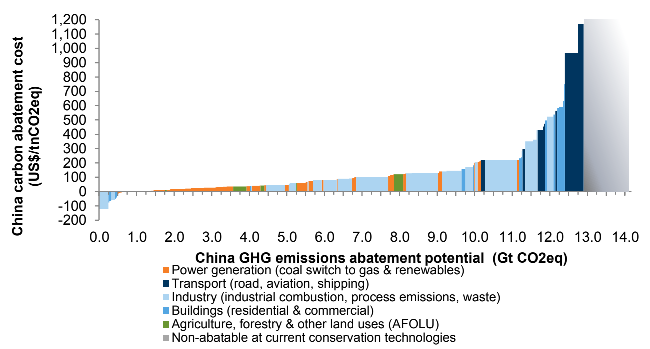
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 4: CO2 emissions in China are skewed towards industry and power generation (c.80% of total)...
Sectoral split of CO2 emissions by region (%)



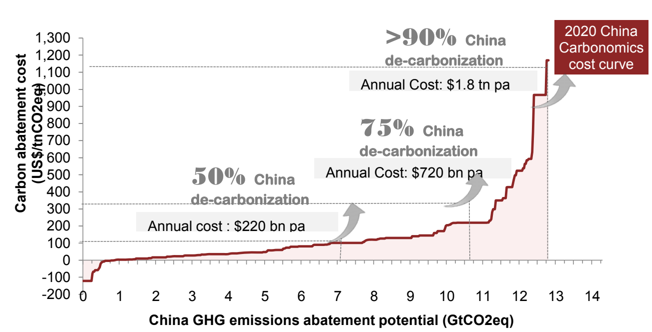
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 5: ...which make up the vast majority of the carbon abatement cost curve.
De-carbonization cost curve for China's anthropogenic GHG emissions, based on current technologies and current costs



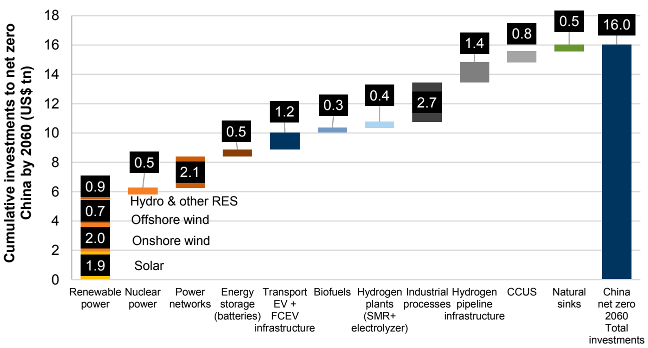
Source: Goldman Sachs Global Investment Research

Exhibit 6: At current technologies, we estimate that 75% de-carbonization would cost China US$720 bn pa
De-carbonization cost curve for China's anthropogenic GHG emissions, based on current technologies and current costs



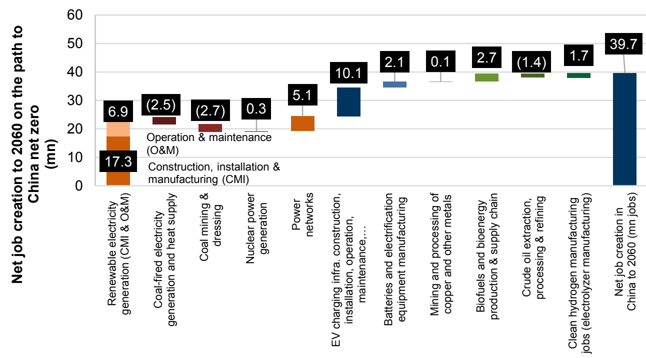
Source: Goldman Sachs Global Investment Research

Exhibit 7: China's net zero path implies a US$16 tn clean tech infrastructure investment opportunity by 2060...
Cumulative investment opportunity across sectors for China net zero by 2060 (US$ tn)



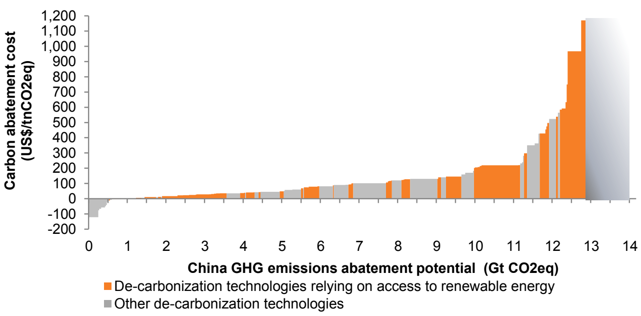
Source: Company data, Goldman Sachs Global Investment Research

Exhibit 8: ...creating c.40 mn net new jobs.
Net job creation bridge on the path to net zero China by 2060 (mn)



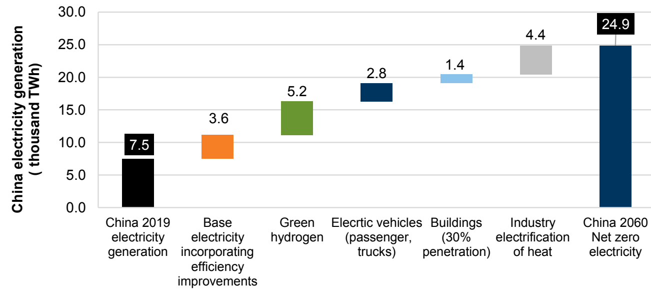
Source: UNEP - ILO - IOE - ITUC, EuropeOn, IRENA, NBSC, Goldman Sachs Global Investment Research

Exhibit 9: Renewable power is the most important technology, potentially aiding the de-carbonization of c.50% of Chinese CO2 emissions...
De-carbonization cost curve for China's anthropogenic GHG emissions, with orange indicating the technologies relying on access to RES electricity



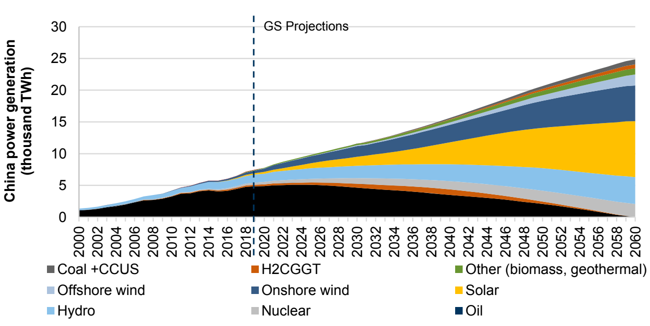
Source: Goldman Sachs Global Investment Research

Exhibit 10: ...as we expect China's power generation to triple by 2060...
China electricity generation bridge to 2060 (thousand TWh)



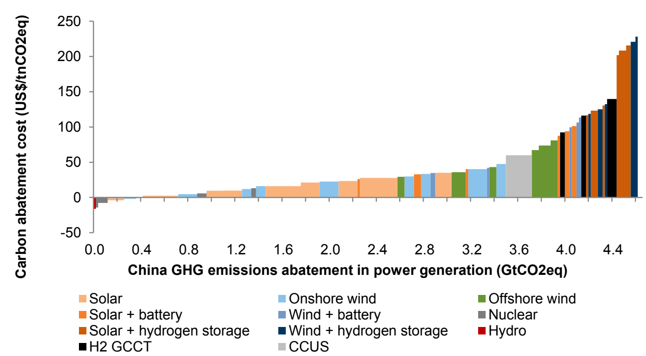
Source: BP Statistical Review, Goldman Sachs Global Investment Research

Exhibit 11: ...driven by solar, wind, nuclear and hydro power generation...
China electricity generation (thousand TWh)



Source: BP Statistical Review, Goldman Sachs Global Investment Research

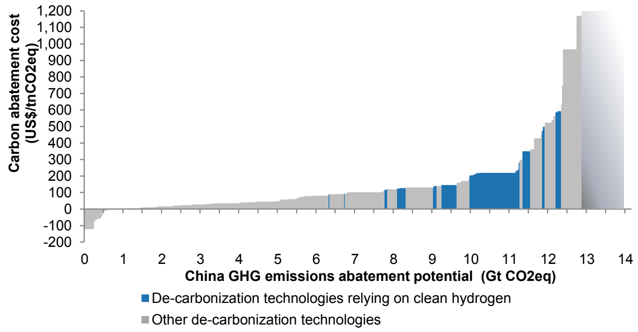
Exhibit 12: ...which dominate the low-cost part of the carbon abatement curve.
China power generation de-carbonization cost curve



Source: Goldman Sachs Global Investment Research

Exhibit 13: Clean Hydrogen is the second most important technology, potentially driving c.20% de-carbonization...

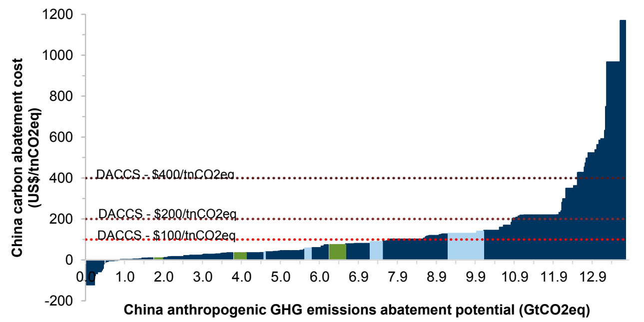
De-carbonization cost curve for China's anthropogenic GHG emissions, with blue indicating the technologies relying on clean hydrogen



Source: Goldman Sachs Global Investment Research

Exhibit 14: ...followed by Carbon Capture, which is key to de-carbonizing China's industrial process emissions.

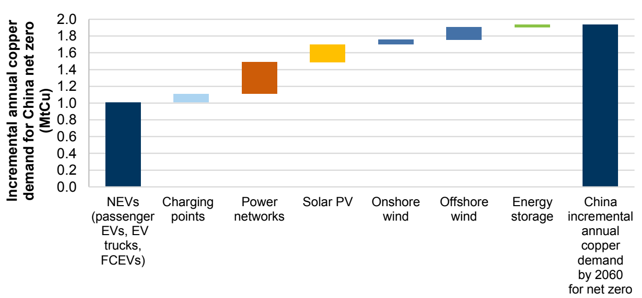
Merged conservation and sequestration cost curve including CCUS and natural sinks



Source: Goldman Sachs Global Investment Research

Exhibit 15: Electrification will lead to a substantial rise in the demand for base metals, such as copper

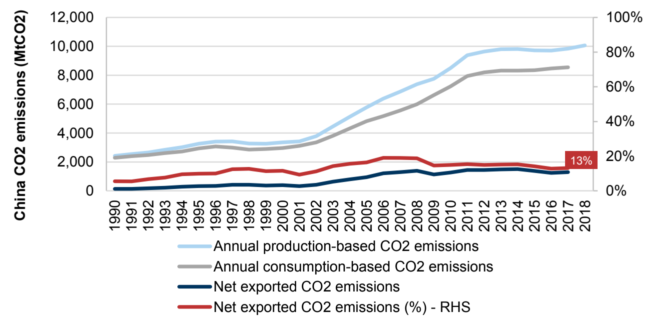
Average annual incremental copper demand for China net zero (MtCu)



Source: IRENA, International Copper Association, Goldman Sachs Global Investment Research

Exhibit 16: 13% of Chinese CO2 emissions (and 16% of the increase since 2000) is embedded in net exports...

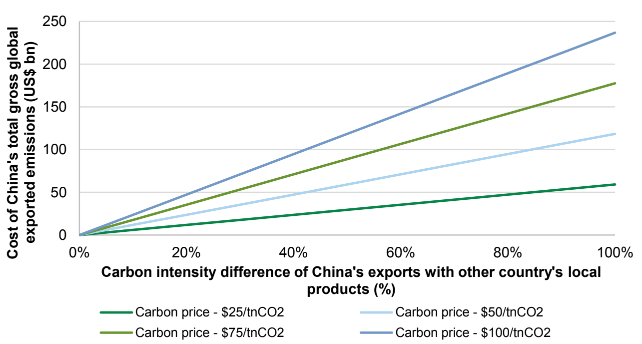
China CO2 emissions produced, consumed and exported (MtCO2)



Source: Our World in Data

Exhibit 17: ...whose competitiveness could be affected by a border adjustment of carbon taxes...

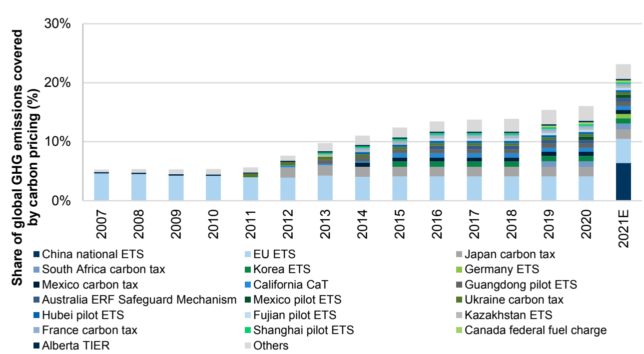
Cost of China's annual gross exported emissions (US$bn)



Source: Goldman Sachs Global Investment Research

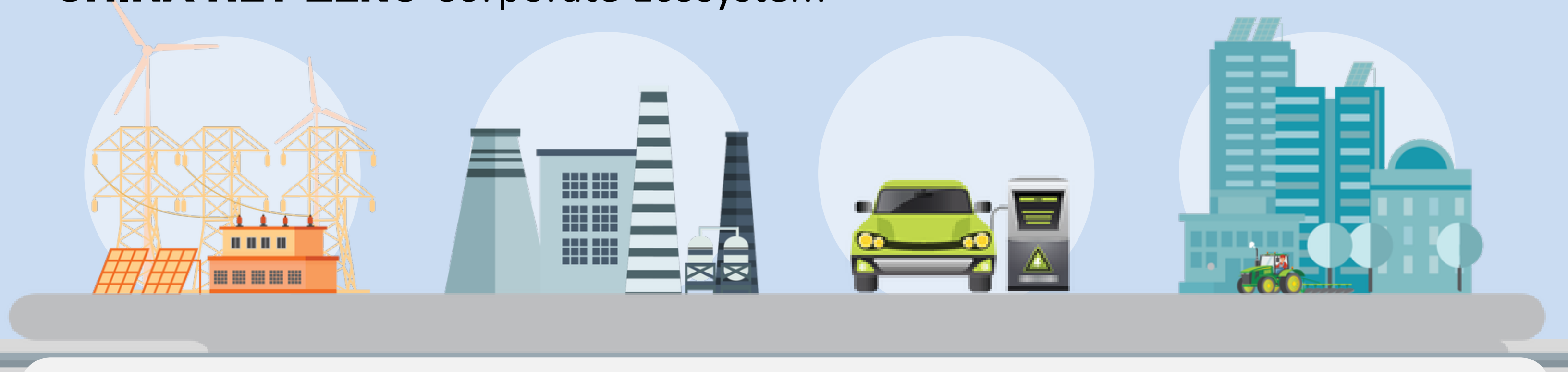
Exhibit 18: ...hence the importance of a clear de-carbonization strategy and implementation of domestic carbon pricing schemes.

Carbon pricing initiatives' share of global GHG emissions covered (%)



Source: World Bank Group

CHINA NET ZERO Corporate Ecosystem



POWER GENERATION

Renewable power utilities & nuclear

Renewable

Longyuan power [0916.HK]
Datang Renewable [1798.HK]
Xinyi Energy [3868.HK]
Zhejiang Chint [601877.SS]

Nuclear

CGN power [003816.SZ]
China National Nuclear Power [601985.SS]

Utility-scale batteries and electrolyzer manufacturers

Yunnan Energy [002812.SZ]
Putailai [603659.SS]
Senior Tech [300568.SZ]
Sungrow [300274.SZ]
Zhejiang Narada Power Source Co Ltd [300068.SZ]

Wind turbines and supply chain

Wind turbines

Goldwind [002202.SZ; 2208.HK]
Mingyang Smart Energy [601615.SS]

Turbine parts

Sinoma Science&Tech [002080.SZ],
Titan Wind Energy [002531.SZ]
Jinlei Wind [300443.SZ]
Riyue Heavy Industry [603218.SS]

Solar panels and supply chain

Solar panels:

Longi [601012.SS]
Jinko Solar [JKS]
JA Solar [002459.SZ]
Trina Solar [688599.SS]

Solar poly/wafer/cell

Daqo [DQ]
Tongwei [600438.SS]
GCL-poly [3800.HK]
Xinte [1799.HK]
Longi [601012.SS]
Aiko Solar [600732.SS]
Zhonghuan [002129.SZ]

Equipment:

Shenzhen SC [300724.SZ]
Maxwell [300751.SZ]
Zhejiang Jingsheng [300316.SZ]

Solar glass/inverter

Xinyi Solar [0968.HK]
Flat Glass [6865.HK/601865.SS]
Sungrow [300274.SZ]
Ginlong [300763.SZ]
Goodwe [688390.SS]

INDUSTRY & WASTE

Metal miners

(lithium, nickel, copper)

Ganfeng Lithium [1772.HK/002460.SZ]
MMG [1208.HK]
Jiangxi Copper [0358.HK/600362.SS]
Zijin [2899.HK/601899.SS]

Hydrogen production distribution & transmission

Sinopec [0386.HK, 600028.SS, SNP]
PetroChina [0857.HK, 601857.SS, PTR]
CNOOC [0883.HK, CEO]

TRANSPORT

Electric vehicle manufacturers

NIO Inc. [NIO]
Li Auto Inc. [LI]
BYD CO. [002594.SZ, 1211.HK]
Guangzhou Auto Group [2238.HK, 601238.SS]
Great Wall Motor Co. [601633.SS, 2333.HK]
BAIC Motor Co. [1958.HK]

EV battery manufacturers

CATL [300750.SZ]
BYD CO. [002594.SZ, 1211.HK]
EVE Energy Co [300014.SZ]
Shanghai Putailai New Energy Co Ltd [603659.SZ]
Lead Intelligent [300450.SZ]

Fuel cell manufacturers

Weichai Power [300750.SZ]
SinoHytec Co [688339.SZ]

Biofuel producers

Cofco Biotechnology Co Ltd [000930.SZ]
Shandong Longlive Bio-technology [002604.SZ]
Sinopec [0386.HK, 600028.SS;,SNP]
PetroChina [0857.HK, 601857.SS, PTR]
Longyan Zhuoyue [688196.SS]

Charging/refueling infrastructure

Qingdao Teld New Energy [300001.SZ]
SAIC AnYo Charging [600104.SS]
Shanghai Potevio [600680.SS]
State Grid [600131.SS]
Star Charge
EV Power
Jiangsu YKC New Energy Technology

BUILDINGS & AGRICULTURE

Heat pumps, boilers & efficiency

Sanhua Intelligent Control [002050.SZ]
Wasion Group [3393.HK]
Sinocera Functional Material [300285.SZ]

Agriculture & natural sinks

Xinghuan Forestry Development Company (private)
Guangxi Longlin Forestry Development Company (private)
Hesheng Forest Silviculture (private)

**We note that the corporate ecosystem presented above is not exhaustive*

PM Summary: China net zero 2060

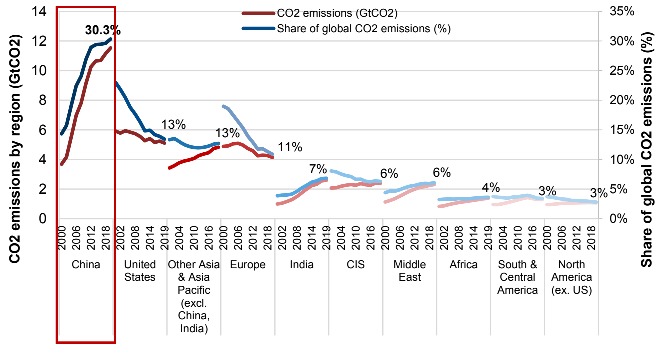
China's commitment to net zero will reshape its economy, starting with the 14th Five-Year Plan, and the global de-carbonization effort

On September 22, the President of the People's Republic of China, Xi Jinping, addressing the general debate of the 75th session of the United Nations General Assembly, stated that China aims to scale up its Intended Nationally Determined Contributions, **reaching a peak in its carbon dioxide emissions before 2030 and achieving net zero carbon emissions by 2060.** Li Gao, head of climate change at the Ministry of Ecology and Environment, reiterated the targets in October while stating that the **14th Five-Year Plan (2021-25) period will be key for China's climate efforts as the country eyes its new targets.** The **finalized proposal of the 14th Five-Year Plan** from the Party, the first five years of China's move towards its second centenary goal, was released in the Fifth Plenum of the 19th Party Congress in late October, and the **detailed plan draft will likely be submitted to the National People's Congress (NPC) for final approval** during the "Two Sessions" in **March 2021**. Net zero will serve as a guiding principle for policymaking that is comprehensively embedded into structural reforms, investment policies and innovation priorities.

China's net zero emissions ambition joins the rapidly increasing number of national net zero pledges worldwide that encompass c.48% of global emissions (61% if we include the US net zero pledge in Joe Biden's programme). Yet the scale of China in the context of climate change and global emissions (China accounted for 30% of total global CO_2 emissions in 2019) and its ongoing economic expansion (accounting for c.64% of the rise in global CO_2 emissions since 2000) **makes the stated ambition unique and a critical milestone for global de-carbonization efforts**. While China is currently the world's largest emissions producer, over the past two decades, the country has **been able to reduce its emissions intensity per unit of GDP by c.40%, one of the largest reductions among key economic regions globally** (the second-largest reduction after the United Kingdom), meeting the national targets set out in key climate change agreements, including its commitments laid out in the Copenhagen Accord and under its 13th Five-Year Plan (FYP) within the set timeline (by 2020).

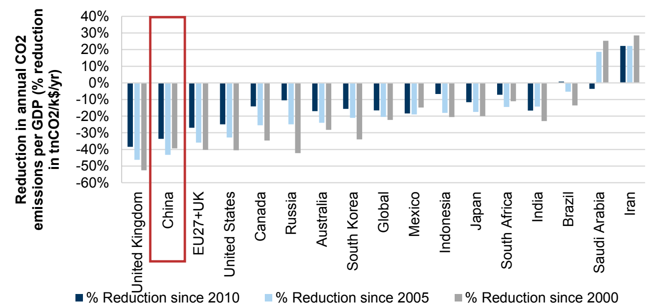
Net zero will require China to embark on an ambitious multi-decade effort to transform its economy and energy ecosystems. China's emissions are distinct not only in terms of scale but also sectoral mix. In 2019, **>80% of the country's emissions** were attributed to **two key emitting sectors**: **power generation** and **industry & industrial waste** (compared with just c.55% for the EU, the other major economic area committed to net zero). This highlights the critical role of energy for China (responsible for power generation, transport, buildings and a large share of industrial emissions), making the **evolution of the country's energy mix** one of the most **important determinants of the de-carbonization path** in the near and medium term. We expect this mix to include **renewable power, clean hydrogen and carbon capture**.

Exhibit 19: China accounts for 30% of global CO2 emissions and 64% of the global increase in CO2 emissions since 2000...
CO2 emissions (GtCO2, LHS) and share of global CO2 emissions by region (%, RHS)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 20: ...despite reducing its GDP carbon intensity more than any other major economy, except the UK
Reduction in annual CO2 emissions per unit of annual GDP (%)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

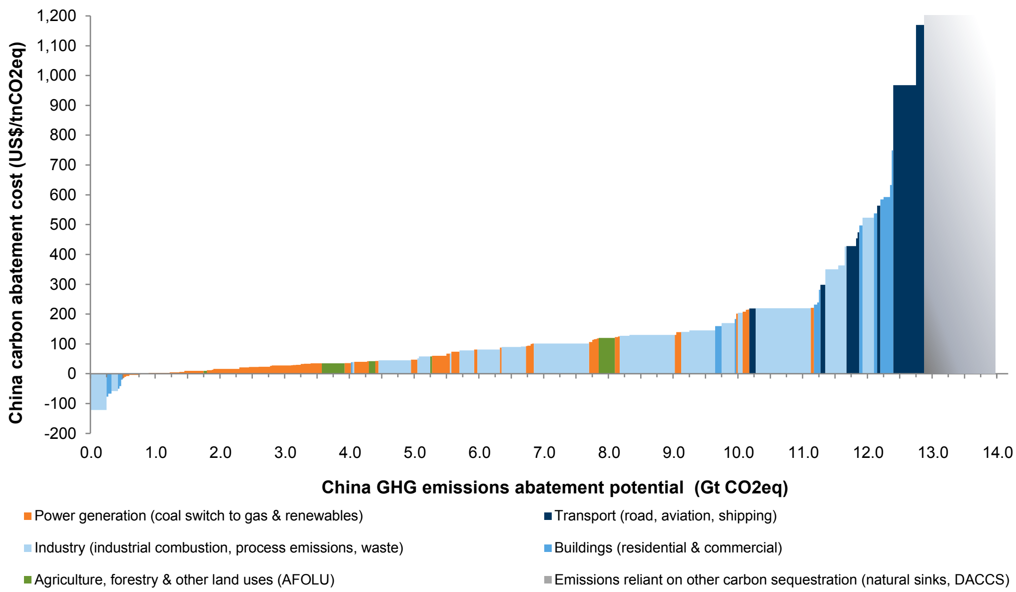
The China Carbonomics cost curve is dominated by power and industry, hence the importance of renewables, clean hydrogen and Carbon Capture technologies

In our deep-dive de-carbonization report, *Carbonomics: Innovation, Deflation and Affordable De-carbonization*, we laid out our global carbon abatement cost curve. **In this report, we introduce a China-specific de-carbonization cost curve, including >100 different applications of GHG abatement technologies** across all key emitting sectors in China. The Carbonomics cost curve comprises de-carbonization technologies that are currently available at commercial scale, at the current costs associated with each technology's adoption in large scale. We expect this cost curve to be dynamic and evolve over time, as these technologies become more widely adopted and economies of scale and technological innovation lead to cost deflation. We include conservation technologies (technologies resulting in the avoidance of emissions) and process-specific sequestration technologies (technologies that sequester emissions back from an emitting plant at point source) across all key emission-contributing industries: power generation, industry (which includes industrial energy and process emissions) and industrial waste, transport, buildings and agriculture. We estimate that **the initial 50% of China's anthropogenic GHG emissions can be abated at an annual cost of US$220 bn and an average carbon cost of US$32/ton**. However, the cost curve steepens rapidly, especially as we move beyond 75% de-carbonization, requiring **US$1.8 tn pa for full de-carbonization at today's costs and available technologies. The steepness of the cost curve highlights the importance of technological innovation, natural sinks, direct air carbon capture (DACC) and efficient financing, in order to flatten the cost curve over time and achieve affordable net zero.**

As we move towards net zero, the **de-carbonization process evolves from being one-dimensional (renewable power, dominating half of the lower-cost part of the cost curve) to a multi-dimensional clean tech ecosystem encompassing** four key interconnected technologies on the path to net zero emissions: **(a) Renewable power**: The technology that dominates the 'low-cost de-carbonization' spectrum today and has the potential to support the de-carbonization of >45% of China's anthropogenic GHG emissions, as well as being critical for the production of clean hydrogen longer term ('green' hydrogen). **(b) Clean hydrogen:** A transformational technology for long-term energy storage enabling increasing uptake of renewables in power generation, as well as aiding the de-carbonization of some of the harder-to-abate sectors, with a critical role in several industrial processes (iron & steel, petrochemicals), long-haul transport, and heating of buildings. **(c) Battery energy storage:** Critical in the electrification of transport and industrial-scale short-term power storage. **(d) Carbon capture technologies:** Vital for the production of clean ('blue') hydrogen, while also aiding the de-carbonization of industrial sub-segments with emissions that are currently non-abatable under alternative technologies (such as cement).

Exhibit 21: The cost curve of de-carbonization for China is very steep yet highlights a wide range of low-cost investment opportunities

De-carbonization cost curve for China's anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase



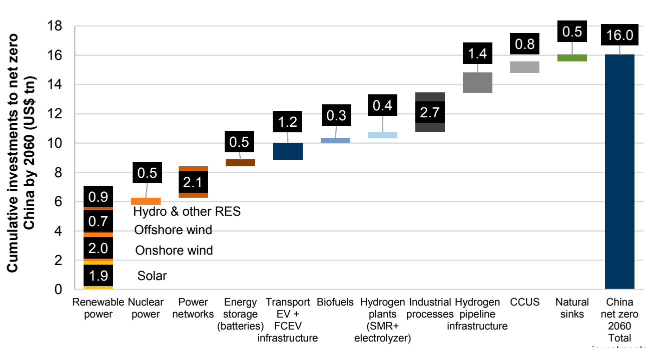
Source: Goldman Sachs Global Investment Research

Laying out a potential path to net zero China: US$16 tn infrastructure investments and 40 mn net new jobs

Leveraging the Carbonomics cost curve, we lay out a possible path to carbon neutrality for China by 2060 (with peak emissions before 2030), in line with the country's stated long-term ambitions. We note that this simply outlines one of the many possible pathways that China could follow in its de-carbonization. The path is, similar to China's de-carbonization cost curve, reliant on currently existing de-carbonization technologies (assuming economies of scale for technologies in the pilot phase) and will evolve with clean tech innovation. Our path to net zero China addresses each of the country's emitting sectors: power generation, transport, industry, buildings and agriculture – utilizing the lower-cost de-carbonization technologies available. For **power generation**, this implies a non-fossil fuel energy share of >95% achieved by 2060; for **road transport**, we model new energy vehicle penetration (including BEVs, PHEVs and FCEVs) of close to 100% by 2060; for **industry**, we factor in transformational improvements in efficiency and increasing penetration of clean hydrogen, electrification and carbon capture, as well as a critical role for the circular economy; in **buildings**, we assume a switch from fossil fuel-sourced heating to clean hydrogen, electrification and deep efficiency improvements; and finally, for **agriculture**, we assume strong improvements in land management practices.

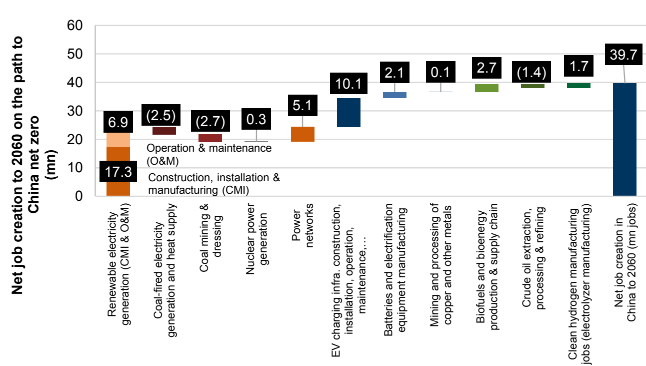
In aggregate, we estimate a total 'green' infrastructure investment opportunity of US$16 tn by 2060 – we estimate US$9 tn will be dedicated to power generation: renewable power, but also a major upgrade of power networks and power storage; US$1.2 tn to transport infrastructure for EVs; c.US$1.2 tn to carbon sequestration (Carbon Capture and natural sinks); and US$2.6 tn to hydrogen infrastructure for transport, industry and heating**.** As we highlight in our report *Carbonomics: The green engine of economic recovery*, clean infrastructure can foster material net job creation as it tends to be more capital- and labor-intensive compared with traditional fossil fuel energy developments, while benefiting from a lower cost of capital, making it an example of a successful pro-growth, pro-environment initiative. We estimate that **China's path towards its net zero ambition could facilitate the creation of c.40 mn jobs by 2060 across sectors**. We primarily focus on the impact of direct employment across the supply chain (we do not address indirect and induced employment in this analysis). The majority of the employment creation that we expect is in sustainable energy ecosystems, dominated by renewable power generation, followed by power networks and electrification infrastructure. Net job losses arise in coal mining and processing, as well as coal power generation and crude oil extraction, processing and refining. We note that in this analysis, we use the available literature regarding employment factors, which may not account for future labor efficiency improvements and increased automation across these processes.

Exhibit 22: We estimate a US$16 tn infrastructure investment opportunity on the path to a net zero China by 2060...
Cumulative investment opportunity across sectors for China net zero by 2060 (US$ tn)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 23: ...with the potential to create c.40 mn jobs by 2060 across all sectors
Net job creation bridge on the path to net zero China by 2060 (mn jobs)



Source: UNEP - ILO - IOE - ITUC, EuropeOn, IRENA, NBSC, Goldman Sachs Global Investment Research

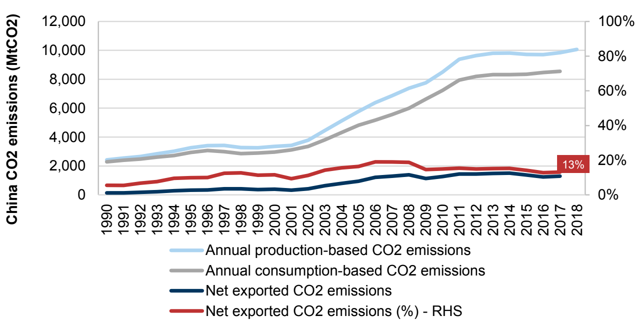
China net zero: Addressing China's export competitiveness in the era of climate change

Net trade contributes c.13% of Chinese CO_2 emissions (c.20% for gross exports), and export competitiveness could be an important consideration in the urgency of China's push for net zero at a time of rising consumer awareness of the carbon content of goods and services and the potential for the EU to request a border adjustment on carbon taxes that could hurt the competitiveness of China's high-carbon exports. In this report, we aim to **address the potential implications of a border carbon tax adjustment applied on China's exports and the resulting impact on its competitiveness**. Using 2019 data, assuming c.20% of emissions are embedded in gross exports, the total cost associated with China's global gross exported emissions could be as high as US$240 bn pa for a carbon tax of US$100/tn$CO_2$ in the extreme case of a global application of border adjustments and higher carbon taxes. This analysis is especially relevant when we consider China's exports to the European Union, given the current proposal for a carbon border tax adjustment by the EU. **We estimate that the annual cost of a carbon border tax adjustment in the EU for China's gross exports to the EU could be as high as US$35 bn if a carbon tax of US$100/tn$CO_2$ were applied on the entire carbon footprint**. If the adjustment were applied only to the difference in carbon intensity with locally produced products, this would result in a lower cost estimate of c.US$15 bn pa.

To illustrate the potential impact of a carbon border tax adjustment implemented by the EU, we consider the example of China's steel exports into the region. Depending on the difference in the carbon intensity of producing steel in the EU compared with China, a carbon tax will have differing impacts on steel export prices. **Using the current carbon intensity of steel produced in China** under a coal blast furnace BF-BOF process (2.1 tnCO_2eq/tn steel) **and comparing it to the average carbon intensity of steel produced in the EU** using a natural gas-based DRI-EAF process (1.1 tnCO_2eq/tn steel with grid electricity), we can determine the incremental cost for steel exports based on the difference in carbon intensity. The results indicate that **a US$100/tn$CO_2$ tax could result in an increase in the cost of China's steel exports of c.US$100/tn steel – based on the difference in emissions intensity**. Alternatively, if the average tonne of steel produced in the EU relied on net zero electricity, then a natural gas DRI-EAF process would have a carbon intensity of 0.6tnCO_2/tn steel, resulting in an increase in the price of exported steel from China of **US$150/tn steel.** Assuming a steel price of US$500/tn, such a price increase would be equivalent to an increase of c.30% in China steel export cost.

Exhibit 24: China's net exported emissions amount to c.13% of its total annual produced CO2 emissions...

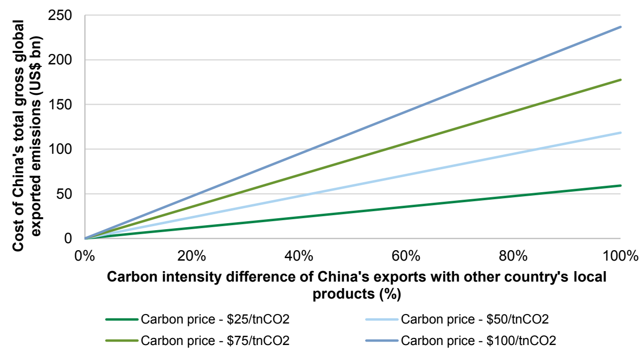
China CO2 emissions produced, consumed and net exported (MtCO2)



Source: Our World in Data

Exhibit 25: ...and the annual cost of a globally applied carbon border adjustment tax on China's gross exported emissions could be as high as US$240 bn at US$100/tnCO2, depending on the difference in carbon intensity between China's exports and the importing country's local products

Potential carbon border adjustment tax cost for China's annual gross globally exported emissions (US$ bn)

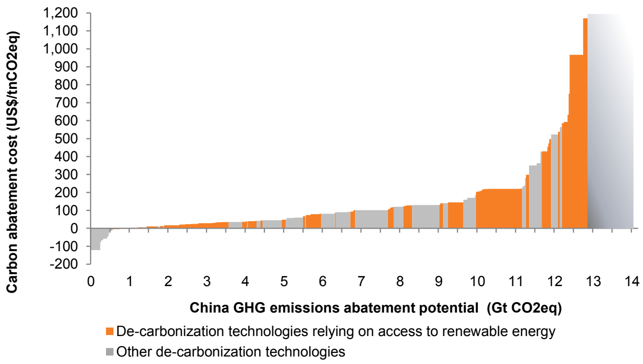


Source: Goldman Sachs Global Investment Research

Transforming (and growing) power generation could de-carbonize around half of China's emissions

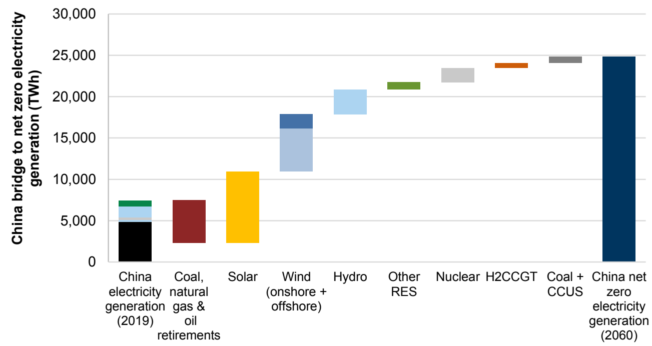
Electrification is a critical driver of the path to net zero. We estimate that **c.50% of the de-carbonization of China's current anthropogenic GHG emissions relies on access to clean power generation**, including electrification of transport, production of green hydrogen and electrification of various industrial processes. We expect that the **total demand for electricity in a net zero China in 2060 could be c.3x that of 2019**, further stressing the importance of de-carbonizing power generation as quickly as possible. **Renewable energy** (solar, wind, hydropower, bioenergy) **is the key driver of power generation de-carbonization and has the potential to revolutionize the current energy system in China,** complemented by an important, but secondary role for nuclear power. Carbon capture could be used to aid the transition for relatively young life coal and gas power plants, but its vital role in other parts of the de-carbonization path such as industry (given a lack of low-cost alternatives) makes us believe that it is likely to have a limited role in de-carbonizing China's power generation. Overall, **the path to net zero will require a radical change in the country's energy mix and current energy ecosystems:** we estimate that non-fossil-sourced power generation penetration will be required to **surpass 50% by 2030, reach c.70% by 2040 and exceed 85%/95% by 2050 and 2060 respectively from c.32% currently –** it is difficult to overstate the revolutionary impact this would have on a power generation system that currently relies on coal for 65% of its electricity and generates 40% of the country's CO_2 emissions. De-carbonizing power generation while tripling electricity generation will require an attractive regulatory and financing framework for power generation; it will also require a complete rebuild of the power network and energy storage system (industrial-scale batteries and green hydrogen), which will be required to connect renewable power production and consumption that sits in very distant geographical regions and is hampered by significant timing and seasonal mismatches.

Exhibit 26: c.50% of the de-carbonization of China's anthropogenic GHG emissions is reliant on access to clean power generation...
De-carbonization cost curve for China's anthropogenic GHG emissions, with orange indicating the technologies relying on access to RES electricity



Source: Goldman Sachs Global Investment Research

Exhibit 27: ...with renewable power growth needed to support this increase in electricity demand in a net zero path
China net zero by 2060 electricity generation bridge 2019-60 (TWh)



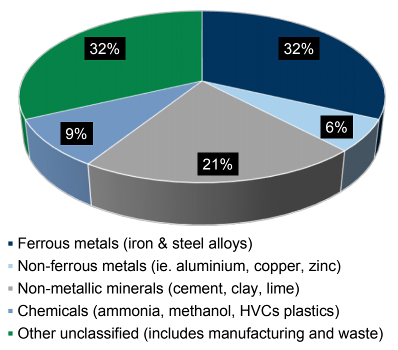
Source: BP Statistical Review, Goldman Sachs Global Investment Research

Industry: Clean hydrogen, CCUS, efficiency, circular economy and electrification set the scene for a clean tech industrial revolution

Industry is currently the sector responsible for the largest share of GHG emissions produced in China (c.48%), with >50% coming from its heavy industries (ferrous and non-ferrous metals manufacturing, non-metallic minerals such as cement and petrochemicals). We believe four key technologies will drive emissions abatement in China's industry beyond a step-up in efficiency improvements: **clean hydrogen, carbon capture (CCUS), electrification, and the circular economy.** In particular, hydrogen has a critical role to play in a number of industrial processes, **including replacing coal in steel mills, serving as a building block for some primary chemicals and providing an additional clean fuel option for high temperature heat**. We estimate that clean hydrogen could contribute to c.20% of China's de-carbonization, with its addressable market growing sevenfold from c.25 Mt in 2019 to c.170 Mtpa in our net zero scenario. Carbon capture (CCUS) also plays a critical role in the de-carbonization of China's industry. Industrial CCUS applications in China can be cost-efficient, and have the potential to unlock deep emission reductions in China's modern industrial facilities and across some of the most difficult to abate emissions, such as those produced in the manufacturing and processing of cement. **We estimate that c.15% of China's anthropogenic GHG emissions could be abated through carbon capture**. A key advantage of carbon capture is that it avoids the rise of stranded industrial assets; many of the industrial plants in China are still relatively young and require only modest retrofits to existing plants and processes.

Exhibit 28: >50% of China's industrial emissions stem from its heavy industries...

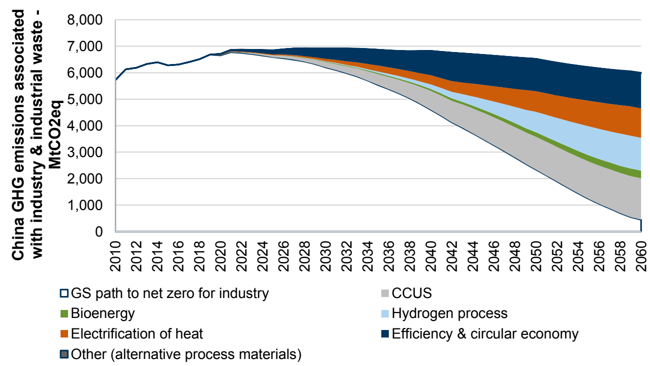
Approximate split of China's industrial GHG emissions, 2019 (%)



Source: Energy Transitions Commission, FAO, IEA, Goldman Sachs Global Investment Research

Exhibit 29: ...requiring clean hydrogen, carbon capture (CCUS), electrification, efficiency and circular economy

China GHG emissions associated with industry, industrial processes and waste (MtCO2eq)



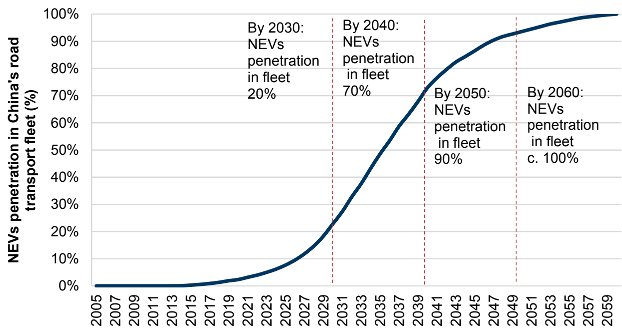
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Transportation: The rise of new energy vehicles (NEVs) and the new charging infrastructure investment opportunity

Transportation, in contrast to power generation, mostly sits in the 'high-cost' spectrum of the de-carbonization cost curve and forms a comparatively low share of the country's CO_2 emissions relative to other key economic regions, at 9%. However, as the country's middle class continues to grow, we expect demand for transportation to also continue to grow, especially for passenger road vehicles and aviation; we estimate that **China's total road fleet will triple by 2060**. As part of our analysis, we lay out the potential path to net zero emissions for transportation for China, addressing all of short- and medium-haul road transport, heavy long-haul transport, rail, domestic aviation and domestic shipping. **For light, short- and medium-haul transport** (primarily constituting passenger vehicles and short/medium-haul trucks), **we consider electrification as the dominant de-carbonization technology**; we estimate that **charging infrastructure is a >US$1 tn investment opportunity** for full electrification of road transport. **For long-haul heavy trucks, we consider clean hydrogen the preferred option**, owing to its faster refueling time, lower weight and high energy content. Our China net zero path would require NEV penetration in the road transport fleet to reach 20% by 2030, close to 70% by 2040, 90% by 2050 and almost 100% by 2060. We look at fleet penetration in this analysis as opposed to vehicle sales, as ultimately the penetration of the fleet is what directly translates into transport emissions. Aviation is one of the toughest sectors to de-carbonize, and we believe that biofuels (sustainable aviation fuels – SAFs), synthetic fuels and improved aircraft efficiency are currently the key parts of the solution. Fleet renewal is likely to be a near-term solution, with new gen aircrafts burning c.15% less fuel than their predecessors. Longer term, we see **bioenergy, and in particular SAFs**, as the key solution for aviation emissions abatement. On our path to net zero China, **we estimate close to 2.5 mn bls/d of biofuels will be required in transport in 2060.**

Exhibit 30: We expect new energy vehicles (including EVs and FCEVs) to reach almost 100% penetration in the road transport fleet...

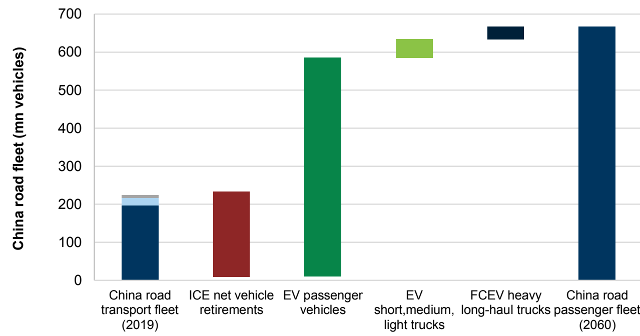
NEVs penetration in China's road transport fleet for net zero (%)



Source: Goldman Sachs Global Investment Research

Exhibit 31: ...with electric vehicles the preferred solution for passenger vehicles and short/medium-haul light trucks and with clean hydrogen the preferred solution for long-haul heavy trucks

China road vehicles fleet bridge (2019-60) for a net zero emissions path



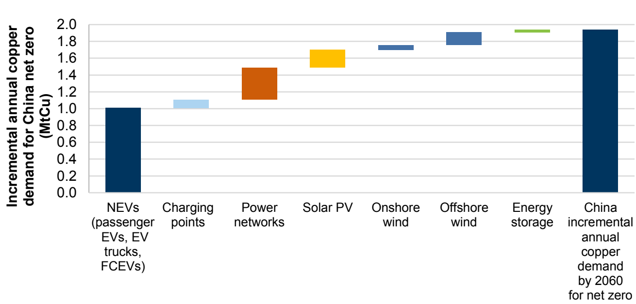
Source: NBSC, Goldman Sachs Global Investment Research

China net zero: A material uplift in base metals demand (Copper +15%)

At the heart of the path to net zero China by 2060 lies the need for access to clean energy and an accelerated pace of electrification for transport and several segments of industry, as we outline in the previous section of this report. **Electrification and clean energy is likely to have an impact on the total Chinese demand for natural resources, and in particular metals such as aluminium, copper, lithium and nickel**, demand for which relies heavily on an acceleration in technologies such as renewables (solar panel, wind turbines manufacturing), power network infrastructure, charging infrastructure, electric vehicles and battery manufacturing. We attempt to quantify the potential impact that the path to net zero China by 2060, as laid out in the previous sections, will have on demand for each of these metals. The results of this analysis are calculated on the basis of incremental demand for each clean technology relative to the conventional technology (such as incremental copper demand per electric vehicle compared with conventional gasoline vehicles). We find that annual copper demand in a net zero China will rise by 2.0 Mt, a c.15% increase on China's 2019 copper demand, and require a cumulative c.77 Mt copper in 2020-60 on a path consistent with net zero.

Exhibit 32: We estimate c.2.0 Mt incremental annual copper demand for China net zero, a c.15% increase from 2019 consumption...

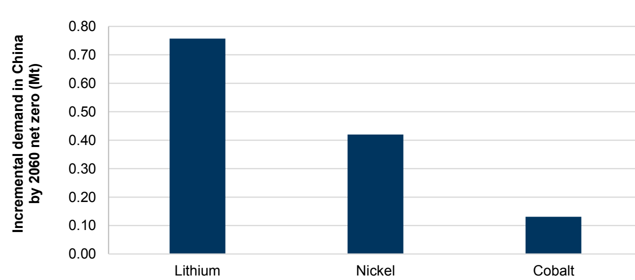
Incremental copper demand in 2060 for China net zero



Source: IRENA, International Copper Association, Goldman Sachs Global Investment Research

Exhibit 33: ...as well as a material increase in demand for electric vehicle battery metal constituents such as lithium and nickel

Incremental demand by 2060 for China net zero (Mt)



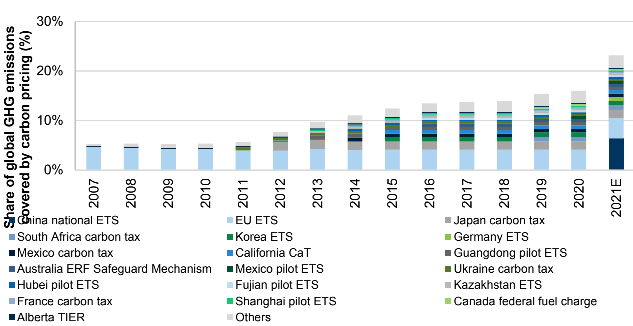
Source: Company data, Goldman Sachs Global Investment Research

China ETS: Getting closer to the implementation of the world's largest national emissions trading scheme

We believe that carbon pricing will be a critical part of any effort to move to net zero emissions, while incentivizing technological innovation and progress in de-carbonization technologies. At present, 64 carbon pricing initiatives have been implemented or are scheduled for implementation, covering 46 national jurisdictions worldwide, according to the World Bank Group, mostly through cap-and-trade systems. These initiatives are gaining momentum, with the **People's Republic of China announcing the implementation of a national emissions trading scheme.** This would be the **world's largest national emissions trading scheme**, bringing a total of 12GtCO2eq of emissions (c.23% of the world's total GHG emissions) under some form of carbon pricing.

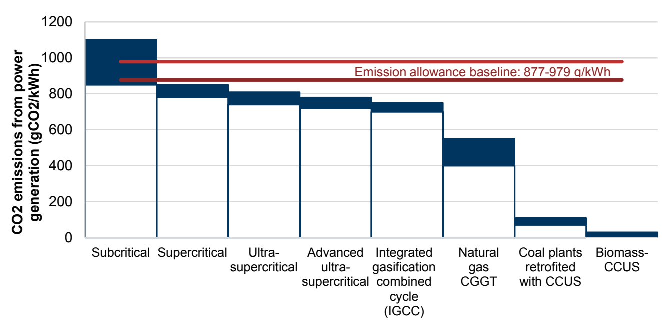
The Ministry of Ecology and Environment (MEE) hosted a media conference on January 5, 2021, confirming that the first compliance cycle of China's national ETS was effectively rolled out on January 1, 2021. **The ETS will initially cover power generation plants**. It will allocate allowances (also known as permits), based on the plant's generation output, with emission benchmarks for each fuel and technology. China's ETS, **set to expand to seven other sectors (aviation, non-ferrous metals, steel, construction materials, chemicals, petrochemicals and paper manufacturing) will be the world's largest globally**. Ultimately, benefits from China's national ETS will come from either **surplus allowance for companies operating below the baseline threshold** (e.g. "clean" coal utilities) or **companies that are able to issue CCERs** (e.g. renewable operators). The latter could also drive demand for renewable projects, which could lead to growth in demand for renewable equipment, benefiting upstream players. Among coal operators, the suggested benchmark is likely to drive asymmetric risk exposure, with some potentially benefiting from the ETS. We base this view on the proposed thresholds and where industry intensity currently stands. The current proposed carbon emission allowance baseline is 0.877-0.979 kg/kWh for conventional coal units, depending on their installed capacity, which will likely affect subcritical coal plants as they have a lower thermal efficiency and a higher emission intensity.

Exhibit 34: China's national ETS would be the world's largest, bringing total global emissions covered by carbon pricing initiatives to 23%
Carbon pricing initiatives' share of global GHG emissions covered (%)



Source: World Bank Group

Exhibit 35: The China ETS' proposed carbon emission allowance baseline could, in the near term, potentially benefit lower-carbon, more efficient coal power plant operators
Emissions from different power generation plants (gCO2/kWh)



Source: IEA, Company data, Goldman Sachs Global Investment Research

China net zero ambition: The most critical piece of the puzzle for global carbon neutrality

On September 22, the President of the People's Republic of China, Xi Jinping, addressing the general debate of the 75th session of the United Nations General Assembly, stated that China aims to scale up its Intended Nationally Determined Contributions, or the post-2020 climate action commitments submitted by countries before reaching the 2015 Paris Agreement, by adopting more vigorous policies and measures. President Xi Jinping announced that China eyes new targets: **reaching a peak in its carbon dioxide emissions before 2030 and achieving net zero carbon emissions by 2060.** Li Gao, head of climate change at the Ministry of Ecology and Environment, reiterated the targets in October while stating that the **14th Five-Year Plan (2021-25) period will be key for China's climate efforts as the country eyes its new targets.**

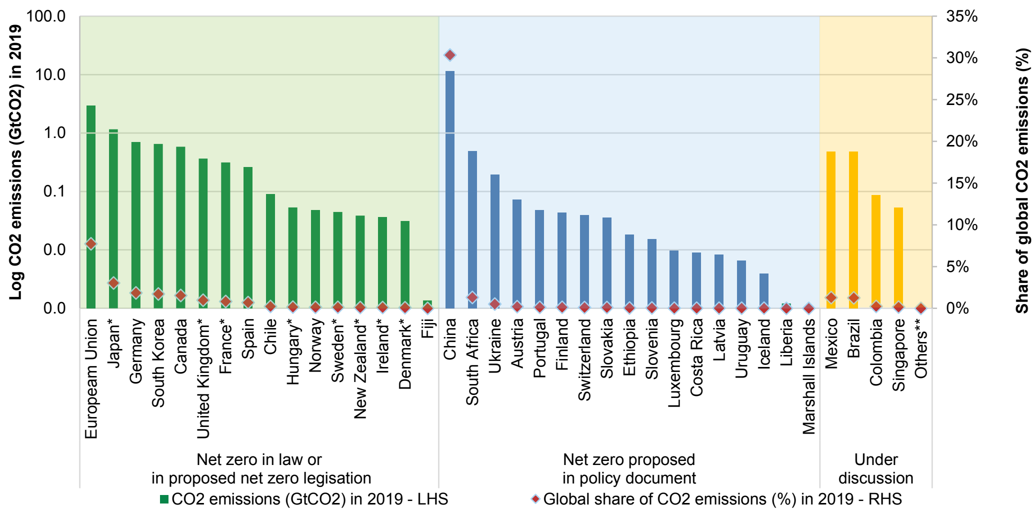
The Five-Year Plans, as outlined in our Asia strategists' report, are a series of social and economic development initiatives issued since 1953 in the PRC in which strategies for economic development, growth and reform targets are mapped out by the Party for the next five years. While each Five-Year Plan is important in its own right, the **strategic importance of the 14th Five-Year Plan period** (2021-25) lies with the fact that it will mark the first five years of China's moves towards its second centenary goal (2049, the 100th-year anniversary of the establishment of the PRC in 1949) to build a "modern socialist country" after achievement of the first centenary (2021, the 100th-year anniversary of the establishment of the CCP in 1921) goal of building a "moderately prosperous society". The **finalized proposal of the 14th Five-Year Plan** from the Party was released in the Fifth Plenum of the 19th Party Congress in late October, and the **detailed plan draft will likely be submitted to the National People's Congress (NPC) for final approval** during the "Two Sessions" in **March 2021**.

China's net zero emissions ambition by 2060 adds to the rapidly increasing number of national net zero pledges worldwide (as shown in Exhibit 36). However, China's importance in the context of climate change and global emissions (it accounted for c.30% of total global CO_2 emissions in 2019) and its strategic position in the global economy (as one of the fastest growing economies) **makes the stated ambition unique and a critical milestone for global de-carbonization efforts**. Up until this point, the nation had yet to commit to a long-term de-carbonization goal, although it has met its national targets set out in key climate change agreements outlined in Exhibit 38, including its commitments laid out in the Copenhagen Accord and under its 13th Five-Year Plan (FYP), within the set timeline (by 2020).

Achieving this goal of net zero emissions would represent a milestone in modern Chinese history, but we believe that to be achieved **it will require China to embark on an ambitious multi-decade effort to transform its economy and energy ecosystems.** Net zero would have to serve as a guiding principle for policymaking that is comprehensively embedded into structural reforms, investment policies and innovation priorities.

Exhibit 36: China's net zero emissions ambition adds to the rapidly increasing number of national net zero pledges worldwide, which now cover c.48% of global CO2 emissions. A potential addition of the United States to the net zero pledges, as suggested by Joe Biden, would bring this coverage to c.61% of global CO2 emissions

Countries that have pledged net zero (in law, in proposed legislation and in proposed policies)



* Denotes net zero pledge is in law, ** Others under consideration includes many countries and regions (list not exhaustive)

Source: Energy & Climate Intelligence Unit, Goldman Sachs Global Investment Research

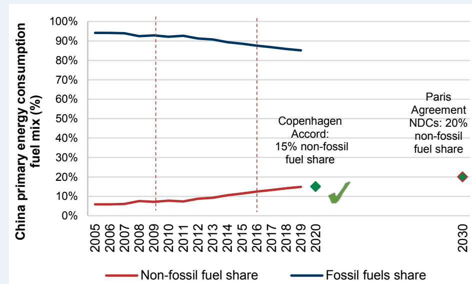
Exhibit 37: Key emission figures for China

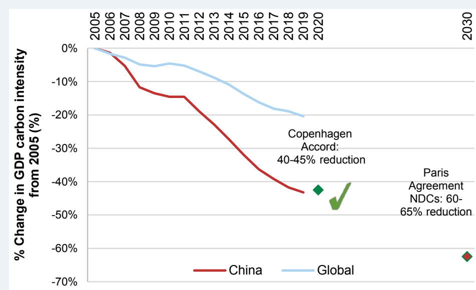
Source: World Bank, European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

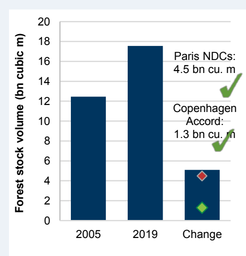
Exhibit 38: Summary of key climate change and de-carbonization related pledges and targets from China

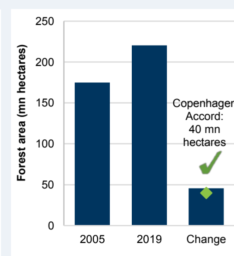
Summary of key climate change and de-carbonization related national pledges and targets from China

Pledge or agreement	Targets and pledges details	Tracking progress
Long-term ambition (announced 2020)	While China has not yet submitted a long-term strategy to the UNFCCC, President Xi Jinping made China's NDC announcement at the United Nations General Assembly, accompanied by the announcement of the intention to **aim to achieve carbon neutrality before 2060 and peak emissions before 2030.** On Dec 12, at the Climate Ambition Summit, President Xi made an important speech titled "Continuing the past and opening the future to start a new journey in global response to climate change", announcing that China will raise national voluntary contributions to fight climate changes to achieve by 2030: (1) Carbon dioxide emissions per unit of GDP will be reduced by more than 65% compared to 2005 (2) Non-fossil energy will account for about 25% of primary energy consumption (3) Forest storage will increase by 6 billion cubic meters compared to 2005 (4) Total installed capacity of wind and solar power generation will reach more than 1,200GW	
Paris Agreement (2016, Unconditional targets to 2030)	In September 2016, China ratified the Paris Agreement and submitted its Nationally Determined Contributions (NDCs) to the UNFCCC, including: **(1) Peak CO2 emissions by 2030 at the latest** **(2) Increase the share of non-fossil energy sources in the total primary energy supply to around 20% by 2030** **(3) Lower the carbon intensity of GDP by 60% to 65% below 2005 levels by 2030** **(4) Increase the forest stock volume by around 4.5 billion cubic metres, compared to 2005 levels by 2030** The following elements were also listed as measures for enhanced climate change action: - Increase the share of natural gas in the total primary energy supply to around 10% by 2020 - Proposed reductions in the production of HCFC22 (35% below 2010 levels by 2020 and 67.5% by 2025) and "controlling" HFC23 production by 2020.	
Copenhagen Accord (2009, Pledges to 2020)	China's 2020 pledges consists of the following elements: **(1) Reduction of CO2 emissions per unit of GDP by 40–45% below 2005 levels by 2020.** **(2) Increase the share of non-fossil fuels in primary energy consumption to around 15% by 2020.** **(3) Increase forest coverage by 40 million hectares and forest stock volume by 1.3 billion cubic metres by 2020 from 2005 levels.**	









Summary of key energy and climate change policies and pledges from Five-Year Plans (FYP)

FYP	Policies and pledges	Tracking progress
11th FYP (2006-2010)	Reduction of 20% in the energy intensity (energy consumption per unit GDP)	c. 19% reduction in the energy intensity by 2010
12th FYP (2011-2015)	1) Reduction of 17% in the carbon intensity (emissions per unit GDP) compared to 2010 2) Reduction of 16% in the energy intensity (energy consumption per unit GDP) compared to 2010 3) 11.4% of non-fossil energy share 4) Forest coverage of 21.7% and forest growing stock to 14.3 bn cubic meters	1) 20% reduction in carbon intensity achieved by 2015 2) 18.2% reduction in energy intensity achieved by 2015 3) 12% non-fossil energy share achieved by 2015 4) 21.63% forest coverage and 15.1 bn cubic m of forest growing stock achieved by 2015
13th FYP (2016-2020)	1) Reduction of 40-45% in the carbon intensity (compared to 2005 level) - consistent with the Copenhagen Accord. Therefore reduction of 18% compared to 2015 2) Reduction of 15% in the energy intensity (energy consumption per unit of GDP) from 2015 levels by 2020 3) 15% of non-fossil energy share 4) Coal power capacity limit at 1,100 GW 5) Forest coverage of 23.04%	1) >40% reduction in carbon intensity achieved in 2019 2) >14% reduction in energy intensity already achieved 3) 15% of non-fossil energy share acheieved in 2019 4) Below coal capacity threshold in 2019 5) 22.96% forest coverage in 2019
14th FYP (2021-25)	FYP outline and 'Vision 2035' expected to be released in March 2021.	

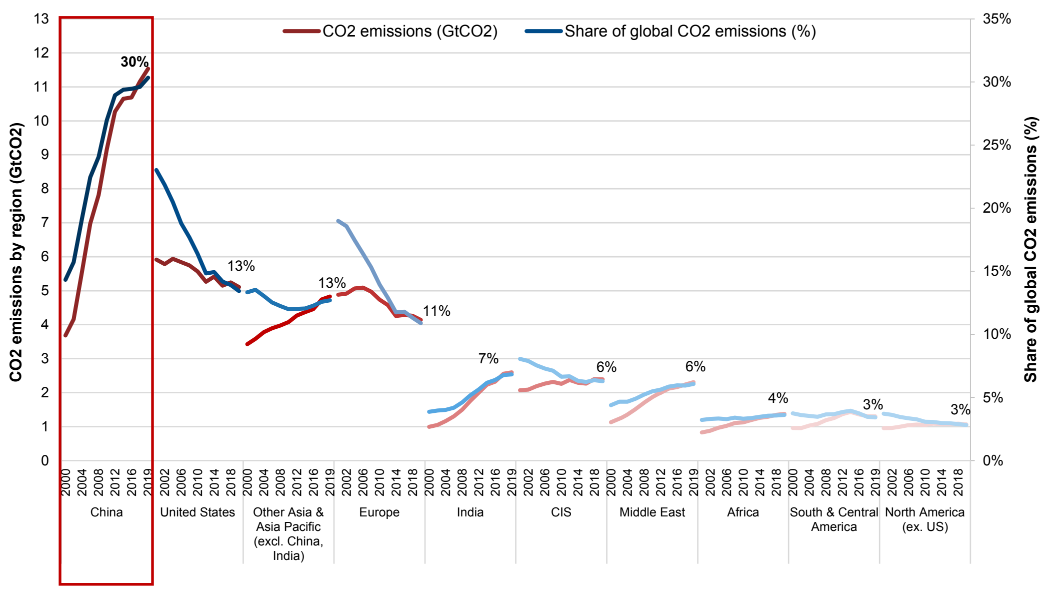
Source: National Bureau of Statistics of China, UNFCCC, World Bank Group, NDC Registry, C2ES, NDRC, European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Differentiated and distinct emissions scale, sectoral mix and path for China

China's emissions are differentiated in terms of scale, path and sectoral mix compared with other key geographical regions globally

China accounts for c.30% and 26% of total global CO_2 and GHG emissions, respectively, the single country with the highest share of global emissions produced in 2019, as shown in Exhibit 39. Its emissions path is distinct from that of other key geographical and economic regions, showing the steepest acceleration in 2000-10, a period marked by the stellar rise in China's economic activity, at a time when other key economies were able to stabilize or even reduce CO_2 emissions. Economic growth has been accompanied by large environmental negative externalities, as the combination of an energy-intensive growth model and carbon-intensive energy supply has led to the build-up of a comparatively large carbon footprint. China's emissions acceleration is, on our estimates, the source of c.45% of the rise in global GHG emissions since the 1970s, as shown in Exhibit 40.

Exhibit 39: China currently accounts for c.30% and c.26% of global CO2 and GHG emissions, respectively, higher than any other country or key geographical region globally, having shown a persistent upward trend
CO2 emissions (GtCO2, LHS) and share of global CO2 emissions by region (%, RHS)

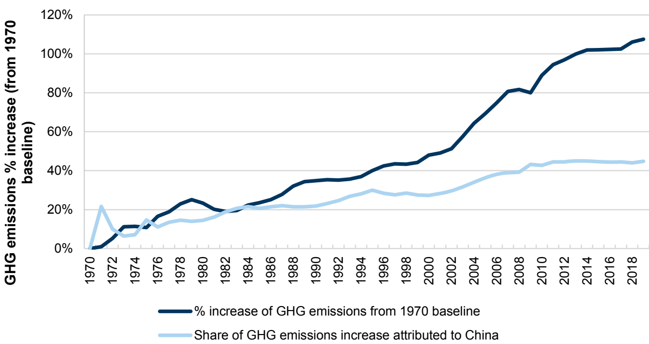


Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

China's emissions are distinct not only in terms of scale but also in terms of sectoral mix compared with other regions globally. In 2019, **c.80% of the country's emissions** were attributed to **two key emitting sectors**: **power generation** and **industry** (including industrial combustion, industrial processes and industrial waste). The **share of power generation and industrial emissions is higher than in any other major region globally**, as shown in Exhibit 42 and Exhibit 43, with transport and buildings emissions having a proportionately smaller share compared with other regions. This highlights the critical role of energy for China (responsible for power generation, transport, buildings and a large share of industrial emissions), making the **evolution of the country's energy mix** one of the most **important determinants of the de-carbonization path** in the near and medium term.

Exhibit 40: Global GHG emissions have doubled since 1970, with c.45% of the increase attributed to China

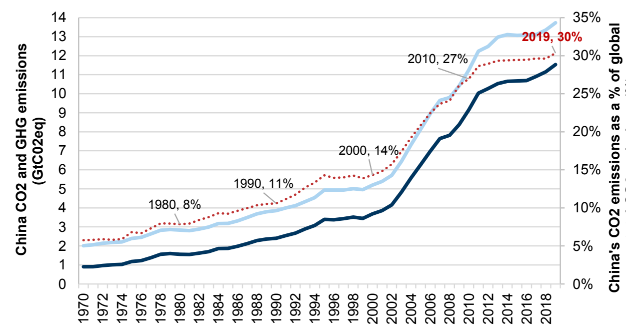
GHG emissions % increase relative to 1970 baseline and proportion of increase attributed to China



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 41: The sharpest increase in emissions occurred in 2000-10, which was marked by the stellar increase in China's economic activity

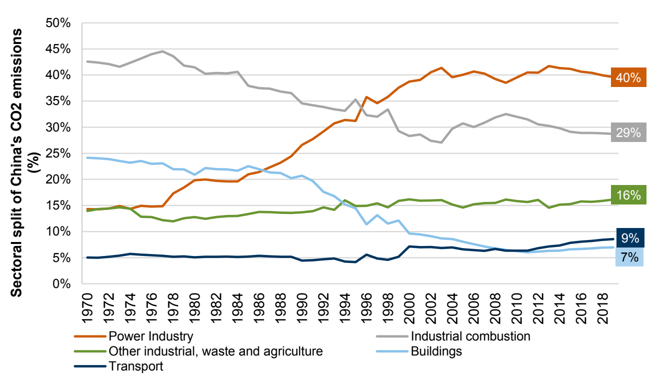
China's CO2 and GHG emissions (GtCO2eq, LHS) and its global share of CO2 emissions (%, RHS)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

Exhibit 42: China's sectoral emissions mix is differentiated, with >80% of the country's CO2 emissions attributed to the power generation and industry sectors...

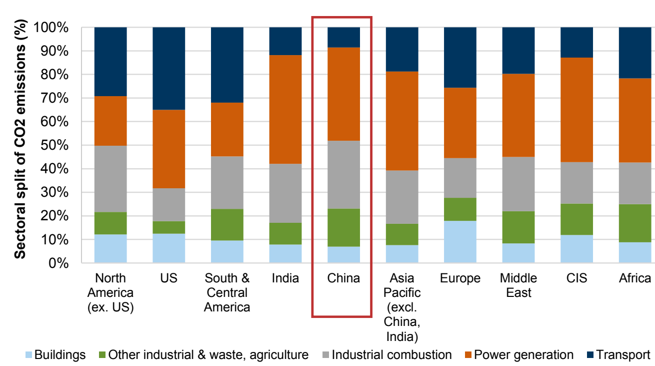
Sectoral split of CO2 emissions in 2019 (%)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 43: ...which together make the largest contribution to country level emissions than in any other key region globally

Sectoral split of CO2 emissions in 2019 (%)

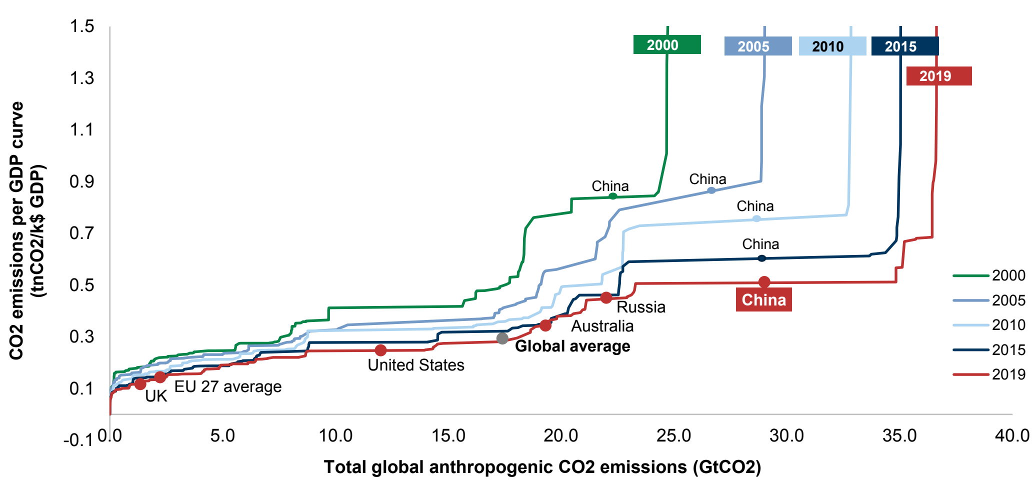


Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Despite the rise in absolute emissions, China has successfully reduced the emissions intensity of its GDP over the past 20 years, facilitating more sustainable economic growth...

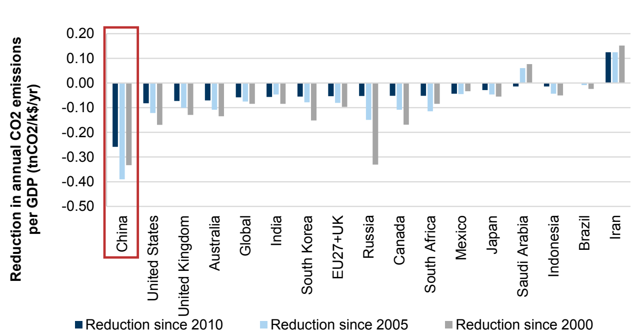
While China is currently the world's largest emissions producer, over the past two decades (since 2000), the country has **been able to reduce its emissions intensity per unit of GDP** (CO_2 emissions per thousand US$ GDP) **by c.40%, one of the largest reductions among key economic regions globally** (the second-largest reduction after the United Kingdom, as shown in Exhibit 46) and has achieved in the same timeframe the largest absolute reduction in emissions intensity (Exhibit 45), accounting for the large downward shift in the global GDP emissions intensity curve shown in Exhibit 44. Therefore, while the country's absolute emissions have been trending upwards, when adjusting for economic growth, **China has been able to consistently achieve more sustainable growth over the past two decades.**

Exhibit 44: While China's current emissions intensity per unit of GDP exceeds the global average, the country has achieved one of the largest reductions in GDP emissions intensity over the past 20 years, accounting for the large downward shift in the global GDP emissions intensity curve
GDP CO2 emissions intensity curve (tnCO2/k$ by region vs. global total CO2 anthropogenic emissions)



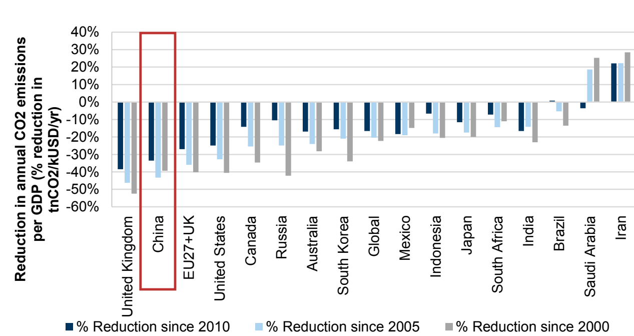
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 45: China has over the past 20 years achieved the largest absolute reduction in CO2 emissions per unit of GDP...
Reduction in annual CO2 emissions per unit GDP (tnCO2/k$ pa)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 46: ...and one of the highest in % terms, following the United Kingdom, among key emitting regions globally
Reduction in annual CO2 emissions per unit GDP (%)



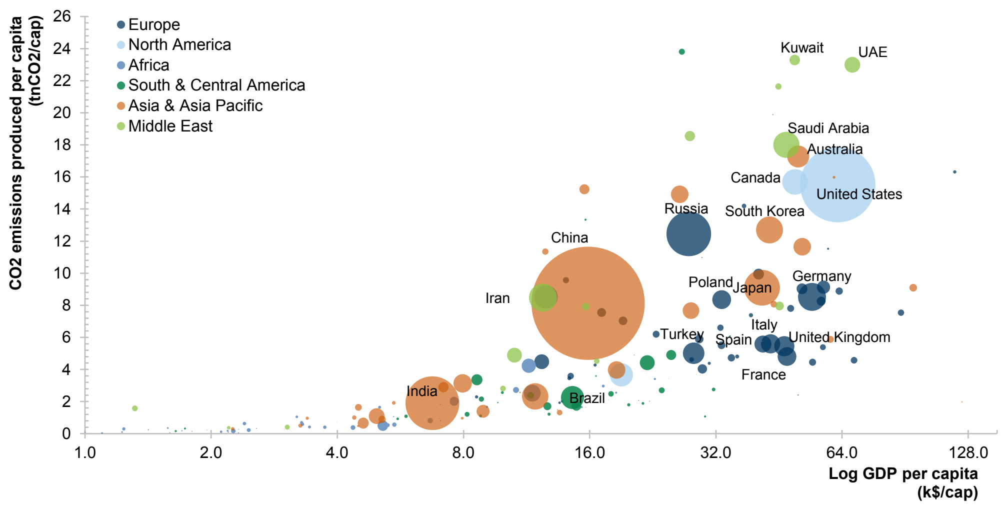
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

...and maintains an average emissions intensity per capita that is below many of the key economic regions globally and close to the global average

China's 2019 CO_2 emissions (produced at a country level) per capita screen broadly in line with the global average and are still well below those of other key regions globally (as shown in Exhibit 47). Countries with higher GDP/capita also tend to have higher CO_2 emissions/capita. This is consistent with the upward trend observed in China's CO_2 emissions per capita over the past two decades, as shown in Exhibit 48.

Exhibit 47: China's produced CO2 emissions per capita (2019) screen broadly in line with the global average and below those of other key economic regions globally

CO2 emissions produced in each country per capita (tnCO2/cap) and GDP per capita (k$/cap) for 2019

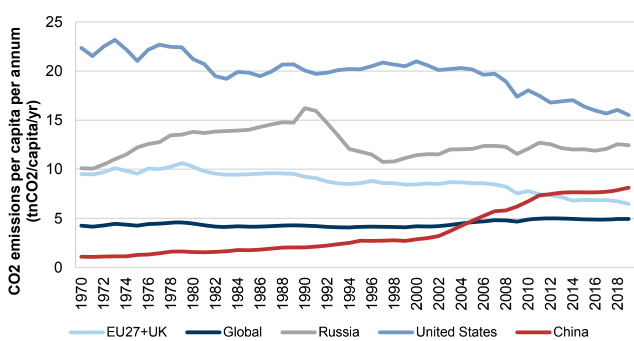


*Note: Bubble size represents the relative size of CO2 emissions produced in each country n 2019

Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

Exhibit 48: While China's CO2 emissions per capita are below the level of many other key economic regions globally, they have increased notably over the past two decades...

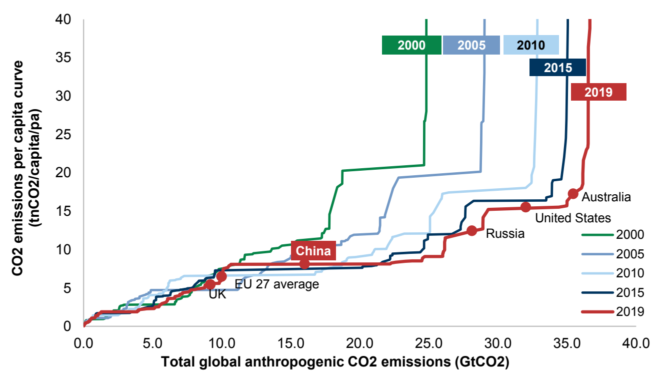
CO2 emissions per capita pa (tnCO2/cap/yr)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0

Exhibit 49: ...moving higher on the CO2 intensity per capita curve

CO2 emissions intensity per capita curve (tnCO2/cap by region vs. global total CO2 anthropogenic emissions)



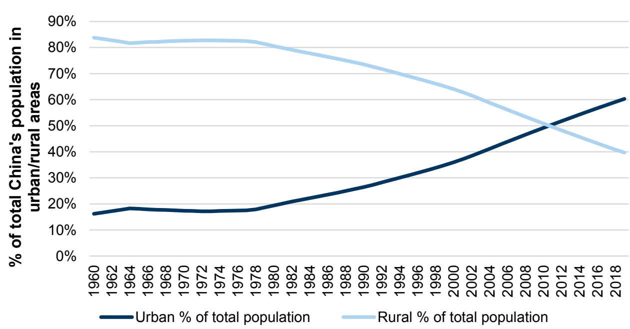
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research

The ongoing urbanization trend in China may see emissions per capita rise towards levels of other developed economies in the absence of a net zero emissions trajectory

China's urban population has increased sharply from c.100 million (1960) to more than 800 million in 2019, with c.60% of China's population currently living in urban areas. As a result, the population density in urban areas in China has increased by almost three times over the past three decades (since 1990), as shown in Exhibit 51, and the country currently shows among the largest population density discrepancies between urban and rural areas globally, as shown in Exhibit 52. Large-scale urbanization in China has led to unprecedented urban expansion and infrastructure development. The urbanization trend and the migration from rural and urban areas is typically associated with higher disposable incomes and subsequently higher consumption expenditure, as shown in Exhibit 53, resulting in higher emissions from this source.

Exhibit 50: The urbanization trend in China continues, with c.60% of the country's population currently living in urban areas vs. <30% three decades ago (1990)...

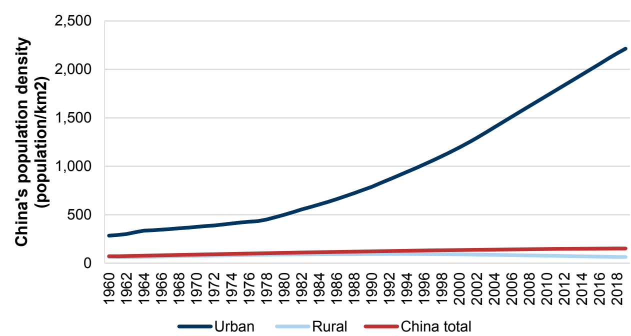
Urban and rural share of China's population (%)



Source: World Bank Group

Exhibit 51: ...and the population density in urban areas has increased almost threefold during this timeframe...

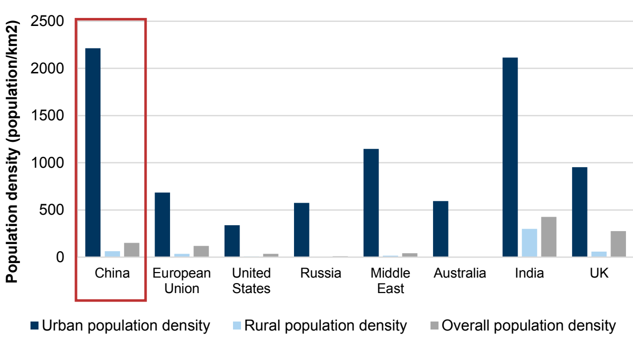
China population density (ppl/km3)



Source: World Bank Group, Goldman Sachs Global Investment Research

Exhibit 52: ...resulting in the largest population density discrepancy between urban and rural areas among key regions globally

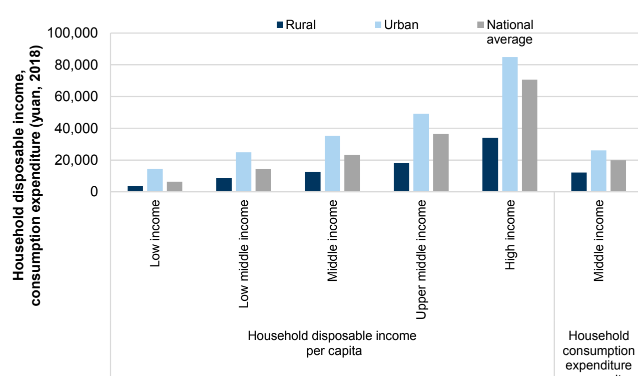
Population density for rural and urban regions, and national average for key regions globally (ppl/km2)



Source: World Bank Group, Goldman Sachs Global Investment Research

Exhibit 53: Urban households' average disposable income and consumption expenditure are >2x higher than rural households', resulting in higher consumption emissions

Chinese household disposable income, consumption expenditure (yuan, 2018)



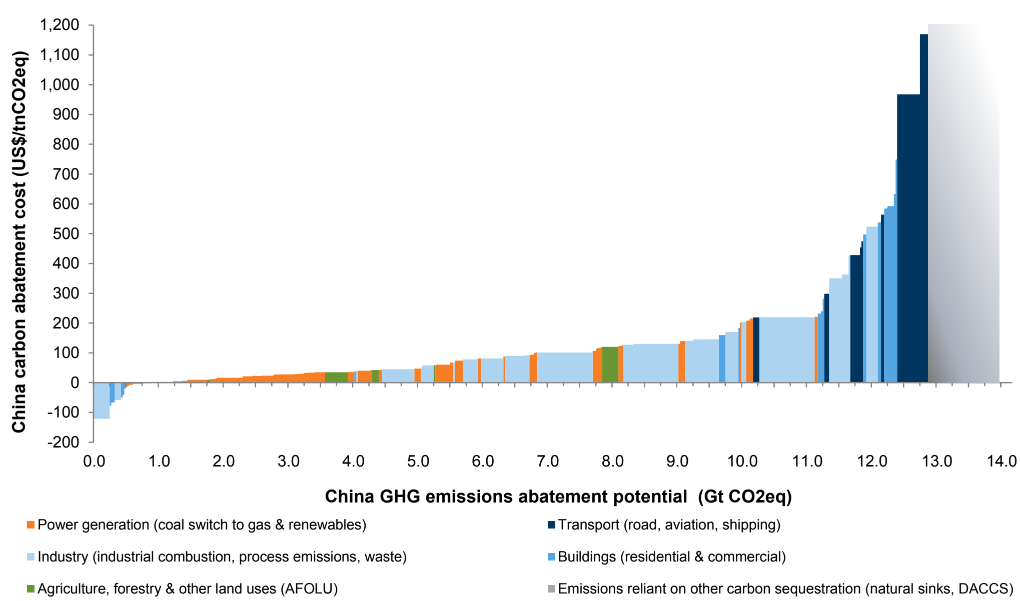
Source: National Bureau of Statistics of China, Goldman Sachs Global Investment Research

The cost curve of de-carbonization for China is very steep yet highlights a wide range of low-cost opportunities

In our deep-dive de-carbonization report, *Carbonomics: Innovation, Deflation and Affordable De-carbonization*, we introduced our global carbon abatement cost curve. We now introduce our first regional, China-specific de-carbonization cost curve. The Carbonomics de-carbonization cost curve shows the reduction potential for anthropogenic GHG emissions produced in China relative to the latest reported China anthropogenic GHG emissions. It primarily comprises de-carbonization technologies that are currently available at commercial scale (commercial operation & development), presenting the findings at the current costs associated with each technology's adoption. We include conservation technologies (technologies resulting in the avoidance of emissions) and process-specific sequestration technologies (technologies that sequester emissions back from the atmosphere, such as industrial carbon capture) across all key emission-contributing industries: power generation, industry (which includes industrial energy and process emissions) and industrial waste, transport, buildings and agriculture. **Our China de-carbonization cost curve addresses >100 different applications of GHG conservation technologies** across all key emitting sectors in China, as shown in Exhibit 54. We note that this curve is constructed on the basis of current costs associated with each technology and as such is likely to be a dynamic cost curve that evolves over time, as these technologies become more widely adopted and as economies of scale and technological innovation lead to cost deflation.

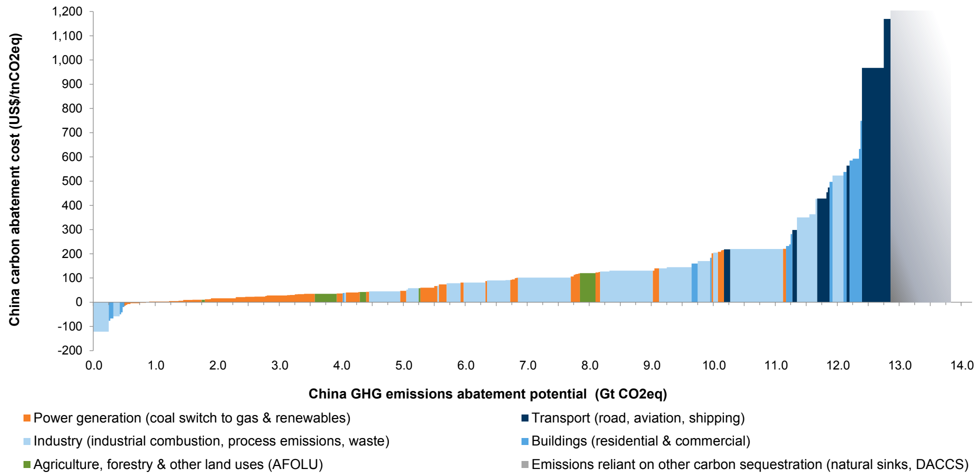
Exhibit 54: China's de-carbonization cost curve shows an abundance of low-cost de-carbonization opportunities (mostly technologies associated with energy emissions abatement) yet becomes very steep beyond 75% de-carbonization on the path to net zero

De-carbonization cost curve for China's anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research

Exhibit 55: Summary of key technologies considered in the construction of the de-carbonization cost curve for China along with the sectoral split of its GHG emissions



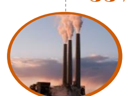
China GHG emissions split

7% — TRANSPORTATION

De-carbonization technologies

- **Domestic Aviation:** The switch to a more efficient aircraft model is considered a viable option for partial de-carbonization in the near term. Sustainable aviation fuels (SAFs, biojet) remain the sole commercially available de-carbonization route longer term.
- **DomesticShipping/marine:** LNG ships a technological option for ships meeting a threshold size, marine biofuels another viable technology, with clean ammonia run ships the key de-carbonization technology longer term.
- **Road short-haul transport:** EVs the key technology for road passenger transport, with a small proportion of de-carbonization achieved through road biofuels for places with constrained electrification infrastructure.
- **Road heavy long-haul transport:** Electrification of short and medium haul trucks and buses a viable option. Hydrogen FCEVs the most promising de-carbonization option for long-haul heavy truck routes and forklifts.
- **Rail**: Rail electrification and hydrogen run trains the two de-carbonization solutions considered.

33% — POWER GENERATION



De-carbonization technologies

- **Switch from coal to renewables:** Switch from coal power plants to renewable energy sources including solar, onshore wind, offshore wind, bioenergy, hydropower is considered the ultimate de-carbonization solution which can achieve full emissions abatement for power generation systems in the presence of storage solutions. We considered the switch to all of these renewable energy sources in the presence of batteries (for intraday storage) and clean hydrogen (for seasonal storage).
- **Switch from gas to hydrogen CGGTs:** Whilst gas can act as a transition fuel, we consider the switch of existing natural gas CGGTS to hydrogen CGGTs in the long-run.
- **Energy storage**: Batteries a key technology for intraday storage with clean hydrogen the preferred solution for seasonal storage enabling the full uptake of renewables in the power generation system.
- **Switch to nuclear:** China maintains a robust nuclear energy expansion program and we therefore consider its role is supporting the above de-carbonization solutions.

5% — AGRICULTURE

De-carbonization technologies

- **Efficiency measures such as Improved land management and livestock management practices**: Improved cropland, grazing land and livestock management practices can help to optimize resource use for the agriculture sector.
- **Precision agriculture**: the use of technology to optimize crop yields, minimize excess use of nutrients and pesticides could all potentially contribute to reduced raw material and energy needs for the sector.

6% — BUILDINGS

De-carbonization technologies

- **Energy & heating**: Hydrogen and renewable electricity-run heat pumps are the two key technologies currently commercially available for de-carbonization of buildings longer-term. Natural gas can act as a transtion fuel with infratsructure potentially utilized for clean hydrogen longer-term. We consider both in our cost curve.
- **Efficiency**: Efficiency improvements can reduce the energy needs for heating and electricity and are thus viable options for de-carbonization. Switch to LED lighting, addition of cavity wall insulation, use of thermostats and highest efficiency HVAC systems can all contribute to efficiency improvements.

48% — INDUSTRY & WASTE

De-carbonization technologies

- **Industrial combustion:** Across major emitting industrial sectors, >50% of emissions are associated with the use of energy, primarily through industrial combustion (heat) processes. Switch from coal, natural gas to **biomass, biogas, electricity or clean hydrogen** are the key technologies in de-carbonizing energy-related emissions in industry.
- **Cement**: Process emissions associated with the materials involved such as clinker. Reducing the ratio of clinker to cement a key technology, along with **CCUS.**
- **Iron & Steel**: The switch from BF-BOF process to natural gas or hydrogen based DIR-EAF a possible near term de-carbonization option. The role of scrap and circular economy is also critical.
- **Petrochemicals:** Clean hydrogen (either blue or green) and bioenergy could aid the de-carbonization of process/raw material-related emissions.Recycling and circular economy also critical.
- **Efficiency**: Across all industrial processes, improvements in efficiency & recycling have the potential to aid de-carbonization.

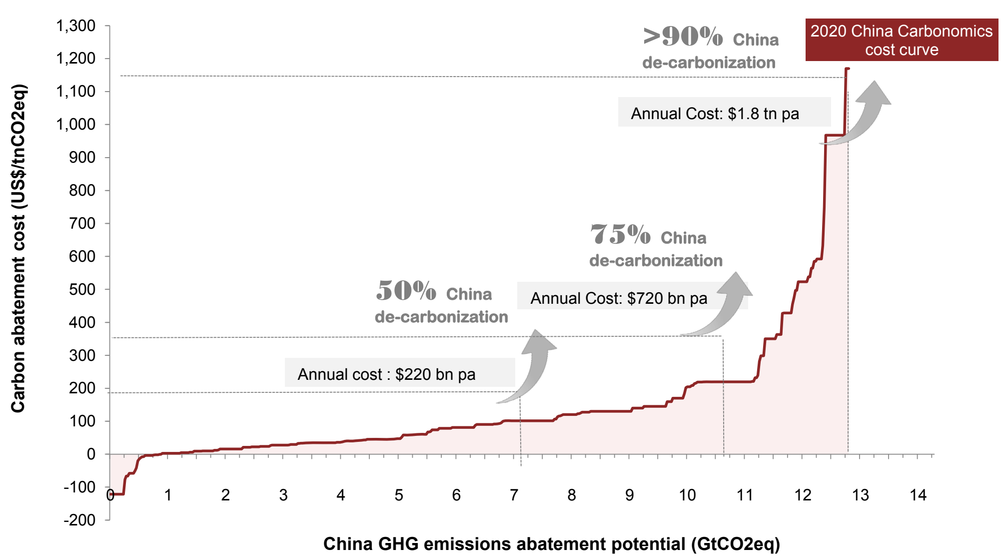
Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

The Carbonomics cost curve results, on our estimates, in a c.US$1.8 tn pa total cost for China's path to net zero emissions

The construction of our de-carbonization cost curve for China enables us to estimate the total annual cost of GHG emissions abatement achieved through the existing, large-scale commercially available de-carbonization technologies addressed in our cost curve (Exhibit 55). As shown in Exhibit 56, the initial c.50% of China's anthropogenic GHG emissions, what we classify as **'low-cost de-carbonization'**, can be abated at an estimated **annual cost of c.US$220 bn**. However, given the steepness of the cost curve, as we move beyond 75% de-carbonization, we enter the territory of **'high-cost de-carbonization'**, which requires up to **c.US$1.8 tn pa for 90% de-carbonization** achievable in the absence of non-process specific sequestration (natural sinks and direct air carbon capture). Overall, this implies up to **c.US$1.8 tn of annual cost as China approaches net zero by 2060.** We note that the remaining 10% of China's anthropogenic emissions, in the absence of new technologies, will have to rely on non-process specific carbon sequestration for abatement – **natural sinks and direct air carbon capture (DACCS)**, which we address separately in a later section in this report. We also note that this curve is constructed on the basis of **current costs** associated with each technology and as such is likely to be a **dynamic cost curve that evolves over time**, as these technologies become more widely adopted and as economies of scale and technological innovation lead to **cost deflation**.

Exhibit 56: The Carbonomics cost curve for China implies an annual cost of c.US$1.8 tn on the path to net zero, yet with plenty of low cost de-carbonization opportunities; c.50% de-carbonization is potentially achievable with an annual cost of US$220 bn

China carbon abatement cost curve for China's anthropogenic GHG emissions with cumulative area under the curve, based on current technologies and assuming economies of scale for technologies in pilot phase



Source: Goldman Sachs Global Investment Research

The four key transformational technologies with the potential to reshape the cost dynamics of China's de-carbonization cost curve

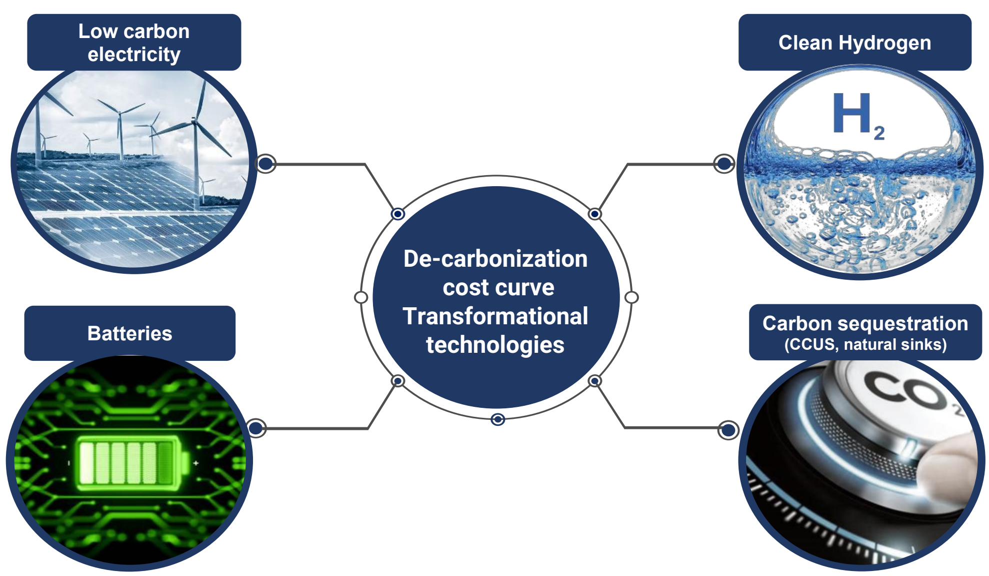
Looking at China's de-carbonization cost curve, we note that as we move towards net zero, the evolution of the energy mix is likely to be one of the most critical determinants of the country's de-carbonization path. As we highlight in our Carbonomics reports, we expect the **de-carbonization process to evolve from being one-dimensional (renewable power) to a multi-dimensional ecosystem.** Four technologies are emerging as transformational, potentially having a leading role in the future evolution of China's cost curve and the path to net zero emissions. Notably, all of these technologies are interconnected:

(a) Renewable power: The technology that dominates the 'low-cost de-carbonization' spectrum today and has the potential to facilitate the de-carbonization of c.50% of China's anthropogenic GHG emissions, supporting a number of sectors including power generation and sectors that require electrification, as well as being critical for the production of clean hydrogen longer term ('green' hydrogen).

(b) Clean hydrogen: A transformational technology for long-term energy storage enabling increasing uptake of renewables in power generation, as well as aiding the de-carbonization of some of the harder-to-abate sectors, with a critical role in several industrial processes (iron & steel, petrochemicals), long-haul transport, and heating of buildings.

(c) Battery energy storage: Extends energy storage capabilities, and is critical in the de-carbonization of short-haul transport through electrification and utility intraday storage.

(d) Carbon capture technologies: Vital for the production of clean ('blue') hydrogen in the near term, while also aiding the de-carbonization of industrial sub segments with emissions that are currently non-abatable under alternative technologies (such as cement).



Source: Goldman Sachs Global Investment Research

Laying out the path to net zero China

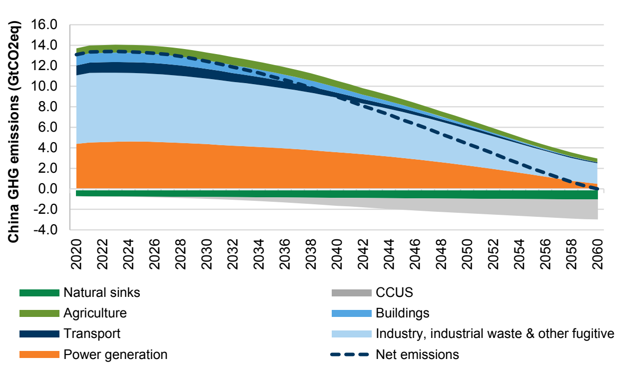
We lay out the possible path to net zero and carbon neutrality for China to 2060, in line with the country's stated long-term ambition

As part of this report, **we lay out a possible path to net zero and carbon neutrality for China to 2060 (with peak emissions before 2030)**, **in line with the country's stated long-term ambition**. We note that this path simply outlines one of the many possible routes that China could follow in its de-carbonization, and is, similar to China's de-carbonization cost curve (Exhibit 54), reliant on currently existing de-carbonization technologies (assuming economies of scale for technologies in pilot phase).

Our path to net zero China is developed using both bottom-up (analysis of each sector separately) and top-down approaches (a hybrid approach), and addresses each of the country's emitting sectors: power generation, transport, industry (including industrial combustion, industrial processes and waste), buildings and agriculture. Overall, we expect all of the key technologies addressed in our de-carbonization cost curve to play a role in facilitating the path to net zero China, each in their respective sector. For power generation, this implies a non-fossil fuel energy share of >95% achieved by 2060; for road transport, this implies new energy vehicles penetration (including BEVs, PHEVs and FCEVs) of close to 100% by 2060; for industry, an imperative improvement in efficiency and increasing penetration of clean hydrogen, electrification and carbon capture, as well as the critical role of circular economy; in buildings, it implies a switch from fossil fuel-sourced heating to clean hydrogen, electrification and the relevant efficiency improvements; and for agriculture, it assumes the required improvement in land management practices. The resulting emissions path for China carbon neutrality by 2060 is presented in Exhibit 57 and Exhibit 58 below.

Exhibit 57: As part of this report, we lay out a possible path for China to reach net zero emissions by 2060, in line with the country's stated ambition...

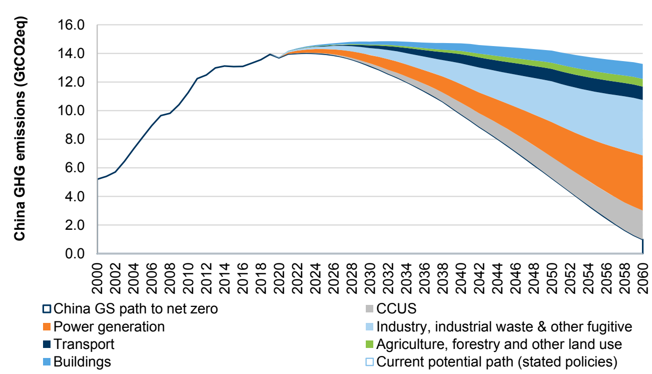
China anthropogenic GHG emissions (GtCO2eq) path to net zero (incl. natural sinks)



Source: Goldman Sachs Global Investment Research

Exhibit 58: ...with a contribution from all key emitting sectors and carbon sequestration

China anthropogenic GHG emissions path to net zero (excl. natural sinks) (GtCO2eq)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research

China net zero and investments: US$16 tn investment opportunity on China's path to carbon neutrality

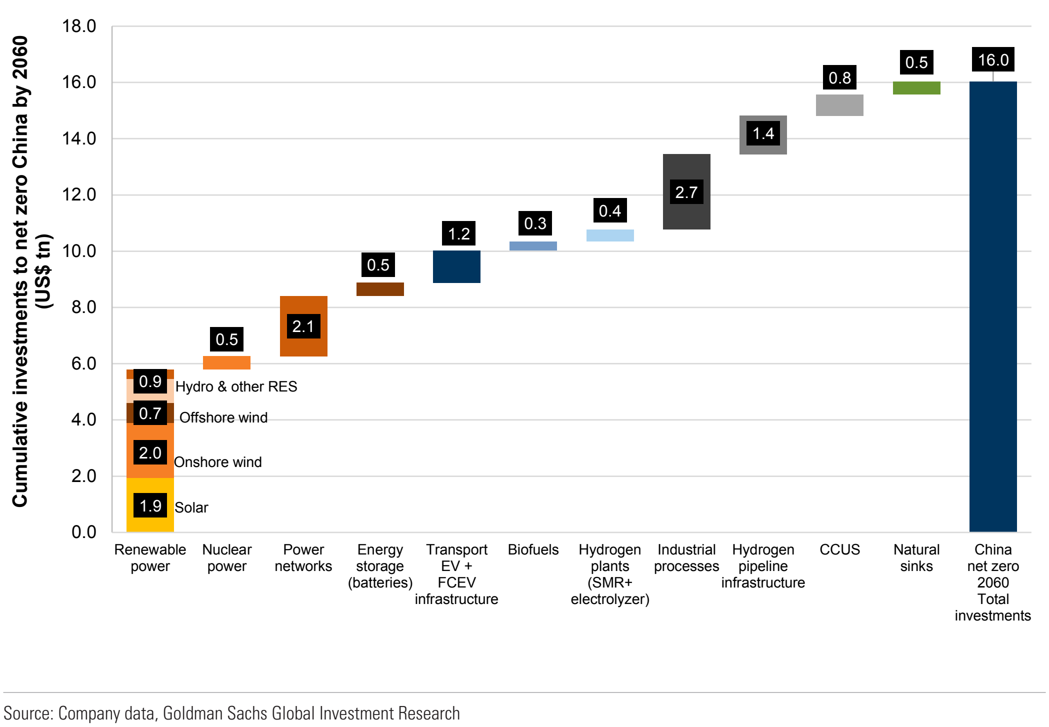
The path to net zero China presents a c.US$16 tn investment opportunity to 2060, on our estimates

A path to a net zero China by 2060 has the potential to transform not only China's energy ecosystems but also its industry and society's standard of living. Exhibit 59 shows the wide range of investment opportunities associated with what we believe are the key technologies required to achieve net zero emissions in China by 2060. These include, among others, the increasing uptake of renewable energy and bioenergy, an increasing focus on infrastructure investments for networks and charging stations that will enable a new era of electrification (as we highlight in our report *From Pump to Plug*), an upgrade of industrial plants (the cleanest available alternative technology), an upgrade of existing heating infrastructure enabling greater uptake of cleaner fuels such as natural gas and eventually clean hydrogen, and finally a greater focus on carbon sequestration (natural sinks and carbon capture).

In aggregate, we estimate a total investment opportunity of c.US$16 tn by 2060 in a scenario consistent with the path to net zero China that we have outlined above, and in line with the country's stated de-carbonization ambition.

Exhibit 59: We estimate that there exists in aggregate a c.US$16 tn investment opportunity across sectors on the path to net zero China by 2060

Cumulative investment opportunity across sectors for China net zero by 2060 (US$ tn)

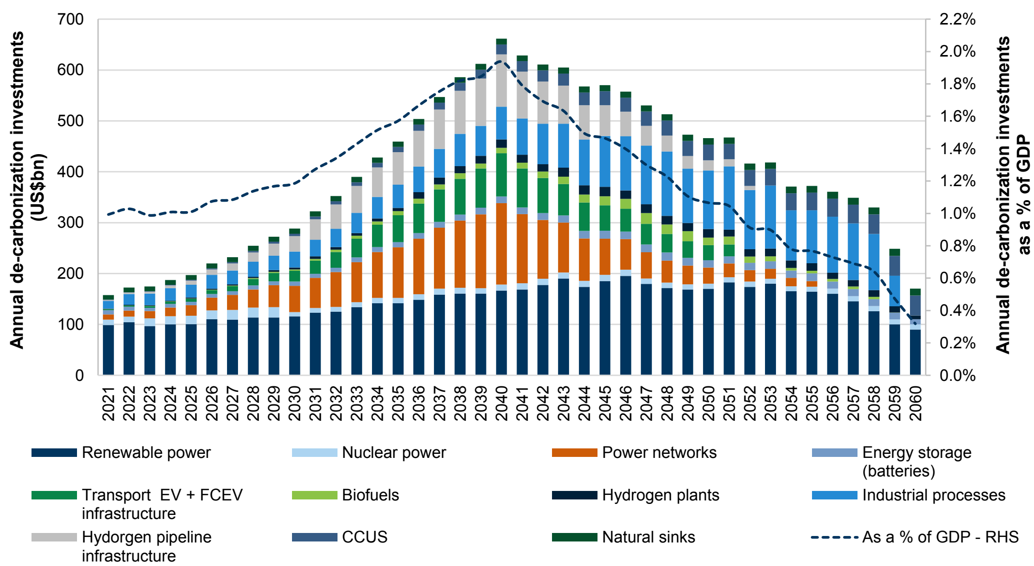


Source: Company data, Goldman Sachs Global Investment Research

As highlighted in Exhibit 59, we estimate a total investment opportunity of c.US$16 tn by 2060 in a scenario consistent with the path to net zero China, but we would not expect this to be evenly distributed annually to 2060. Instead, we anticipate an annual de-carbonization investment profile similar to that shown in Exhibit 60, with an acceleration of investments to 2040, the year when we expect investments to peak, driven largely by the initial infrastructure expansion required for power networks, charging infrastructure and heating pipeline infrastructure to accelerate the penetration of electrification and clean fuel substitution in transport, buildings heating and industry. Overall, the average annual investments in de-carbonization that we estimate over 2021-60 are c.US$400 bn (compared with c.US$100 bn spent on renewable power generation in 2019), with the peak in 2040 (c.US$650 bn) representing up to 2% of the country's GDP (based on our economists' projections).

Exhibit 60: We expect an annual investment profile similar to the one presented in this exhibit for a path consistent with net zero China by 2060, with investments peaking in 2040, representing up to c.2% of the country's GDP

Annual de-carbonization investments in US$ bn (LHS) and as a % of China's GDP



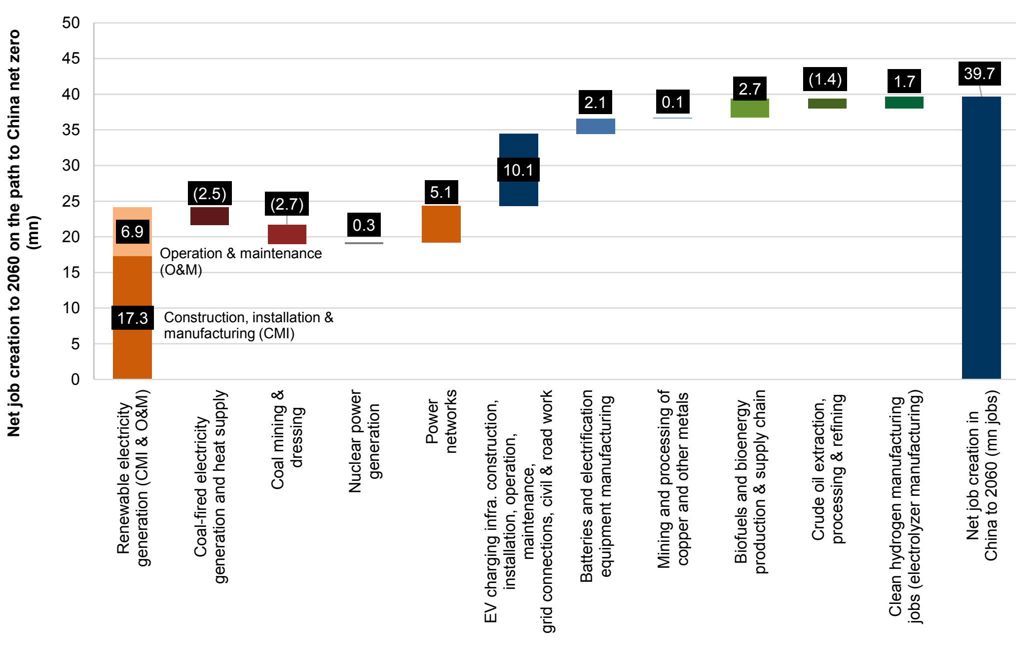
Source: Goldman Sachs Global Investment Research

China net zero and job creation: Potential for the creation of c.40 mn jobs by 2060

As we highlight in our report *Carbonomics: The green engine of economic recovery*, clean infrastructure could play a major role in facilitating a cleaner economy while fostering net job creation as it tends to be more capital- and labor compared with traditional fossil fuel energy developments, while benefiting from a lower cost of capital, making it an example of a successful pro-growth, pro-environment initiative. We estimate that **China's path towards its net zero ambition could facilitate the creation of c.40 mn jobs by 2060 across sectors**. We primarily focus on the impact of direct employment across the supply chain (we do not address indirect and induced employment in this analysis). The majority of employment creation that we expect is in sustainable energy ecosystems, dominated by renewable power generation, followed by power networks and electrification infrastructure. Net job losses arise in coal mining and processing, as well as coal power generation and crude oil extraction, processing and refining. We note that in this analysis, we use the available literature regarding employment factors, which may not account for future labor efficiency improvements and increased automation across these processes.

Exhibit 61: China's path to net zero emissions has the potential to create c.40 mn jobs by 2060 across sectors, on our estimates

Net job creation bridge on the path to net zero China by 2060 (mn jobs)



Source: UNEP - ILO - IOE - ITUC, EuropeOn, IRENA, NBSC, Goldman Sachs Global Investment Research

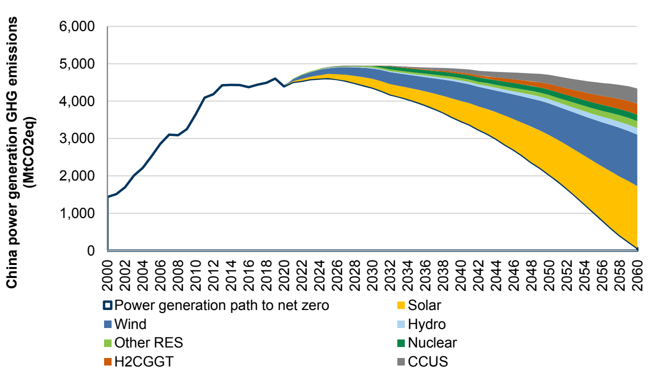
Laying out the path to a net zero China: A sectoral deep dive

1) Power generation: The crucial role of clean electricity for a net zero China and the transformational energy mix changes required

Power generation is (along with general industry), one of the most vital components of China's path to carbon neutrality, contributing c.40%/33% of the country's CO_2 and GHG emissions respectively, and making it a key area for efforts to tackle the net zero challenge. In recent decades, China has moved to the center of global economic growth, a result of economic reforms which resulted in an unprecedented level of urbanization and economic activity. Given the country's abundant coal supplies, its coal-powered power generation ramped up to meet rapidly growing electricity demand, and it now accounts for c.65% of the country's electricity mix (c.68% fossil fuel sources when including natural gas and oil).

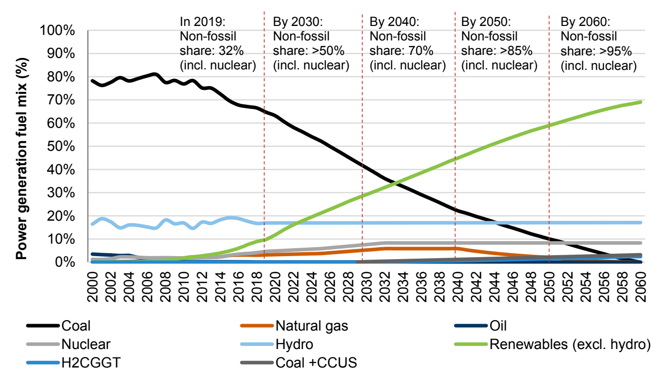
As part of this report, we attempt to lay out the path that China's power generation industry could take to reach net zero emissions by 2060 (and peak emissions by 2030), as we show in Exhibit 62. We also lay out a potential evolution of the electricity mix that could allow net zero emissions from the sector (Exhibit 63). Overall, **we believe the path to net zero will require a radical change in the country's energy mix and current energy ecosystems:** we estimate that non-fossil-sourced power generation will need to **surpass 50% of total generation by 2030, reach c.70% by 2040, and exceed 85%/95% by 2050/60, from c.32% currently.**

Exhibit 62: We lay out a path for China's power generation industry to reach net zero emissions by 2060, and peak emissions by 2030 as part of this report...
China power generation GHG emissions path to net zero (MtCO2eq)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, Goldman Sachs Global Investment Research.

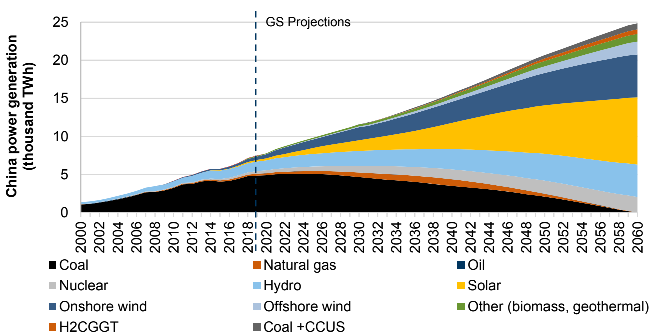
Exhibit 63: ...which will require transformational changes in the country's current power generation mix, with the non-fossil fuel share rising from c.32% in 2019 to >95% by 2060
China's power generation fuel mix (%)



Source: BP Statistical Review, Goldman Sachs Global Investment Research.

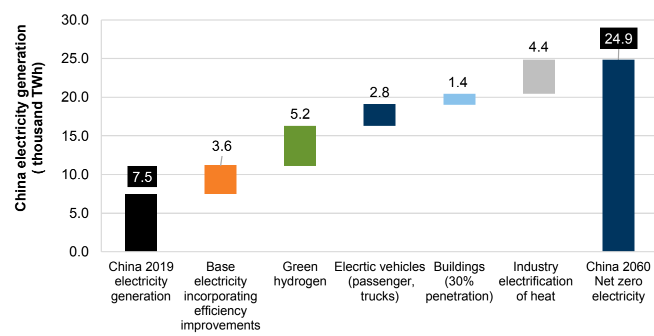
We see **electrification as a critical component of the path to net zero for the country, enabling de-carbonization across sectors** such as road passenger transport, industrial heating, buildings and the production of green hydrogen required for several industrial applications, long-haul transport, heating and seasonal energy storage applications. Overall, we expect **total demand for electricity in a net zero China in 2060 to be c.3x that of 2019,** as we show in Exhibit 66. **Renewable energy** (solar, wind, hydropower, bioenergy) **is without a doubt the most critical component for power generation de-carbonization, and has the potential to revolutionize the current energy system in China** (as highlighted by our Chinese Utilities team). Complemented by the already robust nuclear power expansion program in place (which we believe will likely have a less important role to play as renewables expansion accelerates and benefits from further cost deflation, and as alternative energy storage solutions become more readily available (utility-scale batteries and clean hydrogen)), we believe China could achieve its ambitious net zero emissions goal. Carbon capture could be used to aid the transition for relatively young life coal and gas plants, avoiding stranded assets, but its vital role in other parts of the de-carbonization process (e.g. industry) leads us to believe it is likely to have a limited role to play in power generation by 2060.

Exhibit 64: We see the potential for electricity demand to increase by c.3x, on a path consistent with China's net zero emissions target by 2060...
China electricity generation (TWh)



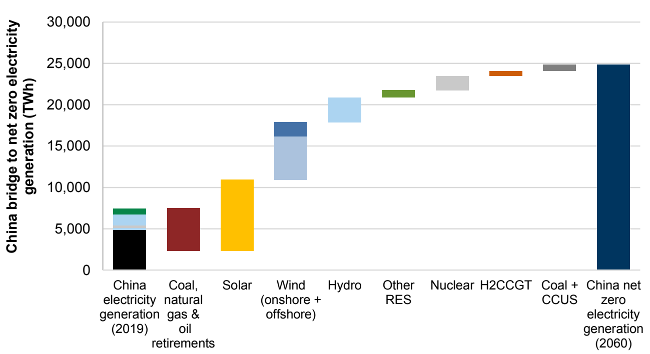
Source: BP Statistical Review, Goldman Sachs Global Investment Research.

Exhibit 65: ...as it is a vital part of the de-carbonization of other sectors such as electrification of transport and buildings, the production of green hydrogen, electrification of heat in industry and more
China electricity generation bridge to 2060E (thousand TWh)



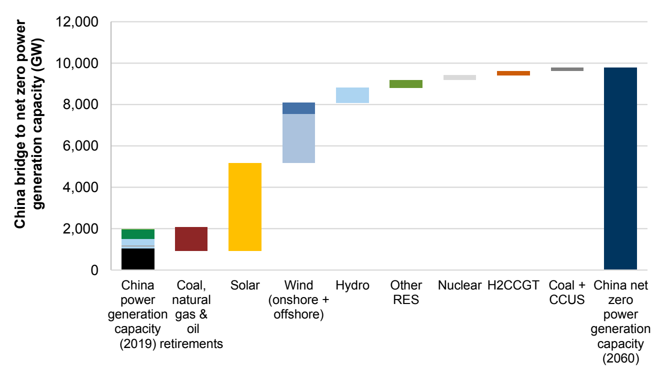
Source: BP Statistical Review, Goldman Sachs Global Investment Research.

Exhibit 66: The significant increase in electricity demand on a net zero path will likely be mostly met by a transformational acceleration of renewable power...
China net zero electricity generation bridge (2019-60E, TWh)



Source: BP Statistical Review, Goldman Sachs Global Investment Research.

Exhibit 67: ...with the potential for >4,000 GW of solar and c.3,000 GW of wind power generation capacity additions to 2060
China net zero power generation capacity bridge (2019-60E, GW)



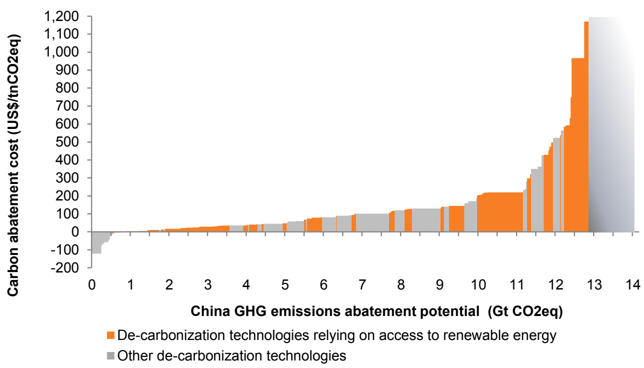
Source: Goldman Sachs Global Investment Research.

Renewable power: The low-carbon technology dominating 'low-cost de-carbonization', benefiting from economies of scale and a bifurcation in the cost of capital for high- vs. low-carbon energy

Renewable power has transformed the landscape of the energy industry and represents one of the most economically attractive opportunities on our de-carbonization cost curve (as shown in Exhibit 69), on the back of lower technology costs as the industry benefits from economies of scale and a lower cost of capital. We estimate that **c.50% of the de-carbonization of China's anthropogenic GHG emissions is reliant on access to clean power generation** (as shown in Exhibit 68), including electrification of transport and various industrial processes, electricity used for heating and more.

Exhibit 68: Access to renewable power is the most critical component, being more broadly vital for the de-carbonization of c.50% of the current China anthropogenic GHG emissions abatement across sectors

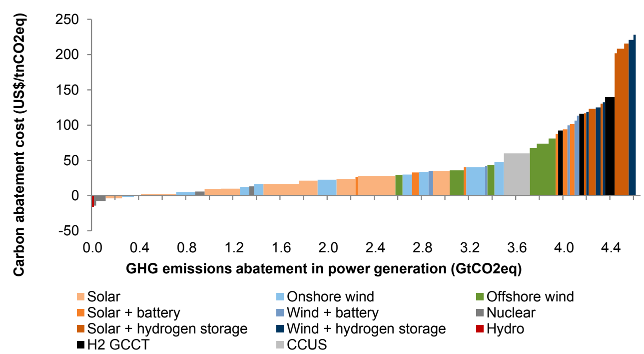
China anthropogenic GHG emissions de-carbonization cost curve with orange indicating technologies reliant on access to renewable power



Source: Goldman Sachs Global Investment Research.

Exhibit 69: Direct power generation de-carbonization through renewable energy is among the lowest-cost technologies on our China de-carbonization cost curve, even when energy storage is required

Power generation China de-carbonization cost curve

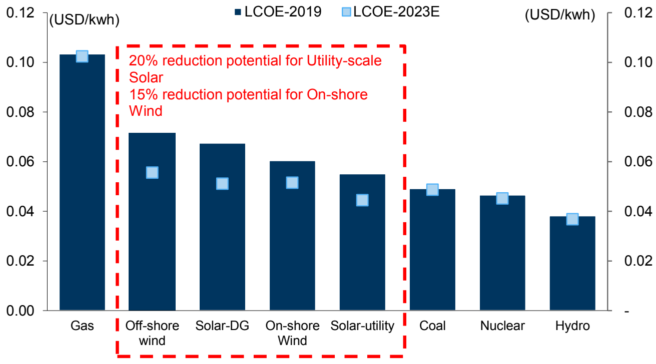


Source: Goldman Sachs Global Investment Research.

Renewable power costs have fallen >70% in aggregate across technologies over the past decade, and current renewable power LCOEs in China are now close to conventional fossil fuel power such as coal, as shown in Exhibit 70 below. We note that along with the operational cost reduction that renewable energy has enjoyed over the past decade, owing to economies of scale, the ongoing downward trajectory in the cost of capital, as we highlight in our report *Carbonomics: Innovation, Deflation and Affordable De-carbonization*, for these low-carbon developments has also made a meaningful contribution to the overall affordability and competitiveness of clean energy. We show in Exhibit 72 how the reduction in the cost of capital has contributed to one-third of the reduction in LCOEs of renewable technologies since 2010. In contrast, financial conditions keep tightening for long-term hydrocarbon developments, creating higher barriers to entry, lower activity, and ultimately lower oil & gas supply, in our view. This has created an unprecedented divergence in the cost of capital for the supply of energy, as we show in Exhibit 73, with the continuing shift in allocation away from hydrocarbon investments leading to hurdle rates of 10%-20% for long-cycle oil & gas developments compared with c.3%-5% for the regulated investments in Europe.

Exhibit 70: Renewable energy LCOEs in China are currently close to that of conventional fossil fuel power generation such as coal, particularly for solar-utility and onshore wind...

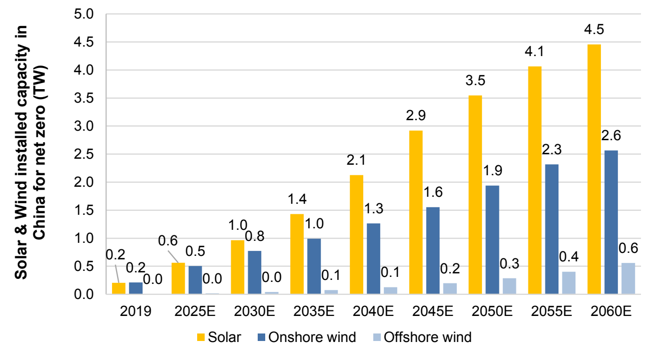
LCOE (USD/kWh)



Source: Goldman Sachs Global Investment Research.

Exhibit 71: ...and we expect stellar growth in capacity for both technologies, for a path consistent with net zero emissions by 2060

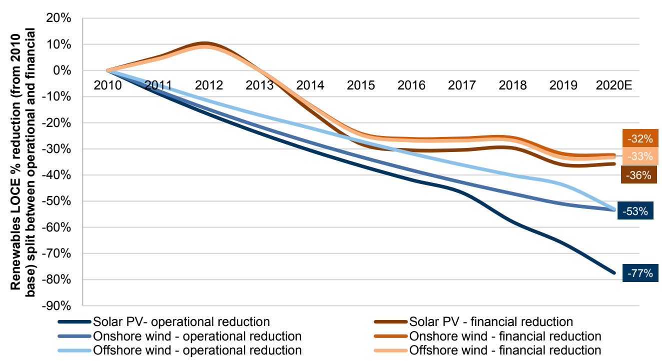
Solar and wind capacity additions in China for net zero (TW)



Source: Goldman Sachs Global Investment Research.

Exhibit 72: Renewable power LCOEs have decreased by >70% in aggregate across technologies, benefiting from a reduction in the cost of capital for these clean energy developments, contributing c.1/3 of the cost reduction since 2010

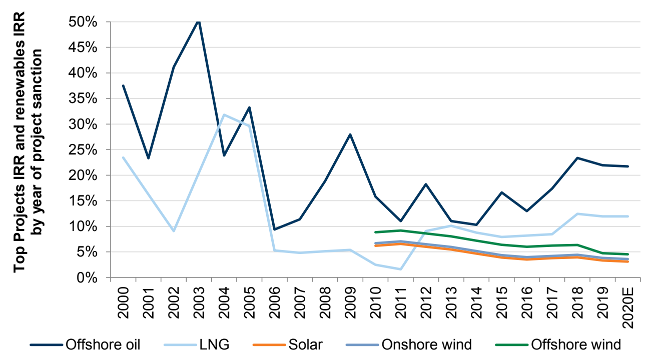
LCOE for solar PV, wind onshore and wind offshore for select regions in Europe (EUR/MWh)



Source: Goldman Sachs Global Investment Research.

Exhibit 73: The bifurcation in the cost of capital for hydrocarbons vs. renewable energy developments is widening, on the back on investor pressure for de-carbonization

Top Projects IRR for oil & gas and renewable projects by year of project sanction

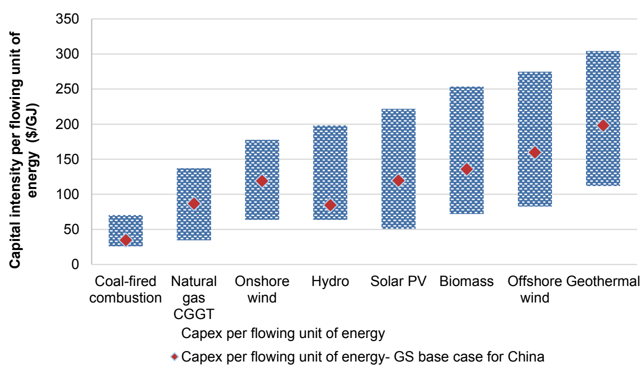


Source: Goldman Sachs Global Investment Research.

Higher capital and labor intensity of renewable power to act as a major source of investment and employment creation in the path to net zero China

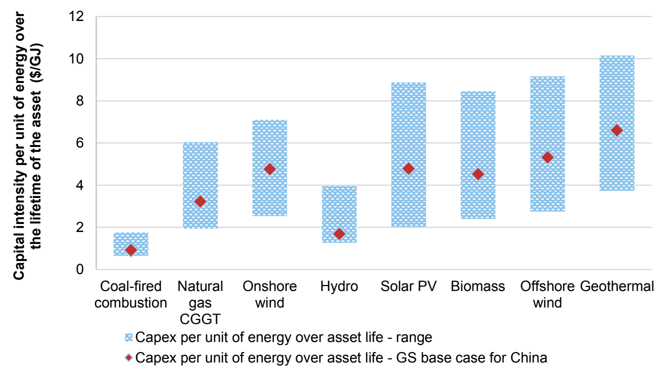
Earlier in this report, we highlighted the substantial potential investment and job creation opportunity associated with a path consistent with net zero emissions in China by 2060. Renewable power generation acts as a major contributor to both investments (Exhibit 59) and job creation (Exhibit 61). This is mainly attributed to the higher capital and labor intensity of these technologies and their associated infrastructure, compared with traditional fossil fuel energy developments. In the exhibits that follow, we present the capital intensity (capex) per unit of output energy for each type of power generation technology. We present the results both in units of capex per flowing unit of energy (US$/GJ of peak energy capacity) and per unit of energy over the life of the asset (US$/GJ). This shows higher capital intensity per unit of energy as we move to cleaner alternatives for power generation. However, this does not necessarily translate into higher costs for the consumer, thanks to the availability of very cheap financing (under an attractive and stable long-term regulatory framework) and lower opex, compared with traditional hydrocarbon developments.

Exhibit 74: Renewable clean technologies in power generation have higher capital intensity compared with traditional fossil fuel sources, based on per flowing unit of energy...
Capex per flowing unit of energy (US$/GJ)



Source: Company data, IRENA, Goldman Sachs Global Investment Research.

Exhibit 75: ...and over the lifetime of the asset
Capex per unit of energy over the life of the asset (US$/GJ) for each technology

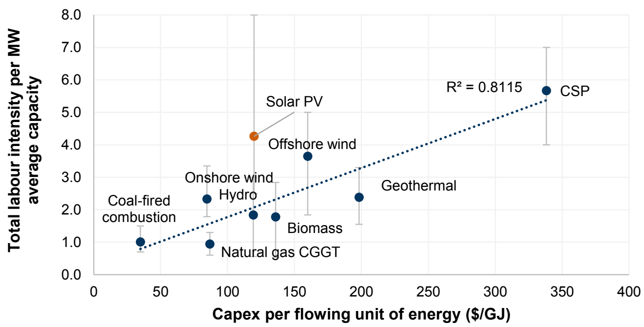


Source: Company data, IRENA, Goldman Sachs Global Investment Research.

Clean technologies have a higher average capital intensity than conventional fossil fuel power, based on both per unit of flowing output energy and per unit of energy over the asset/technology lifetime. The low-carbon economy's higher capital intensity is likely to foster employment creation, as indicated by the strong correlation between the capital intensity per unit of energy and its labor intensity (jobs per unit of average capacity over asset life) presented in the exhibits below. Solar PV is, according to the International Labour Organization (ILO) and the International Renewable Energy Agency (IRENA), the most labor-intensive clean technology in power generation (including construction, manufacturing, installation, operating & maintenance), albeit there exists a wide range of labor intensity factors depending on utility scale vs. rooftop PV.

Exhibit 76: The capital intensity of clean technologies in power generation shows a >80% correlation with labor intensity in the industry

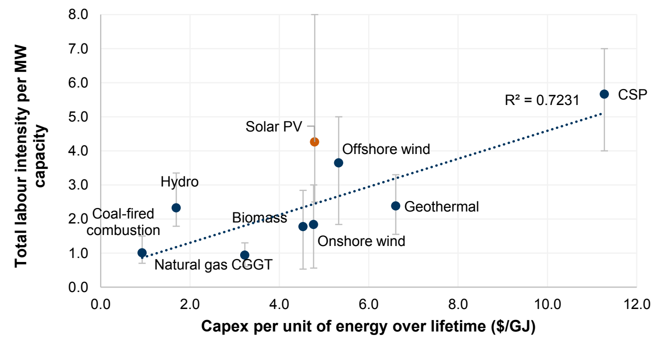
Capex per unit of energy over asset life vs. total labor intensity per MW average capacity



Source: Wet et al. as illustrated by IRENA, UNEP - ILO - IOE - ITUC, Goldman Sachs Global Investment Research.

Exhibit 77: Solar PV is the technology that deviates from the trend, with a labor intensity that varies widely depending on the development (particularly in rooftop vs. large-scale utility)

Capex per flowing unit of energy vs. total labor intensity per MW average capacity



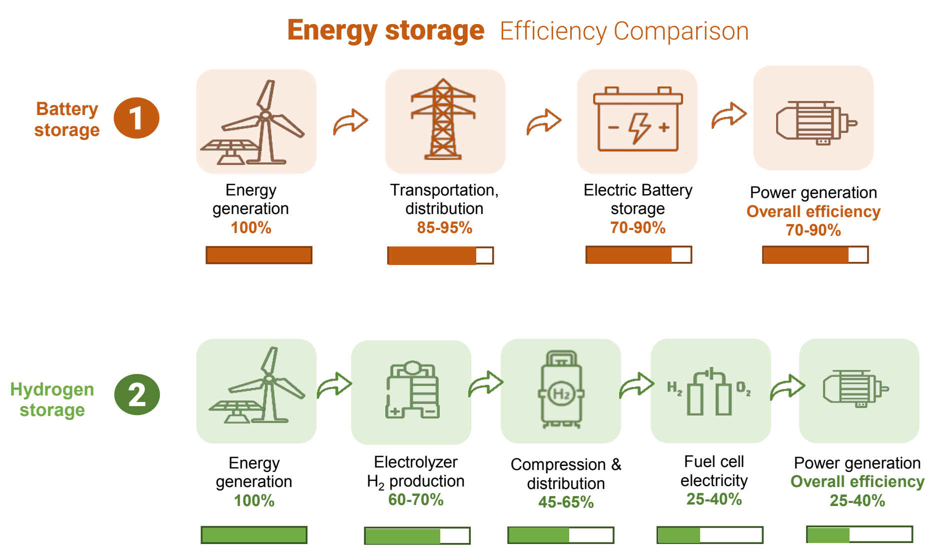
Source: Wet et al. as illustrated by IRENA, UNEP - ILO - IOE - ITUC, Goldman Sachs Global Investment Research.

The rising importance of energy storage and extensive network infrastructure

As the growth in renewable power accelerates, intraday and seasonal variability has to be addressed through energy storage solutions. To reach full de-carbonization of power markets, we believe two key technologies will likely contribute to solving the energy storage challenge: utility-scale batteries and hydrogen, each having a complementary role. We incorporate both of these technologies in our path to net zero and expect utility scale batteries for energy storage to surpass 400 GW by 2060, while clean hydrogen-run CGGTs reach c.3% in the electricity generation mix in a similar timeframe. **Energy storage and the need for extensive network infrastructure** is a particularly **important consideration for China,** as the **areas with the largest potential for solar and wind appear to be far from the main industrial hubs and city centers where most power demand arises,** as shown in Exhibit 79. In light of China's geographical complexity, a careful balance needs to be struck between the competitiveness of the wind and solar resources in sparsely populated regions, especially in the Northwest, and the difficulties of integration and network development.

While batteries are currently the most developed technology for intraday power generation storage, we consider hydrogen as a more relevant technology for seasonal storage, implying the need for innovation and development of both technologies. Batteries, for instance, are particularly suited to sunny climates, where solar PV production is largely stable throughout the year and can be stored for evening usage. Hydrogen on the other hand, and the process of storing energy in chemical form and reconverting it to power through fuel cells, could be used to offset the seasonal mismatch between power demand and renewable output. Yet, with fuel cells overall currently having efficiencies that vary between 50% and 65%, the overall efficiency of energy storage becomes a weak point for hydrogen, where we estimate the life-cycle of energy storage efficiency to be in the range of c.25%-40% overall, compared with c.70%-90% for batteries, as shown in Exhibit 78.

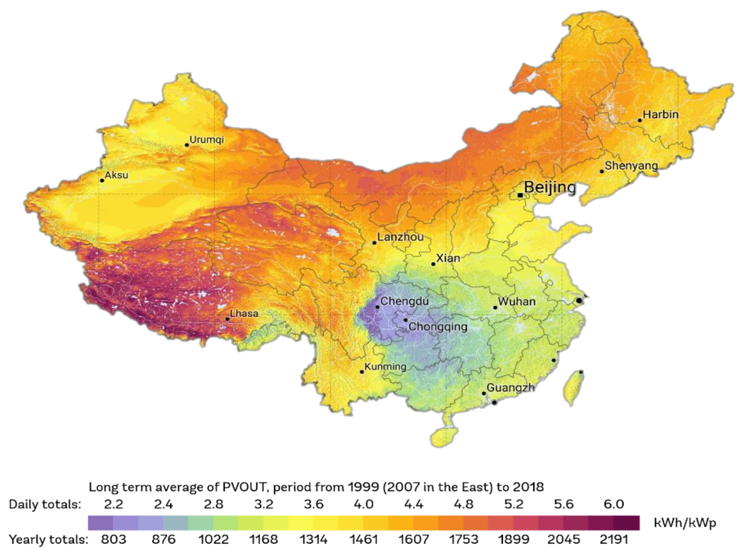
Exhibit 78: We see utility scale batteries and hydrogen as the two key complementary technologies to address the energy storage challenge

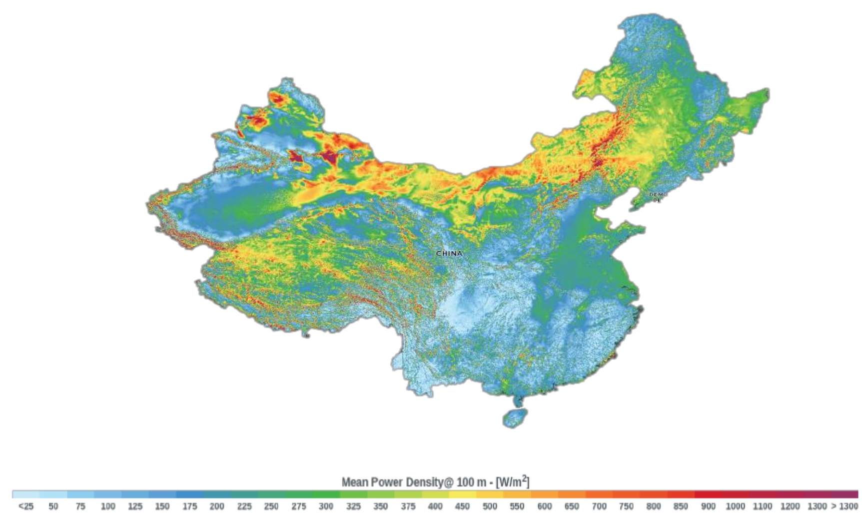


Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 79: Photovoltaic power potential and mean wind power density in China appears to be higher in the west and north parts of the country, far from the most of the large urban centres with higher power needs, highlighting the key role of energy storage and extensive network infrastructure

Photovoltaic power potential solar resource map (Global Solar Atlas) and mean wind power density map (Global Wind Atlas) for China





*The maps were obtained from the Global Solar Atlas 2.0, developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP) and the Global Wind Atlas 3.0, developed, owned and operated by the Technical University of Denmark (DTU) and released in partnership with the World Bank Group, utilizing data provided by Vortex, using funding provided by the Energy Sector Management Assistance Program (ESMAP).

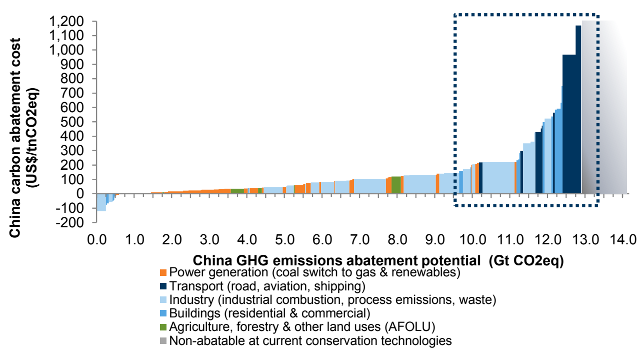
Source: Global Solar Atlas 2.0 - World Bank Group, Solargis, ESMAP, Global Wind Atlas 3.0 - World Bank Group, Technical University of Denmark (DTU), Vortex.

2) Transportation: The rise of new energy vehicles (NEVs) and the new charging infrastructure investment opportunity

Transportation, in contrast to power generation, mostly sits in the 'high-cost' spectrum of the de-carbonization cost curve, yet when it comes to China, transport emissions form a comparatively lower share of the country's CO_2 and GHG emissions, relative to other key economic regions, at c.9%/7% respectively (as shown in Exhibit 43). As part of our analysis, we lay out the path to net zero emissions for transportation for China, as shown in Exhibit 81, addressing short and medium-haul road transport, heavy long-haul transport, rail, domestic aviation and domestic shipping.

Exhibit 80: Transport sits at the higher end of the de-carbonization cost curve for China...

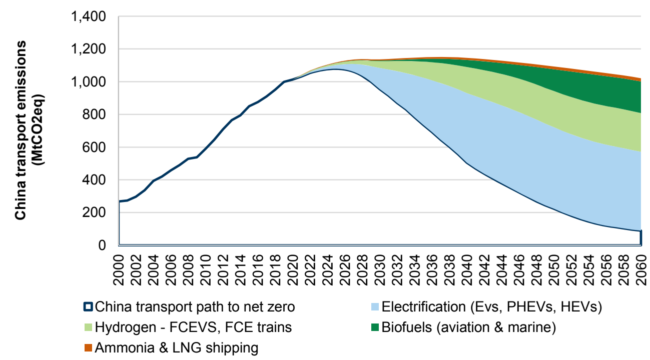
De-carbonization cost curve for China's anthropogenic GHG emissions, based on current technologies and current costs, assuming economies of scale for technologies in the pilot phase



Source: Goldman Sachs Global Investment Research.

Exhibit 81: ...yet a combination of electrification, clean hydrogen and bioenergy could successfully achieve a path consistent with net zero emissions in China by 2060

China transport emissions (MtCO2eq)



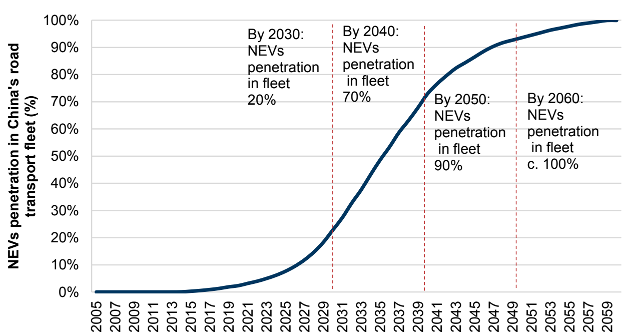
Source: Goldman Sachs Global Investment Research.

Road transport (passenger and short, medium-haul trucks): Electrification at the heart of the transport evolution

We believe road transport is at the start of its most significant technological change in a century, with electrification, autonomous driving and clean hydrogen at the core of the de-carbonization challenge. For light, short and medium-haul transport (primarily constituting passenger vehicles and short/medium-haul trucks), we consider electrification the key de-carbonization technology. For long-haul heavy trucks, we consider clean hydrogen a preferred option, owing to its faster refueling time, lower weight and high energy content. Overall, we estimate that China's total road fleet (including passenger vehicles, short, medium and long-haul trucks) will increase three-fold to 2060 (from a 2019 base), with **new energy vehicles – NEVs (including all of BEVs, PHEVs and FCEVs) reaching almost 100% penetration in the road transport fleet** as shown in Exhibit 82, for a path consistent with net zero emissions in China by 2060 and peak emissions before 2030. This path would require NEV penetration in the road transport fleet to reach 20% by 2030, close to 70% by 2040, 90% by 2050 and almost 100% by 2060. We look at fleet penetration in this analysis, rather than vehicle sales, as it is ultimately the penetration of the fleet that directly translates into transport emissions.

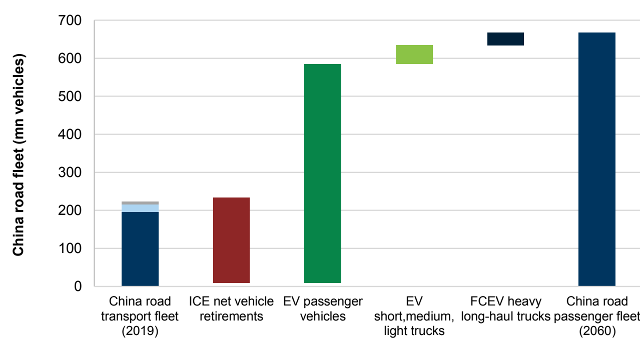
While we project considerable growth in pure battery vehicles (essential for a net zero path), we expect multi-energy powertrain to account for the largest segment of industry demand over the next 15 years. Multi-energy is defined as plug-in hybrid EV (green plate, mostly transmission-driven), range-extended EV (green plate, full motor-driven), and light emission hybrid cars (blue plate, full transmission-driven). On our current projections (current path), in line with the government's volume target, we model these multi-energy vehicles accounting for 47% of China's total car sales in 2025, versus pure battery cars at 13%, and pure non-battery cars (i.e. ICE-only) at 40%. We believe the ability to competitively integrate electric powertrain (control system supports autonomous technologies) with fuel system (compatible with infrastructure) will likely appeal to a majority of customers, especially outside the top municipalities (only six cities have ICE car plate restrictions, versus China's >600 cities), thus providing structural advantages in terms of brand and data collection. We expect the trend to drive long-term expansion of Li Auto (all range extended) and GAC's Japanese joint ventures (Honda's i-MMD, Toyota's hybrid synergy drive), owing to their advantageous hybrid IPs.

Exhibit 82: For a path consistent with net zero emissions in China by 2060, we expect new energy vehicles (including EVs and FCEVs) to reach almost 100% penetration in the road transport fleet....
NEVs penetration in China's road transport fleet for net zero (%)



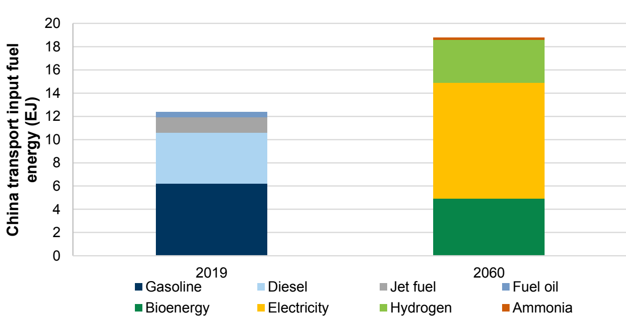
Source: Goldman Sachs Global Investment Research.

Exhibit 83: ...with electric vehicles the preferred solution for passenger vehicles and short, medium-haul light trucks and with clean hydrogen the preferred solution for long-haul heavy trucks
China road vehicles fleet bridge (2019-60E) for a net zero emissions path



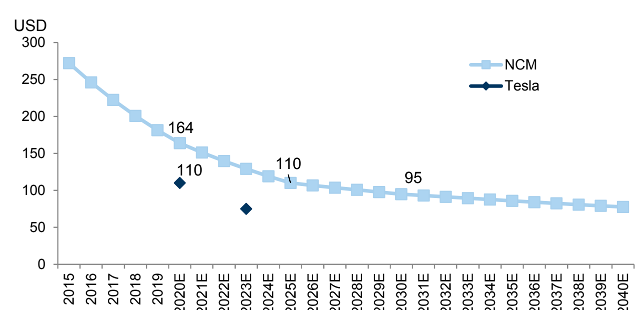
Source: NBSC, Goldman Sachs Global Investment Research.

Exhibit 84: A path to net zero demands a drastic change in the current input energy fuel mix in transport and efficiency, with electrification, clean hydrogen, bioenergy and ammonia dominating the 2060 transport fuel mix
Transport input energy fuel mix (Exajoules)



Source: Goldman Sachs Global Investment Research.

Exhibit 85: Electrification benefits from the ongoing deflation of battery technology, which we expect to continue, albeit at a slower pace post 2030E
Battery pack cost over time (US$/kWh)



Source: Company data, Goldman Sachs Global Investment Research.

China has already put in place targets encouraging electrification efforts, as outlined by our Asia autos team here. On October 27, 2020, the China Society of Automotive Engineers (China-SAE) unveiled its Energy Saving and New Energy Vehicle Technology Roadmap 2.0, outlining its development plans for new energy vehicles (NEVs) through 2035. The roadmap includes a sales weighting target for internal combustion engine (ICE) vehicles of 0% in 2035, suggesting that efforts toward realizing a low-carbon society are being stepped up in China. The target of 0% ICE in 2035 breaks down as 50% hybrids and 50% NEVs (EVs and plug-in hybrids), and suggests that China-SAE has major expectations, not only for EV market expansion, but also for growth in hybrid sales. We believe that for the path to a net zero China by 2060 to materialize, these targets have scope for even further increases, with a greater focus on net zero vehicles and less focus on hybrid vehicles.

Exhibit 86: China-SAE targets 50% NEV and 0% pure-ICE in 2035
China NEV roadmap through 2035

	~2025	~2030	~2035
Passenger Vehicle (PV)	- Fuel efficiency to be better than 4.6L/100km (WLTC) for new PV (incl. NEV)	- Fuel efficiency to be better than 3.2L/100km (WLTC) for new PV (incl. NEV)	- Fuel efficiency to be better than 2.0L/100km (WLTC) for new PV (incl. NEV)
Commercial Vehicle (CV)	- Freight car: fuel efficiency to be more than 8% better than 2019 level - Bus: fuel efficiency to be more than 10% better than 2019 level	- Freight car: fuel efficiency to be more than 10% better than 2019 level - Bus: fuel efficiency to be more than 15% better than 2019 level	- Freight car: fuel efficiency to be more than 15% better than 2019 level - Bus: fuel efficiency to be more than 20% better than 2019 level
Internal Combustion Engine (ICE)	- Fuel efficiency to be better than 5.6L/100km (WLTC) for new ICE - HEV accounts more than 50% of ICE	- Fuel efficiency to be better than 4.8L/100km (WLTC) for new ICE - HEV accounts more than 75% of ICE	- Fuel efficiency to be better than 4.0L/100km (WLTC) for new ICE - HEV accounts 100% of ICE
New Energy Vehicle (NEV)	- NEV accounts about 20% of total demand - FCV owned should be around 100k units	- NEV accounts about 40% of total demand - FCV owned should be around 100k-1mn units	- NEV accounts about 50% of total demand - FCV owned should be around 1mn units

Source: China-SAE

Road transport (heavy long-haul trucks): The role of clean hydrogen

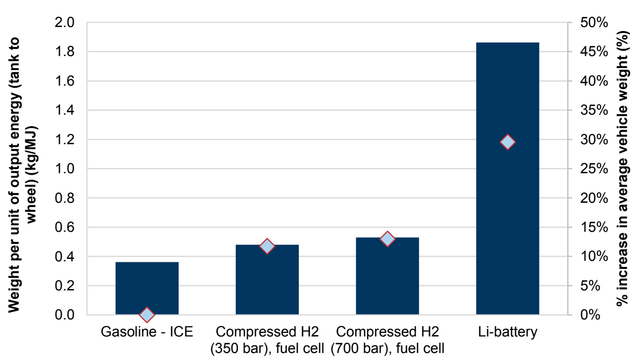
While we believe that electric vehicles screen as the most attractive de-carbonization solution for passenger vehicles and short and medium-haul transport, we believe that clean hydrogen could be the key technology when long-haul heavy transport is considered, given its high energy content per unit mass and faster refueling time. Although there are estimated to be only 6,180 FCEVs in China in 2019 (IEA), owing to a limited product offering, non-competitive price points and little infrastructure, we see the recent policy drive towards de-carbonization as a reason to reconsider the potential for FCEVs. Despite small absolute volumes, the growth of FCEVs accelerated notably in 2019, with the number of refueling stations increasing threefold in China in 2019 (from 20 to 61), giving China the fourth-largest number of stations. China has **already announced a target to deploy one million FCEVs by 2030, and to have >1,000 stations, 50,000 FCEVs and >300 stations by 2025**. Further regional initiatives explore the use of hydrogen for de-carbonization, with Wuhan announcing plans to become the first Chinese Hydrogen City by 2025 and Shanghai launching its Fuel Cell Vehicle Development Plan. For a deep dive on the future of trucking, please see our global team's published report and presentation.

Hydrogen's key attributes (low weight and high energy per unit mass, short refueling time, zero direct emissions when sourced from renewable energy sources) make it an attractive candidate as a transportation fuel. Hydrogen can be used in its pure form in fuel cell electric vehicles (FCEVs), but can also be converted into hydrogen-based fuels including synthetic methane, methanol and ammonia in a process commonly known as 'power-to-liquid', potentially applicable for aviation and shipping, where the use of direct hydrogen or electricity is particularly challenging. For all hydrogen applications, the volume requirement for on-board storage remains, along with the comparatively low overall well-to-wheel (or power generation to wheel) efficiency, the two key challenges for use of hydrogen.

The exhibits that follow present our **comparative analysis for hydrogen** fuel cell electric vehicles (FCEVs) and how these screen on a weight per unit of output energy and volume per unit of output energy basis, compared with other large-scale employed commercial vehicles – electric vehicles (EVs) and gasoline internal combustion engine vehicles (ICE). Exhibit 87 shows that for a fully loaded (or fully charged) average passenger vehicle, compressed hydrogen FCEVs screen attractively compared with Li-battery EVs on a weight per unit of output energy basis (tank-to-wheel). Similarly, hydrogen in its compressed form leads to FCEVs screening attractively on a volume per unit of energy output, compared with EVs. For the purpose of this analysis, we consider the weight and the volume of the system that stores and converts input energy to output energy across all three types of vehicles. This includes the internal combustion engine and gasoline tank components for ICE passenger vehicles, the Li-battery for EVs, and the fuel cell and compressed hydrogen storage tank for FCEVs.

Exhibit 87: FCEVs using compressed hydrogen screen attractively on a weight per unit of output energy basis when compared with Li-battery EVs...

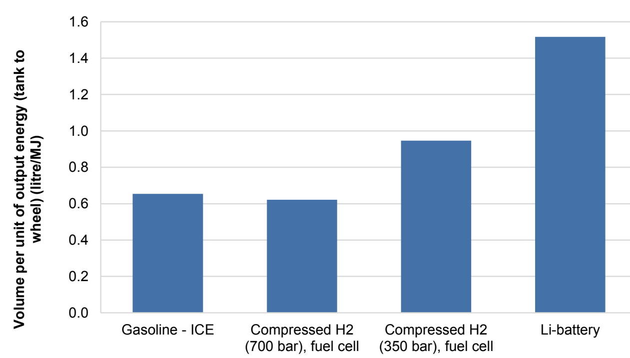
Weight per unit of output energy (tank-to-wheel basis, kg/MJ) for different average passenger vehicles and % increase in average vehicle weight



Source: EIA, Company data, Goldman Sachs Global Investment Research.

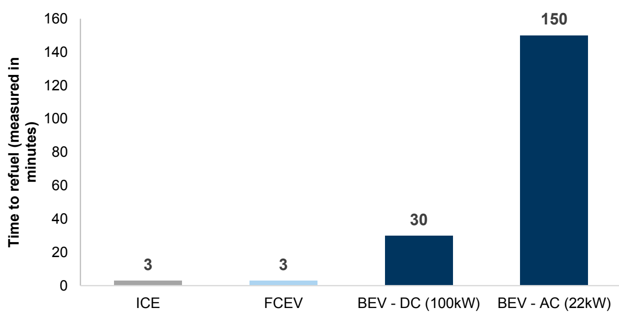
Exhibit 88: ...and considering the compressed form of hydrogen used in FCEVs, they also screen attractively on a volume per unit of output basis

Volume per unit of output energy (tank-to-wheel basis) (litre/MJ)



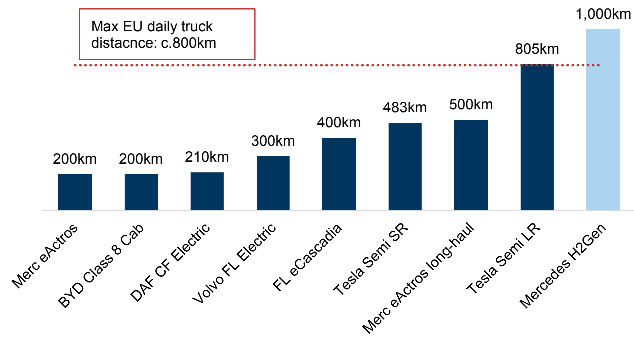
Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 89: Hydrogen outperforms significantly when we compare the refueling times of FCEVs versus BEVs at different kW charging ratings...
mins to refuel/recharge



Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 90: ...and also provides a range advantage for long-haul transport applications
ZEV Class 8 trucks and range (km)



Source: Transport & Environment, EU, Company data, Goldman Sachs Global Investment Research.

However, FCEVs screen less attractively in terms of cost (US$). The cost per unit of energy output for FCEVs becomes more competitive when considering long-haul heavy transport, as their long range implies less frequent refueling required and as large capacity (>300kWh) batteries in EVs remain costly. This makes **FCEVs attractive for long-haul transport applications such as buses and trucks and presents an area where economies of scale can bring further cost deflation benefits.**

Exhibit 91: Based on current prices, FCEV trucks are more expensive on a TCO basis, but with large cost reduction potential
Total cost of ownership of a Class 8 truck (15 years)

Model	Hydrogen truck		BEV truck		Diesel Truck
	2020	2025	2020	2025	2020
Model					
Cost of Truck	$250,000	$210,000	$250,000	$190,000	$120,000
Cost of fuel	$6 per kg/H2	$4.80 per kg/H2	0.10 $ per kWH	0.10 $ per kWH	$2.58 per gallon
Fuel consumption	7.5 miles per kg	7.5 miles per kg	0.4 miles per kWh	0.45 miles per kWh	8 MPG
Fuel cost over 15 years	$1,200,000	$960,000	$375,000	$333,333	$483,750
Maintenance costs	$259,500	$259,500	$242,400	$242,400	$311,800
Battery costs	$8,400	$5,688	$120,000	$81,262	$0
Payload losses	$0	$0	$266,667	$200,000	$0
Total cost	$1,717,900	$1,435,188	$1,254,067	$1,046,996	$915,550
$ per mile	$1.15	$0.96	$0.84	$0.70	$0.61
$ per mile (ex-payload)	$1.15	$0.96	$0.66	$0.56	$0.61

Source: Company data, Goldman Sachs Global Investment Research.

Charging infrastructure: An US$ >1 tn investment opportunity

Achieving close to 100% NEVs penetration on the road fleet requires massive infrastructure investments, both for power networks and for charging stations. For the first time, the "Report of the Work of the Government" delivered by Premier Li during the 2020 Two Sessions meeting emphasized the government's focus on accelerating New Infrastructure construction and development. "New Infrastructure" has been frequently mentioned by government authorities since the beginning of 2020. On March 4, 2020, the Politburo Standing Committee held a meeting to emphasize the investment focus in seven key areas of infrastructure: (1) 5G base stations and networks, (2) data centers, (3) Ultra High Voltage (UHV), (4) electric vehicle charging piles, (5) artificial intelligence, (6) Industrial IoT, and (7) intercity rail/urban transit network, where the charging piles for electric vehicles are classified as "New infrastructure".

Consequently, local governments have made corresponding action plans to support the "New Infrastructure":

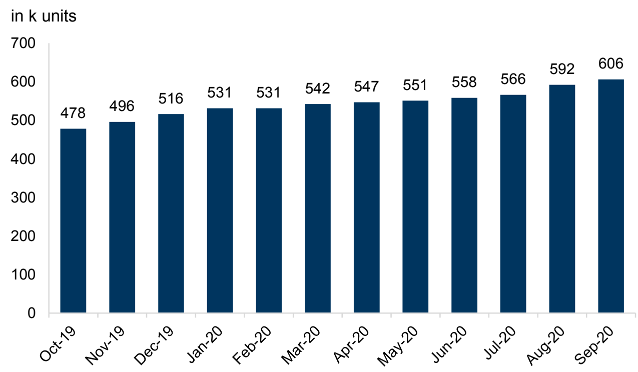
Guangzhou: On May 8, 2020, Guangzhou approved 73 key projects in New Infrastructure involving Huawei, Baidu, JD, etc. (total investments at Rmb180bn across 2020-22E). This move is the first step in their three-year plan for accelerating the development of 5G, IIoT, EV charging piles, and artificial intelligence infrastructure. Specifically, it plans to build more than 70k EV charging facilities, 4k charging stations and 3GWh charging capacity by 2022E.

Beijing: On June 10, 2020, Beijing Municipal Commission of Development and Reform published "Beijing Action Plan to Accelerate New Infrastructure Construction (2020-2022)" which set goals for 5G base station, IDC, EV charging piles, IIoT, AI development as well as the digital infrastructure's applications in various industries. Specifically, it targets to build 50k EV charging piles and c.100 battery swap stations in three years.

Shanghai: On June 19, 2020, Shanghai Municipal Government released the "Three-year Action Plan (2020-2022E)" to promote industrial internet innovation and upgrade and achieve the "Shanghai Industrial Capability Upgrade goal", which outlined concrete action items for IoT construction and end-applications. Specifically, it targets building 100k EV charging stations, 45 taxi EV charging stations and 20 hydrogen refueling stations by 2022.

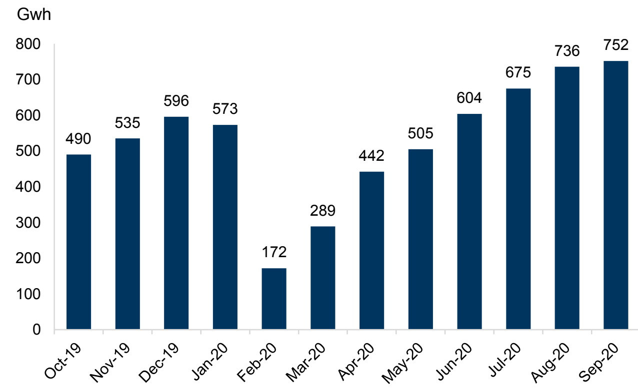
According to China Electric Vehicle Charging Infrastructure Promotion Alliance (EVCIPA), by September 2020, there were 1.4 mn charging facility units in China (including 606k public charging stall/station units and 812k private charging stall units). In terms of breakdown by provinces, Guangdong, Shanghai, Jiangsu, Beijing and Zhejiang are the top-5 provinces with the highest public charging piles/station fleets as at September 2020.

Exhibit 92: By September 2020, there were cumulatively 606k public charging facilities in China...



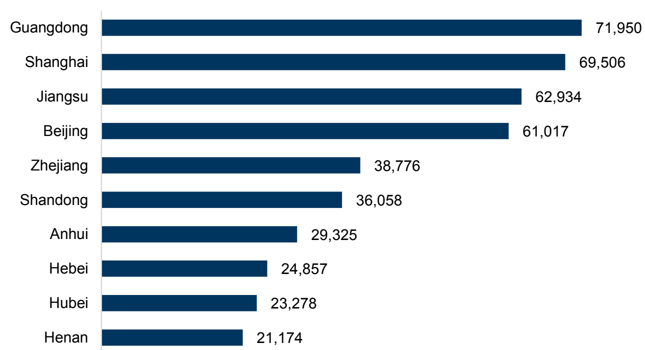
Source: China Electric Vehicle Charging Infrastructure Promotion Alliance.

Exhibit 93: ...consuming c.750GWh of electricity in China



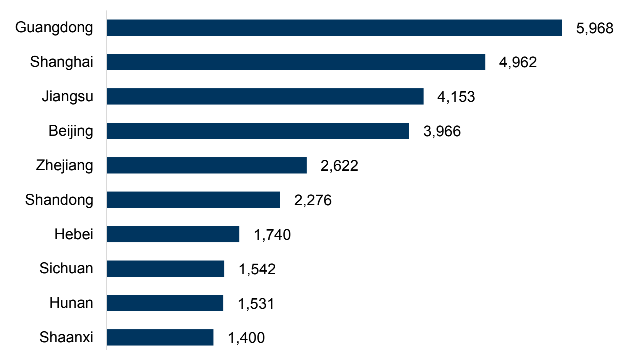
Source: China Electric Vehicle Charging Infrastructure Promotion Alliance.

Exhibit 94: Top-10 provinces in terms of public charging piles fleet (in units)



Source: China Electric Vehicle Charging Infrastructure Promotion Alliance.

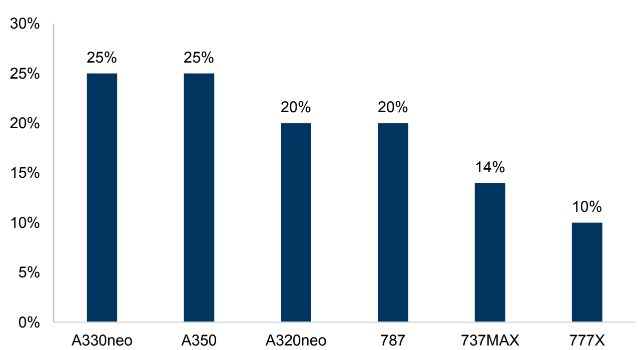
Exhibit 95: Top-10 provinces in terms of public charging station fleet (in units)



Source: China Electric Vehicle Charging Infrastructure Promotion Alliance.

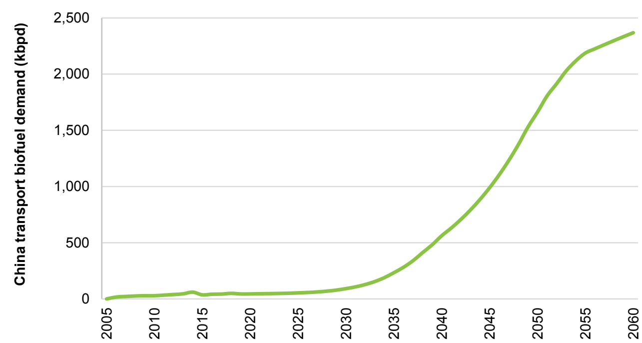
Aviation: Aviation is one of the toughest sectors to de-carbonize, and we believe that biofuels (sustainable aviation fuels – SAFs), synthetic fuels and improved aircraft efficiency are currently key parts of the solution. Fleet renewal is likely to be a near-term solution, with new gen aircrafts burning c.15% less fuel than their predecessors. Longer term, we see **bioenergy, and in particular SAFs**, as the key solution for aviation emissions abatement. SAFs can be used interchangeably with jet fuel in current aircraft, and have the potential to cut emissions by up to 80% vs. kerosene. That said, SAF requires significant investment before it can be considered an economically viable alternative, with the current production cost typically c.4x that of jet fuel. On our path to a net zero China, we estimate demand close to 2,500 kblpd of biofuels will be required in transport in 2060.

Exhibit 96: The switch to a more efficient aircraft could be a near-term complement to aviation de-carbonization...
Fuel burn improvement vs. previous generation as per company data



Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 97: ...with bioenergy ultimately the key currently available clean alternative, resulting in c.2,500 kbpd of biofuel (SAF) demand in our China net zero path by 2060
China transport biofuels demand (kbpd)



Source: BP Statistical Review, Goldman Sachs Global Investment Research.

Rail: We view electrification and clean hydrogen as the two key technologies for the path of locomotives to net zero emissions, and we address both of these technologies in our path to net zero emissions. Hydrogen trains in particular could revolutionise current long-haul locomotive routes, leveraging the key advantages outlined above: high energy content per unit mass, short refueling time and zero emissions when produced via clean routes ('blue' and 'green' hydrogen). At the end of 2018, two fuel cell trains produced by Alstom became operational in Germany, and it has been announced that another 14 will be put into service in 2021. A fuel cell tram began operating in Foshan (China) in 2019, with China exploring further possibilities for H_2-fuelled rail.

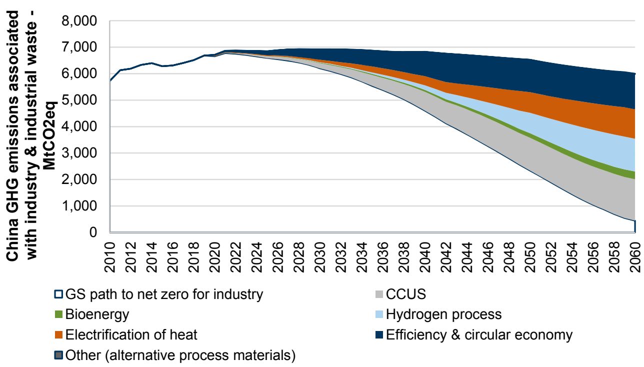
Domestic shipping: Domestic shipping accounts for only a small amount of emissions, and we consider LNG bunkers (for the near term) and clean ammonia (longer term) as the two key de-carbonization solutions.

3) Industry: Clean hydrogen, CCUS, efficiency, circular economy and electrification setting the scene for a new industrial technology revolution

Industry (including industrial combustion, industrial process and waste emissions) is currently the sector responsible for the largest share of GHG emissions produced in China (c.48%). Industrial emissions are typically split into three distinct categories; energy emissions associated with industrial combustion, industrial process emissions associated with the relevant process routes and feedstocks, and industrial waste emissions (including fugitive). While the exact split of industrial emissions is subject to uncertainty, with differences between sources, we estimate that >50% of China's emissions from industry come from its heavy industries as shown in Exhibit 99 (ferrous and non-ferrous metals manufacturing, non-metallic minerals such as cement, petrochemicals). We believe four key technologies will form the primary pillars that will enable the emissions abatement of China's industry: **clean hydrogen, carbon capture (CCUS), electrification, efficiency improvements and circular economy.**

Exhibit 98: We see clean hydrogen, carbon capture (CCUS), electrification, efficiency and circular economy as the key pillars for the abatement of China's industrial emissions...

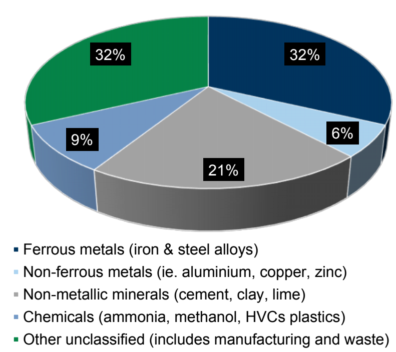
China GHG emissions associated with industry, industrial processes and waste (MtCO2eq)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research.

Exhibit 99: ...with >50% of the country's industrial emissions stemming from its heavy industries (ferrous and non-ferrous metals, non-metallic minerals such as cement)

China industry & waste GHG emissions split (2019)



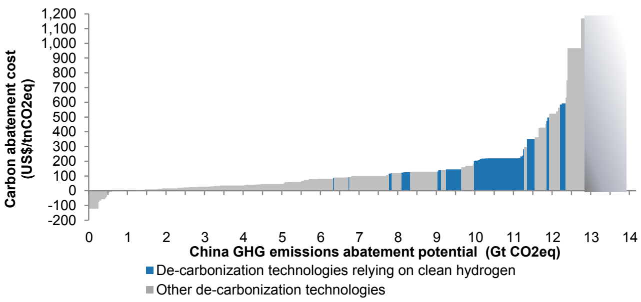
Source: Energy Transitions Commission, FAO, IEA, Goldman Sachs Global Investment Research.

The rise of clean hydrogen: The missing piece of the puzzle, connecting two critical components of the de-carbonization technological ecosystem, carbon sequestration and clean power generation

Hydrogen offers an opportunity to indirectly extend electricity's reach beyond power generation, and it can be produced by increasingly abundant renewables, including in Western China. Hydrogen has a critical role to play in a number of industrial processes in our view, **including replacing coal in steel mills, serving as a building block for some primary chemicals and providing an additional clean fuel option for high temperature heat**. While the basic scientific principles behind clean hydrogen are well understood, most of these technologies applied in their respective industrial sectors are still at the demonstration or pilot stage. We estimate that clean hydrogen can contribute to c.20% de-carbonization in China with its addressable market growing 7x from c.25 Mt in 2019 to c.170 Mtpa on the path to net zero.

Exhibit 100: Clean hydrogen has the potential to contribute to c.20% of China's de-carbonization cost curve we believe...

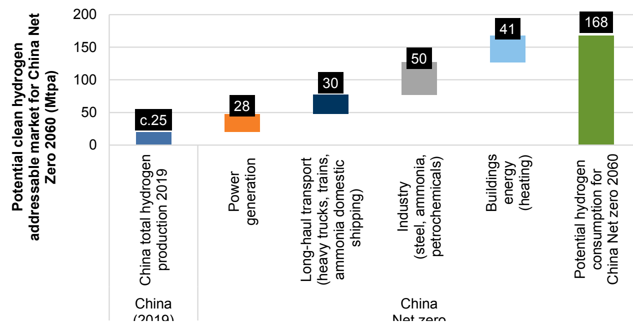
China anthropogenic GHG emissions de-carbonization cost curve with blue indicating technologies reliant on access to renewable power



Source: Goldman Sachs Global Investment Research.

Exhibit 101: ...and we estimate a hydrogen addressable market of c.170 Mtpa by 2060 (a seven-fold increase) on a path consistent with China net zero emissions

Potential clean hydrogen addressable market for China net zero (Mtpa)

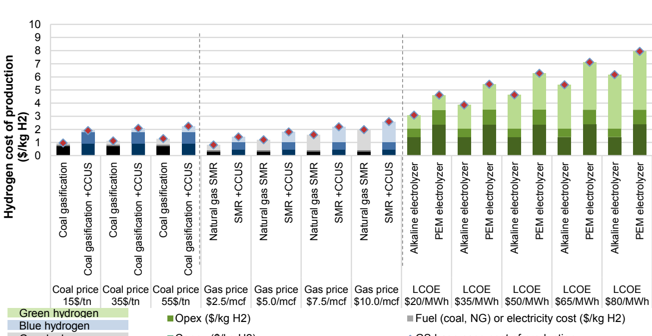


Source: Goldman Sachs Global Investment Research.

While hydrogen has gone through several waves of interest in the past 50 years, none has translated into sustainably rising investment and broader adoption in energy systems. Nonetheless, over the past few years, the intensified focus on de-carbonization and climate change solutions has led to renewed policy action aimed at the wider adoption of clean hydrogen. Policy support, and the acceleration of low-cost renewables and electrification infrastructure, seem to be converging to **create unprecedented momentum in the use of hydrogen, paving the way for potentially more rapid deployment and investment**. We believe there is a need for China to **develop a national hydrogen strategy** that would guide the sustainable development of the burgeoning hydrogen industry. The low-carbon intensity pathways for hydrogen production and the facets that make the fuel **uniquely positioned to benefit from two key technologies in the clean tech ecosystem – carbon capture and renewable power generation –** are '**blue**' and '**green**' hydrogen. 'Blue' hydrogen refers to the conventional natural gas-based hydrogen production process (SMR or ATR) coupled with carbon capture, while 'green' hydrogen refers to the production of hydrogen from water electrolysis whereby electricity is sourced from zero carbon (renewable) energies.

Exhibit 102: Blue and green hydrogen the two clean hydrogen production routes...

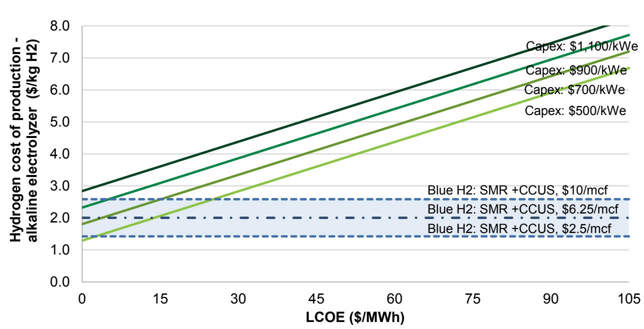
LCOH for hydrogen by method of production (US$/kgH2)



Source: Company data, Goldman Sachs Global Investment Research.

Exhibit 103: ...benefiting from cost deflation in carbon capture, renewable electricity and electrolyzer costs

Hydrogen LCOH for different electricity and electrolyzer costs

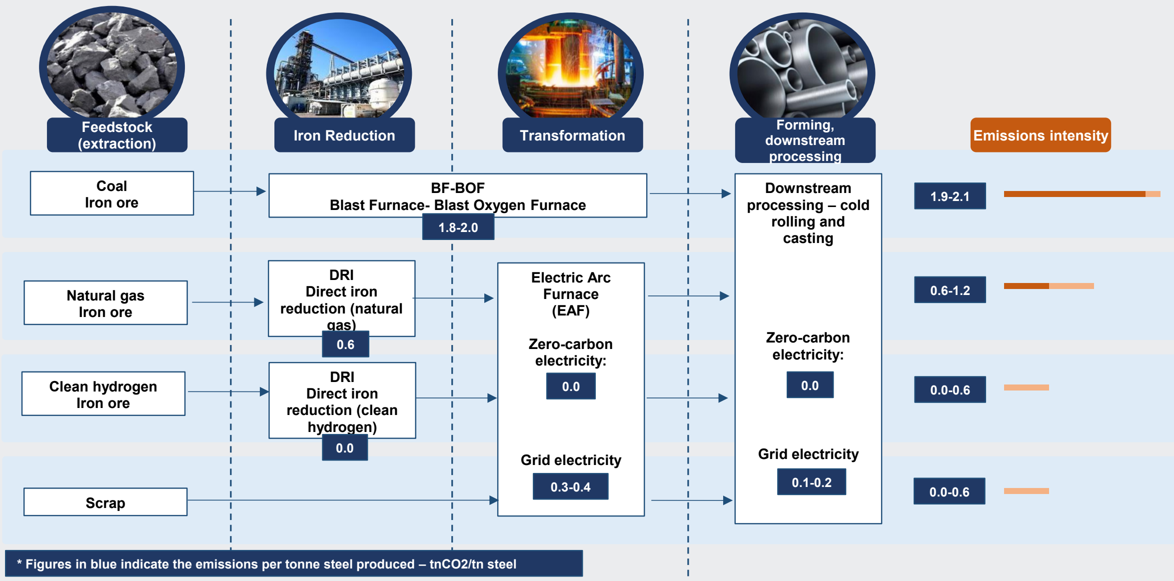


Source: Goldman Sachs Global Investment Research.

Clean hydrogen and its role in the de-carbonization of steel

As we highlight in the section above, one of the key industrial applications of clean hydrogen that has recently attracted industry interest is the production of net-zero carbon steel, to help meet the growing global steel demand with lower emissions. This is particularly important for China, with ferrous metals (iron & steel alloys) manufacturing contributing c.2GtCO2eq of GHG emissions (c.32% of China's total industrial emissions).

Exhibit 104: Schematic summary of possible steel manufacturing routes and associated emissions intensity (tnCO2eq/tn steel)



Source: Energy Transitions Commission, Company data, Goldman Sachs Global Investment Research.

A number of projects are currently underway to develop these processes and move towards commercialization, as outlined below.

- **HYBRIT:** In 2016, SSAB, LKAB and Vattenfall formed a partnership for the de-carbonization of steel through a modified DRI-EAF process, aiming at producing the first fossil-free steel making technology with a net zero carbon footprint. During 2018, a pilot plant for fossil-free steel production in Luleå, Sweden, started construction. The total cost for the pilot phase is estimated at Skr1.4 bn. The Swedish Energy Agency will contribute more than Skr500 mn towards the pilot phase and the three owners, SSAB, LKAB and Vattenfall, will each contribute one third of the remaining costs. The Swedish Energy Agency earlier contributed Skr60 mn to the pre-feasibility study and a four-year research project.
- **SALCOS:** An initiative undertaken by Salzgitter AG and the Fraunhofer Institute to develop a process for hydrogen-based reduction of iron ore using the DRI-EAF route. The process initially involves the reduction of iron ore to iron with the aid of natural gas and a higher volume of hydrogen in a direct reduction reactor. Based on this method, a reduction of iron of up to 85% can be achieved according to the operators, with CO_2 savings of initially up to 50% theoretically possible.
- **ΣIDERWIN:** A research project by ArcelorMittal which is in the pilot phase. It utilizes an electrochemical process supplied by renewable sources to transform iron oxides into steel plate with a significant reduction of energy use.

- **COURSE 50:** An initiative from the Japanese Iron and Steel Federation which aims to reduce the carbon footprint of steel production through the use of a higher proportion of hydrogen for iron ore reduction, as well as capture the CO_2 content of the process streams.
- **HIsarna:** In 2004, a group of European steel companies (including Tata Steel) and research institutes formed ULCOS, which stands for Ultra-Low Carbon Dioxide Steel making. Its mission is to identify technologies that might help reduce carbon emissions of steel making by 50% per tonne by 2050. HIsarna is one of these technologies and is a process involving an upgraded smelt reduction that processes iron in a single step. The process does not require the manufacturing of iron ore agglomerates such as pellets and sinter, nor the production of coke, which are necessary for the blast furnace process.

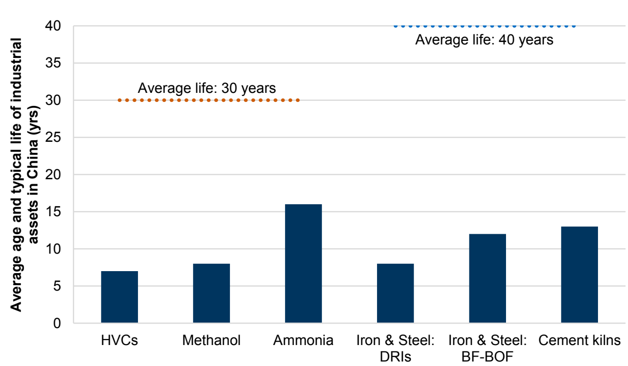
Carbon Capture: Vital technology for some of the harder-to-abate industrial processes that remains nonetheless largely under-deployed

In addition to its contribution to the electricity sector (which we anticipate to be relatively small in the face of the powerful renewables acceleration), carbon capture (CCUS) plays a much more critical role for Chinese industry. Industrial CCUS applications in China are often cost-efficient and have the potential to unlock deep emission reductions in China's modern industrial facilities and across some of the most difficult-to-abate emissions, such as those produced in the manufacturing and processing of cement. As shown in Exhibit 58, **we estimate that c.15% of China's anthropogenic GHG emissions could be abated through carbon capture**. A key advantage of carbon capture is that it avoids the rise of stranded industrial assets, with many of the industrial plants in China still relatively young (as shown in Exhibit 105), and requiring only modest retrofits to existing plants and processes. China more broadly sits at the lower end of the cost ranges across most carbon capture technological applications, given the lower raw material, labor costs and the higher carbon intensity of its industrial streams.

While China has by far the largest potential role for CCUS, given its large industrial sector and relatively young facilities, the **current deployment policies require a material step-up to align with the country's net zero ambition**. On July 8, 2020, its central bank, along with the National Development and Reform Commission and the China Securities Regulatory Commission, published The Green Bond Endorsed Projects Catalogue: 2020 Edition 35, which for the first time included CCS, expanding project financing channels. Of the c.26 large-scale CCUS projects currently operating globally, only three are located in China, and of more than 40 CCUS projects in development around the world, only four are located in China. CCUS development is strongly policy dependent, and we believe China will need to put in place an appropriate investment framework, providing incentives that match those in other regions (such as the Q45 tax in the US).

Exhibit 105: Carbon capture can be a key de-carbonization solution for many hard-to-abate industrial emissions, particularly given China's relatively young industrial plant base...

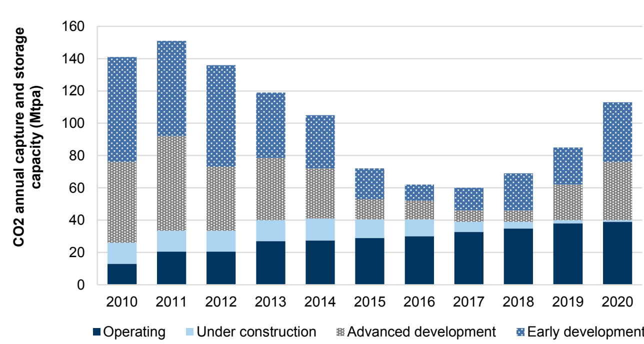
Average age and typical life of industrial assets in China (years)



Source: IEA.

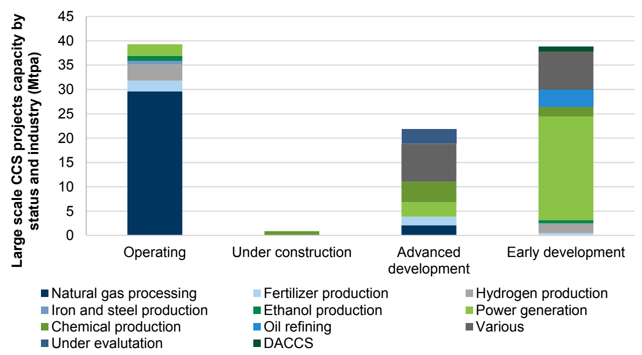
Exhibit 106: ...and the global pipeline of large-scale CCS facilities is regaining momentum after a 'lost decade'...

Annual CO2 capture & storage capacity from large-scale CCS facilities



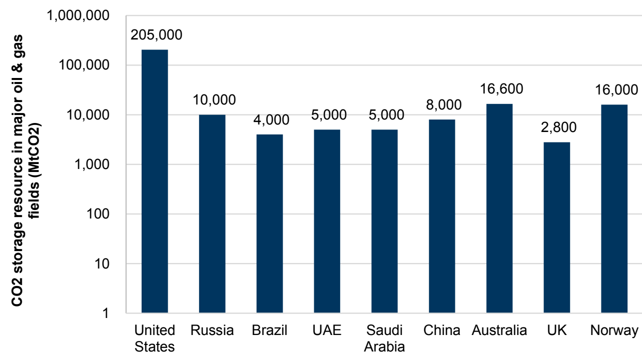
Source: Global CCS Institute Status report 2020.

Exhibit 107: ...as more projects in the development stage start to focus on industries with lower CO2 stream concentrations (industrial & power generation as opposed to natural gas processing)
Large-scale CCS projects by status and industry of capture (Mtpa, 2019)



Source: Global CCS Institute, Goldman Sachs Global Investment Research.

Exhibit 108: According to the latest status report by the Global CCS Institute, China's current CO2 storage potential in oil & gas fields alone (not including the large saline formations storage potential) is sufficient to meets its de-carbonization needs
CO2 storage resource in majors oil & gas fields (MtCO2)

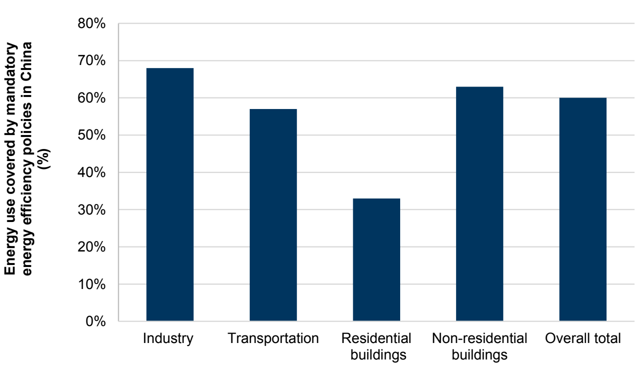


Source: Global CCS Institute status report 2020.

Energy efficiency & circular economy

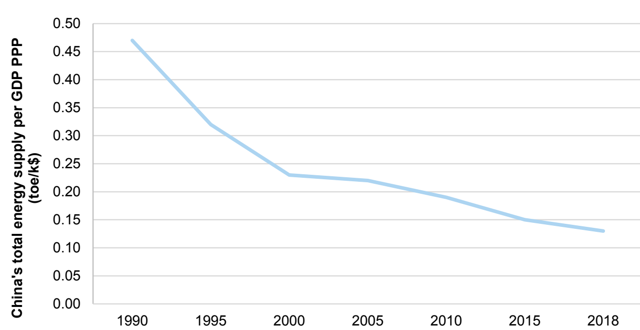
We view energy efficiency as a critical component of China's de-carbonization strategy. China has been one of the global leaders in energy efficiency improvements over the past decade, with most of its efficiency gains stemming from the industry sector. China's policy has proven to be successful over the past decade and at present 60% of final energy use is covered by mandatory energy efficiency policies according to the IEA. The industry sector has higher policy coverage, at nearly 70%, because of the mandatory energy efficiency improvement targets introduced through the Top 1,000 and Top 10,000 Programmes. Energy intensity per unit of GDP reduction has been a policy focus for the country, with quantitative targets set during the previous 5-year plans (FYP) as shown in Exhibit 38. In addition to efficiency improvements, in our industrial emissions path to net zero we also incorporate technologies that encourage circularity within the industrial ecosystem. Examples of these include the use of scrap steel, aluminum and other metals, as well as plastics recycling.

Exhibit 109: Industry is one of the sectors with the highest policy coverage with respect to energy use and efficiency...
Energy use covered by mandatory energy efficiency policies in China (%)



Source: IEA.

Exhibit 110: ...and the country's overall energy intensity of GDP has been trending downwards over the past three decades
China total energy supply per GDP PPP (toe/k$)

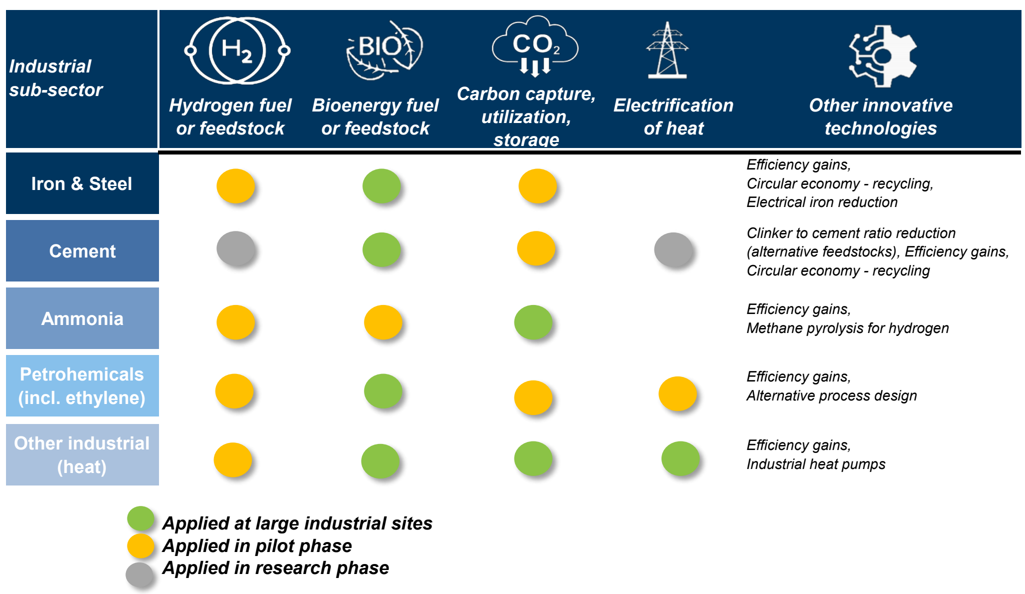


Source: IEA, World Bank Group.

Electrification of heat and other clean alternative fuels

Industrial combustion for the production of heat contributes a significant portion (>60%) of emissions stemming from industry. These emissions can be abated through a fuel switch such as switching to furnaces, boilers, and heat pumps that run on bioenergy, clean hydrogen or zero-carbon electricity. In several cases, electrifying heat can involve a change in the production processes, such as in ethylene production, where the installation of both electric furnaces and electrically driven compressors is required. The biggest challenge associated with heat electrification stems from the incredibly high energy requirements of these processes (processes such as cement require temperatures exceeding 1,000 degrees Celsius). This highlights the critical importance of 100% carbon-free electricity availability to ensure emissions abatement is achieved. While heat electrification has been successfully achieved in low- and medium-heat manufacturing processes, it remains in research and at the pilot/demonstration stage for several high-temperature processes. In such high temperature processes, alternative fuels such as clean hydrogen could be more economic and technologically feasible sources of energy.

Exhibit 111: Summary of key de-carbonization technologies for the major industrial emitting sub-sectors

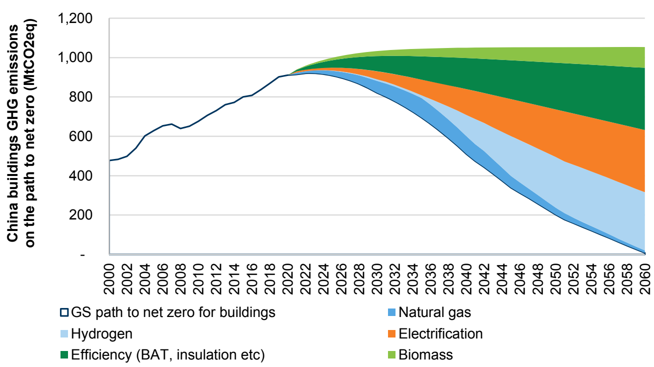


Source: Company data, Goldman Sachs Global Investment Research.

4) Buildings and Agriculture: Fuel switch and efficiency to govern emissions reduction path

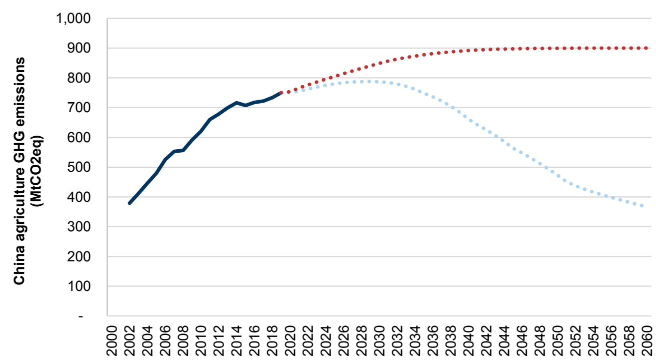
Finally, we have constructed a potential path to net zero GHG emissions for China's buildings and agriculture, the two sectors with the smallest relative contribution to the country's total annual emissions (c.6% and 5% for buildings and agriculture respectively). We note that these paths are not the only potential de-carbonization routes available for China to achieve net zero emissions, yet reflect our views of the potentially winning technologies in the space.

Exhibit 112: We lay out a suggested path to net zero emissions in the buildings sector in China to 2060E, relying primarily on electrification, efficiency improvements and fuel switch (clean hydrogen & bioenergy)...
China buildings GHG emissions and path to net zero (MtCO2eq)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research.

Exhibit 113: ...and an emissions reduction path for agriculture, the emissions of which are primarily non-CO2 and harder to abate in the absence of natural sinks sequestration
China agricultural emissions (MtCO2eq)



Source: European Commission Joint Research Centre (JRC). Emission Database for Global Atmospheric Research (EDGAR) release version 5.0, FAO, Goldman Sachs Global Investment Research.

Regarding buildings, we expect a combination of **efficiency** measures (already implemented in the sector as shown in Exhibit 109 and with the country aiming for 70% of its new buildings to be green by 2022 as shown in Exhibit 116), increasing **electrification** (heat pumps) and other **alternative clean fuels switch** (such as clean hydrogen, biomass, solar thermal, waste heat) to facilitate the transition to a net zero emissions building ecosystem. We believe that while natural gas can form a key transition fuel in the near term, ultimately clean hydrogen is likely to be the preferred net zero fuel choice, and therefore argue for natural gas pipeline infrastructure to be designed and be built to be compatible with hydrogen from the onset of the transition and the infrastructure build.

With heating and cooling the major energy consumers in the building sector, China is typically divided into five major climate zones[1] according to different thermal design requirements with different design codes applying to specific climate zones and rural and urban areas. North China requires space heating and this is met differently in rural and urban areas. The high density of urban areas (as we show earlier in the report in Exhibit 52) makes it suitable for district heating systems, while rural areas typically rely

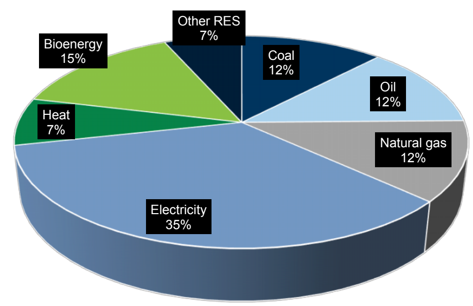
[1] Assessment of Energy Saving Potential by Replacing Conventional Materials by Cross Laminated Timber (CLT)—A Case Study of Office Buildings in China, by Yu Dong ,Xue Cui, Xunzhi Yin, Yang Chen, Haibo Guo. Appl. Sci. 2019, 9(5), 858; https://doi.org/10.3390/app9050858

on individual household heating systems. Cooling requirements on the other hand are applicable to the whole country, with individual air conditioning units common in residential buildings and district cooling systems often used in commercial buildings.

Exhibit 114: China is typically divided into five major climate zones when it comes to heating and cooling requirements...
Map of China's five key climate zones

Source: MDPI.

Exhibit 115: ...and we expect a path consistent with net zero China by 2060 to require a radical change in households' current fuel energy mix, with a higher reliance on electricity and efficiency improvements and the replacement of coal, oil, natural gas with clean hydrogen longer term
China buildings' energy use split by fuel (%, 2019)



Source: IEA, Goldman Sachs Global Investment Research.

Exhibit 116: China aims for 70% of all new buildings to be 'green' by 2022

Target	In Jul 2020, China's central policymakers announced that green buildings shall account for 70% of all new buildings by 2022

Additional requirements of Star-rated green buildings evaluation			
	1-Star	**2-Star**	**3-Star**
(a) Decoration		**Basic decoration for all buildings**	
(b) % of improvement from basic national standards			
Building envelope thermal performance	5%	10%	20%
Air condition capacity	5%	10%	15%
Heat transfer coefficient of exterior windows in cold and severe cold regions	5%	10%	20%
Water efficiency of sanitary appliances	Grade 3	Grade 2	
Indoor air pollutant concentration	10%	20%	
Airtight performance of external windows		Sealed attachement of the glass panel and window frame	

Source: Goldman Sachs Global Investment Research.

Agriculture is, in our view, one of the toughest sectors to de-carbonize, with the vast majority of emissions being non-CO_2 and stemming from enteric fermentation by animals and cropland management. We believe that there is still scope, however, for improved efficiency and land management practices, which include among others, improvements in cropland, grazing land and livestock management, utilization of precision agriculture for optimization in crop yields and minimization of excess use of nutrients and pesticides, and reduced agricultural waste. Ultimately, for agriculture to reach net zero emissions, we believe forestry (reforestation, afforestation and agroforestry) needs to be addressed, collectively referred to as carbon sequestration through natural sinks, which we address in the following section of this report.

Natural gas: A transition fuel towards China net zero

As China moves towards the goal of electrifying and decarbonizing its economy, gas is among the preferred choices as a transition fuel. Compared with coal, gas emits 50%-60% less carbon when combusted for power generation, and can ramp up quickly when the intermittent renewable energy is unavailable. Further, the availability of gas infrastructure helps facilitate the potential switch from gas to green or blue hydrogen in the longer term. For example, low-pressure gas pipelines are typically made of PE and could transport hydrogen-natural gas mixtures without incurring additional investment.

Compared with 2017-19, when average gas demand growth was 14% yoy, we expect slower growth of China gas demand in 2022-24, a CAGR of 8%. Despite the market's attention on China's coal-to-gas substitution policies, we believe that economic growth has been a primary driver of China's gas demand, given that the industrial sector accounts for 40% of total gas demand and is highly cyclical in nature. As such, we expect robust growth in China gas demand in 2021, driven by the low base of 2020 and continued economic recovery. Through 2022-24, however, China's rebalancing towards the service sector, as expected by our economists, will likely lead to slower growth in the industrial sector, which in turn could drive slower gas demand growth for industrial use. Together with slower rural C2G substitution on the back of shrinking connectable households, we expect the growth of total gas demand to moderate over the next three years.

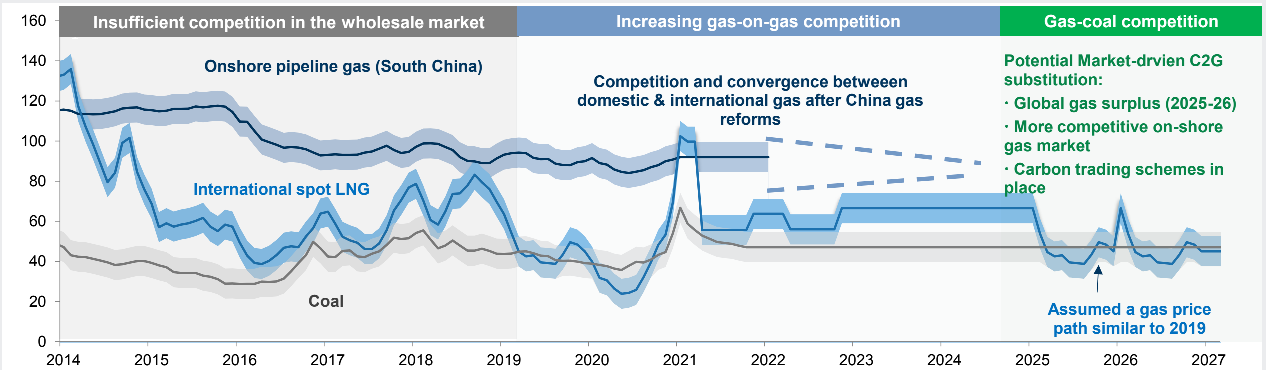
That said, China's gas industry landscape is set to be substantially reshaped by ongoing reforms, which may introduce market-driven coal-to-gas substitution towards mid-decade (2025-26). PipeChina, the newly formed national pipeline company, has started to offer public access to its LNG terminals this winter and is set to build more pipelines and terminals for public use. This should gradually reduce the SOEs' dominant market power in the domestic gas market, contributing to a gradual convergence of the onshore and offshore gas prices (Exhibit 117). By mid-decade, we expect the next global LNG oversupply to lead to low gas prices and market-driven coal-to-gas substitution in China, potentially driving meaningful gas demand acceleration (Exhibit 118).

Exhibit 117: The ongoing industry reforms are liberalizing China's wholesale gas markets...

Source: CEIC, Company data, Goldman Sachs Global Investment Research.

Exhibit 118: ...and as a result, we expect China's gas industry to go through two phases: from gas-on-gas competition to a potential gas-coal competition

South China power generation cost (pre-carbon cost)



Source: Wind, Refinitiv, Goldman Sachs Global Investment Research.

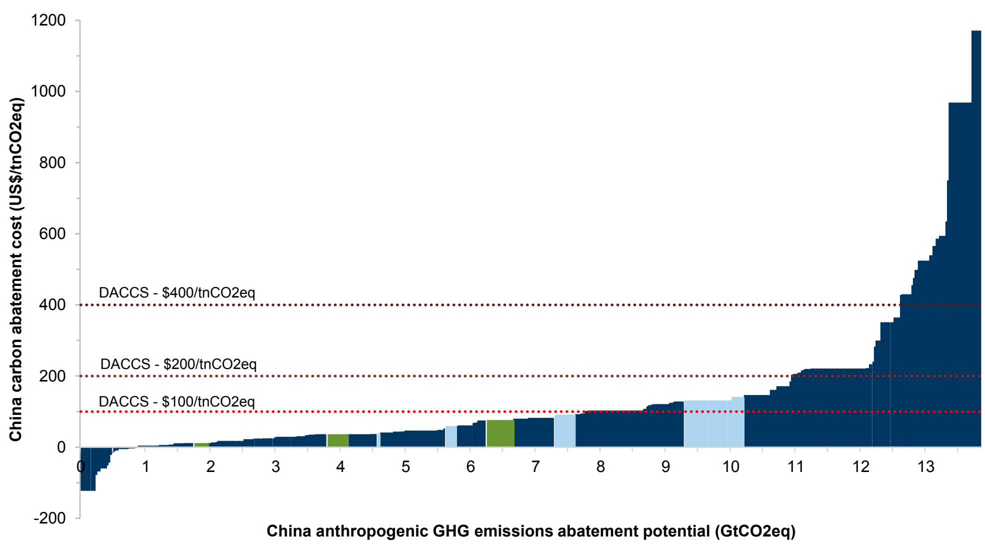
This section on natural gas was contributed by Amber Cai (China Oil & Gas analyst).

China net zero: The role of carbon sequestration

We envisage two complementary paths to enable China and the world to reach net zero emissions: **conservation and sequestration**. The former refers to all technologies enabling the reduction of gross greenhouse gases emitted and the latter refers to natural sinks and carbon capture, usage and storage technologies (CCUS) that reduce net emissions by subtracting carbon from the atmosphere. **We have already incorporated and addressed conservation technologies, as well as process-specific carbon capture technologies, in our China de-carbonization cost curve** in Exhibit 55. The need for technological breakthroughs to unlock the potential abatement of China's current anthropogenic GHG emissions that cannot at present be abated through the conservation technologies makes sequestration a critical component in solving the climate change challenge and leading China to net zero carbon emissions at the lowest possible cost. As part of our global de-carbonization analysis, we have **constructed a merged carbon abatement cost curve for sequestration and conservation that includes natural sinks**, shown in Exhibit 119. Overall, we estimate that c.15-20% of emissions can abated through sequestration (a combination of carbon capture and natural sinks, as shown below).

Exhibit 119: The merged cost curve of de-carbonization for China combines conservation and sequestration (carbon capture and natural sinks) technologies and indicates that c.55% of emissions can be abated at a price <US$100/tnCO2, comprising mostly clean alternatives in power generation and industry and natural sinks

China merged conservation and sequestration de-carbonization cost curve for anthropogenic GHG emissions, based on current technologies and associated costs



Source: Goldman Sachs Global Investment Research

Carbon sequestration efforts can be broadly classified into three main categories:

1) Natural sinks, encompassing natural carbon reservoirs that can remove carbon dioxide. Efforts include reforestation, afforestation and agro-forestry practices.

2) Carbon capture, utilization and storage technologies (CCUS) covering the whole spectrum of carbon capture technologies applicable to the concentrated CO_2 stream coming out of industrial plants, carbon utilization and storage. We have already addressed the carbon capture potential in China for industrial applications in the previous section of this report (*Laying out the path to a net zero China: A sectoral deep dive)*.

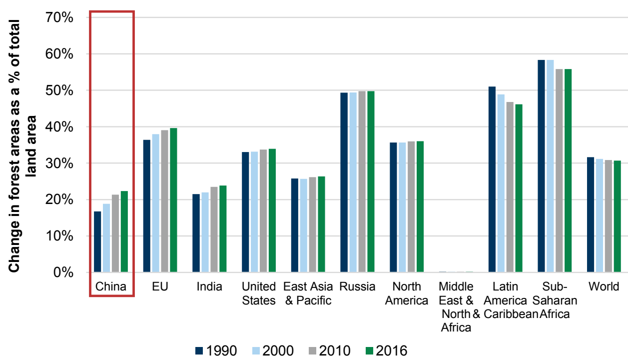
3) Direct air carbon capture (DACCS), the pilot carbon capture technology that could recoup CO_2 from the air, unlocking almost infinite de-carbonization potential, irrespective of the CO_2 source.

Natural sinks: China already making substantial progress, with more to come

While China has among the lowest forest area coverage as a percentage of total land area among key economic regions globally, it has achieved remarkable results over the past three decades in increasing its forest area. According to data from the World Bank Group, China has added >520,000 square km of forest land since 1990, a c.34% increase in its forest area; currently, c.23% of the country's land area is considered forest area, up from only 17% in 1990. This is in contrast to the global average, which has exhibited a downward trend on the back of notable forest area reductions in Latin America and Sub-Saharan Africa, as shown in Exhibit 120 and Exhibit 122. This comes on the back of ongoing policy support, with China incorporating quantitative targets for forest area coverage and forest stock volumes in the Copenhagen Accord, the Paris Agreement and its five-year plans (FYP), as summarized in Exhibit 38. Given the low cost of these natural solutions (we estimate it to lie mostly below US$50/tn$CO_2$), we believe that natural sinks can help bridge the gap between total emissions remaining under a net zero scenario due to lack of available clean alternatives and absolute zero emissions. We incorporate natural sinks into our path to net zero by 2060.

Exhibit 120: While China has among the lowest forest area coverage as a % of total land area among key economic regions globally…

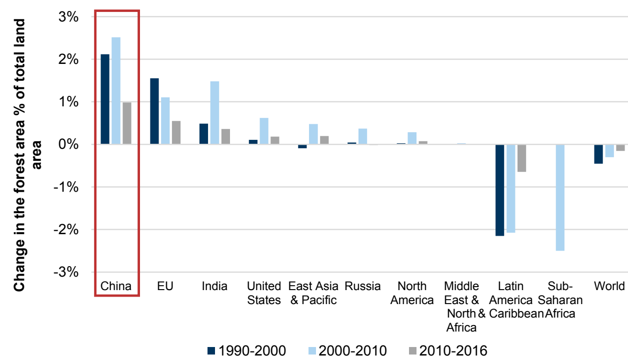
Forest area as a % of total land area



Source: World Bank Group, Goldman Sachs Global Investment Research

Exhibit 121: …over the past three decades, it has increased its forest coverage as a % of land area more than any other major economic region globally

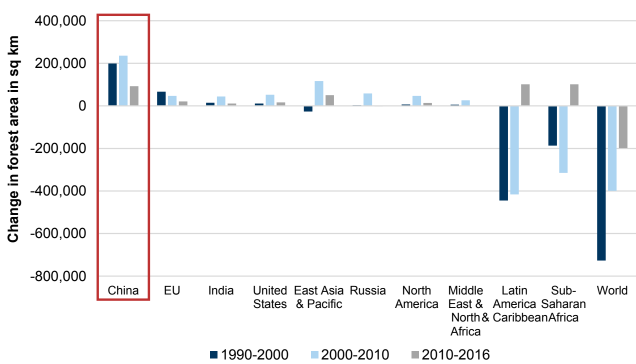
Change in forest area % of total land



Source: World Bank Group, Goldman Sachs Global Investment Research

Exhibit 122: China has added >520,000 sq km of forest area since 1990...

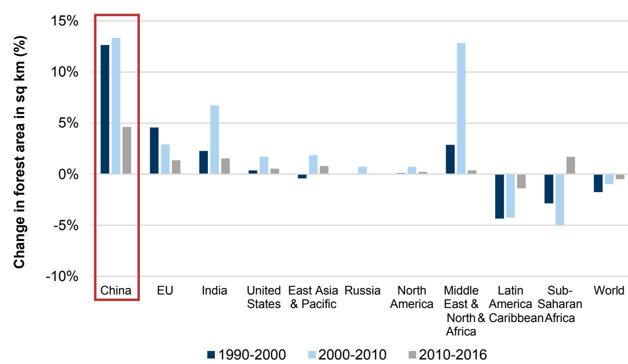
Change in forest area in square km



Source: World Bank Group, Goldman Sachs Global Investment Research

Exhibit 123: ...a c.34% increase in its forest area in sq km2 in total during the period

Change in forest area in square km (%)



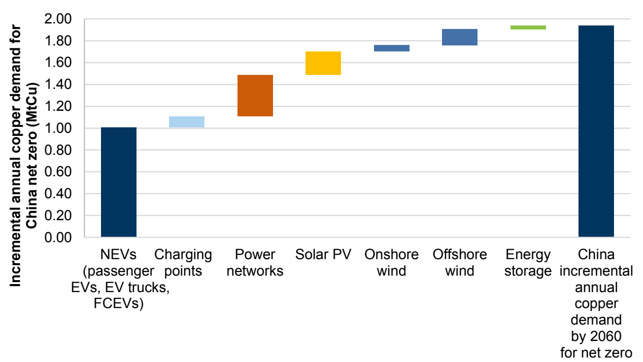
Source: World Bank Group, Goldman Sachs Global Investment Research

China net zero: The potential implications for natural resources demand

At the heart of the path to net zero China by 2060 lies the need for access to clean energy and an accelerated pace of electrification for transport and several segments of industry, as we outline in the previous section of this report. **Electrification and clean energy is likely to have an impact on total Chinese demand for natural resources, and in particular metals such as aluminium, copper, lithium and nickel,** demand for which relies heavily on an acceleration in technologies such as renewables (solar panel, wind turbines manufacturing), power network infrastructure, charging infrastructure, electric vehicles and battery manufacturing. We attempt to quantify the potential impact that the path to net zero China by 2060, as laid out in previous sections, will have on the demand for each of these metals, as shown in the exhibits that follow.

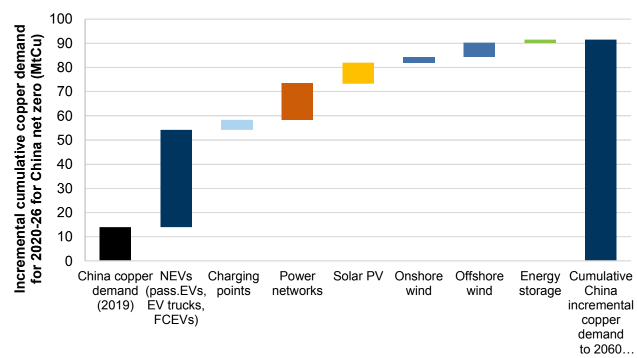
The results of this analysis are calculated on the basis of incremental demand for each clean technology relative to the conventional technology (such as incremental copper demand per electric vehicle compared with conventional gasoline vehicles). We find that annual copper demand in net zero China will rise by 2.0 Mtpa, a c.15% increase from China's copper demand in 2019, and require a cumulative c.77 Mt copper in 2020-60 on a path consistent with net zero.

Exhibit 124: We estimate c.2.0 Mt incremental average annual copper demand by 2060 for China net zero, representing a c.15% increase from China's annual copper consumption in 2019...
Incremental copper demand in 2060 for China net zero



Source: IRENA, International Copper Association, Goldman Sachs Global Investment Research

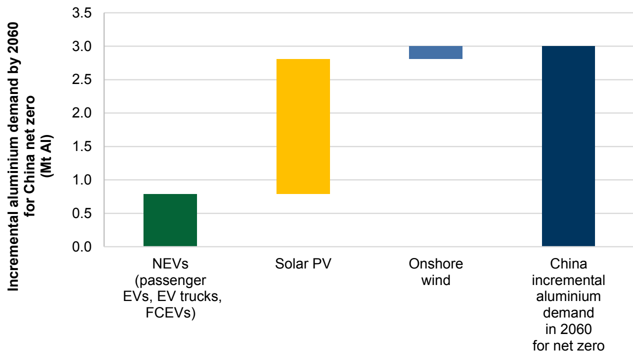
Exhibit 125: ...with c.77 Mt of cumulative incremental copper demand from China over 2020-60 for net zero
Cumulative incremental copper demand for China, 2020-60 (MtCu)



Source: IRENA, International Copper Association, Goldman Sachs Global Investment Research

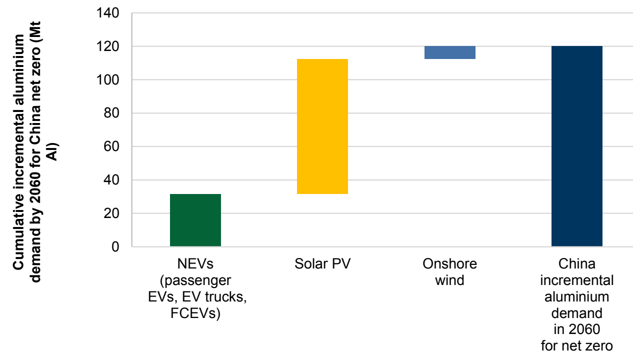
Similarly, as shown in the exhibits that follow, we expect the electrification trend to lead to a material increase in demand for metals such as aluminium, lithium, nickel and cobalt. Overall, we estimate c.3.0 Mt average incremental aluminium demand to 2060, representing a c.8% increase on China's annual aluminium consumption in 2019. We expect lithium demand from China to increase by c.0.76 Mt to 2060, ten times the global lithium production in 2019, and nickel demand to increase by 0.42 Mt, a c.32% increase from China's 2019 consumption.

Exhibit 126: We estimate c.3.0 Mt incremental aluminium demand by 2060 for China net zero, representing a c.8% increase from China's annual aluminium consumption in 2019...
Incremental aluminium demand by 2060 for China net zero (Mt Al)



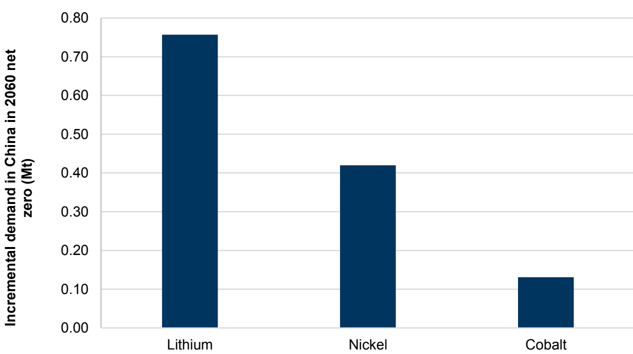
Source: IRENA, World Bank, Goldman Sachs Global Investment Research

Exhibit 127: ...and 120Mt of cumulative incremental aluminium demand to 2060 in a path consistent with net zero
Cumulative incremental aluminium demand 2020-60 for net zero China (Mt Al)



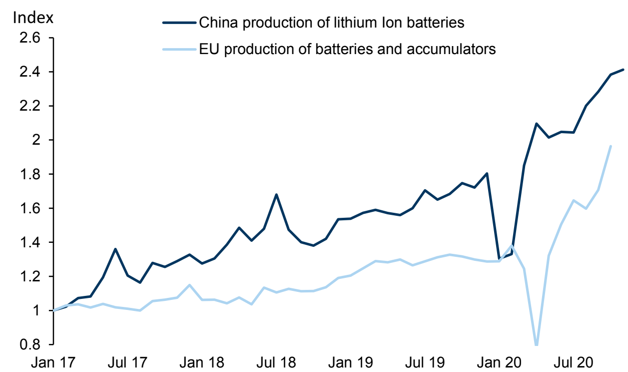
Source: IRENA, World Bank, Goldman Sachs Global Investment Research

Exhibit 128: We estimate c.0.76, 0.42 and 0.13 Mt of incremental lithium, nickel and cobalt demand in China in 2060, depending on the type of NCM battery used...
Incremental nickel, lithium, cobalt demand in 2060 for China net zero (Mt)



Source: Company data, Goldman Sachs Global Investment Research

Exhibit 129: ...as EV battery production continues to increase
Indexed China and EU production of lithium ion batteries

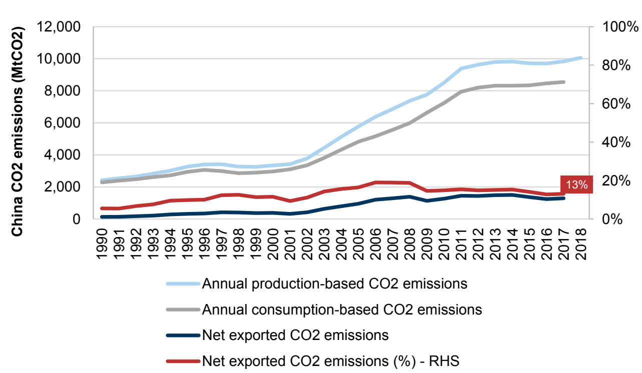


Source: Haver Analytics, Goldman Sachs Global Investment Research

China net zero: Addressing China's export competitiveness in the era of climate change

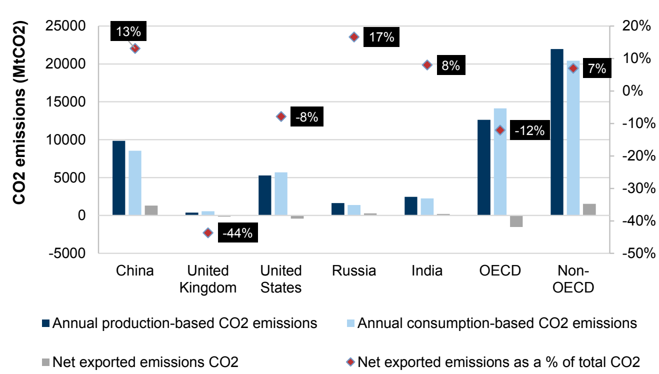
Adjusting for international trade, c.13% of China's emissions are exported to other countries globally on a net basis (c.20% when considering gross exports)...
Official emission accounting data (used throughout this report) typically associate emissions with the country in which these emissions were produced, typically referred to as 'territorial emissions'. However, this presents a key challenge, as countries contributing little to direct emissions may have net imported emissions associated with the products these regions consume. In contrast, countries such as China, which tend to be net emissions exporters (as highlighted by our Asia macro team), produce more emissions than they consume domestically. As a result, to be able to estimate the 'consumption'-related emissions associated with each country, adjustments that account for international trade (emissions embedded in goods that are being traded internationally) are required. We reference two studies in this report which both attempt to quantify the impact of international trade on emissions (using an inter-country input-output table methodology, which tracks the international trade of goods). Those include a working paper published by OECD[2] *and the 'Our World in Data' database[3]*. The results of both studies are broadly consistent, indicating that the **share of China's net exported emissions is c.13%** (2018), a proportion that has remained broadly constant over the past few years as shown in Exhibit 130. China has one of the highest proportions of net exported emissions, following the Russian Federation. When looking at China's emissions associated with **gross exports** (as opposed to net), this figure becomes **c.20% of China's CO_2 emissions.**

Exhibit 130: China's net exported emissions amount to c.13% of its total annual produced CO2 emissions...
China CO2 emissions produced, consumed and exported (MtCO2)



Source: Our World in Data

Exhibit 131: ...one of the highest % of net exported emissions following the Russian Federation
CO2 emissions and % of CO2 emissions that is net exported



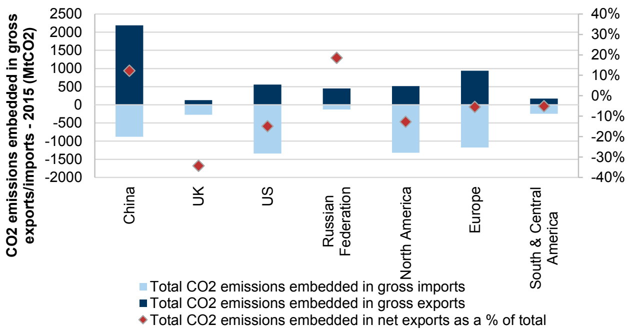
Source: Our World in Data, Goldman Sachs Global Investment Research

[2] Wiebe, K. S. and N. Yamano (2016), "Estimating CO2 Emissions Embodied in Final Demand and Trade Using the OECD ICIO 2015: Methodology and Results". OECD Science, Technology and Industry Working Papers, No. 2016/5, OECD Publishing, Paris.

[3] H. Ritchie (2019) – "How do CO2 emissions compare when we adjust for trade ". Published online at OurWorldInData.org. Retrieved from: 'https://ourworldindata.org/consumption-based-co2' [Online Resource] Based on Global Carbon Project; Carbon Dioxide Information Analysis Centre; BP; Maddison; UNWPP

Exhibit 132: The % of net exported emissions by China is broadly consistent across studies and has remained relatively constant over recent years at around c.13%...

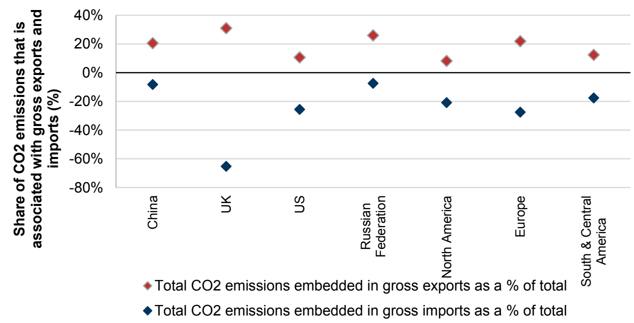
CO_2 emissions embedded in gross exports/imports by region (2015, $MtCO_2$) according to a working paper of the OECD



Source: OECD Stat, Goldman Sachs Global Investment Research

Exhibit 133: ...and when looking at gross exported emissions as opposed to net, the figure is close to 20% of its total emissions

Share of CO_2 emissions associated with gross exports and gross imports



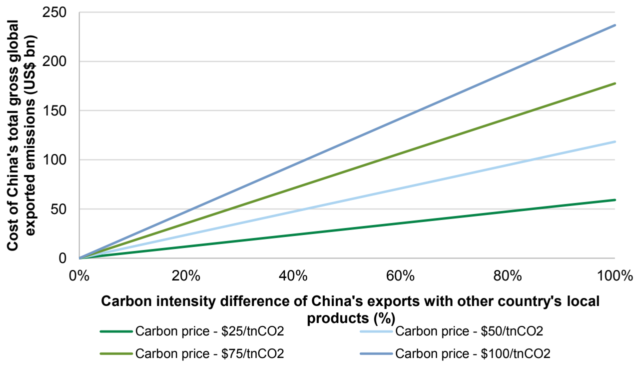
Source: OECD Stat, Goldman Sachs Global Investment Research

...and a global carbon tax border adjustment of US$100/tn$CO_2$ could cost the country as much as US$240 bn pa

In this section, we aim to **address the potential implication of a border carbon tax adjustment applied on China's exports and the resulting impact on their competitiveness**. For the purposes of this analysis, we consider gross exported emissions from China (as opposed to net) a more relevant metric, and we assume that in 2019 they remained at c.20% of the country's total CO_2 emissions (in line with the level concluded from the OECD working paper mentioned above). This implies that in 2019, c.2.4 GtCO2eq of emissions were associated with China's gross exports. Applying different carbon prices and assuming varying levels of carbon content difference with locally produced products, we can estimate the total cost associated with China's global gross exported emissions. This is presented in Exhibit 134 and could be as high as US$240 bn pa for a carbon tax of US$100/tn$CO_2$, depending on the carbon intensity difference between China's exports and the importing country's local product. This methodology and analysis is particularly applicable when we consider China's exports to the European Union, given the current proposal for a carbon border tax adjustment by the EU. We estimate that the annual cost of a carbon border tax adjustment in the EU for China's gross exports in the area could be as high as US$35 bn if a carbon tax of US$100/tn$CO_2$ were applied and assuming net zero products in EU. We estimate the difference in carbon intensity of products produced locally in the EU vs. Chinese exports to be close to c.40-50% (driven entirely by differences in the energy intensity of the industrial manufacturing processes of the two regions and broadly matching the difference in carbon intensity between coal and natural gas). This would result in a lower cost estimate of c.US$15 bn pa.

Exhibit 134: The annual cost of a globally applied carbon border adjustment tax on China's gross exported emissions could be as high as US$240 bn at US$100/tnCO2, depending on the difference in carbon intensity of China's exports and the importing country's local products...

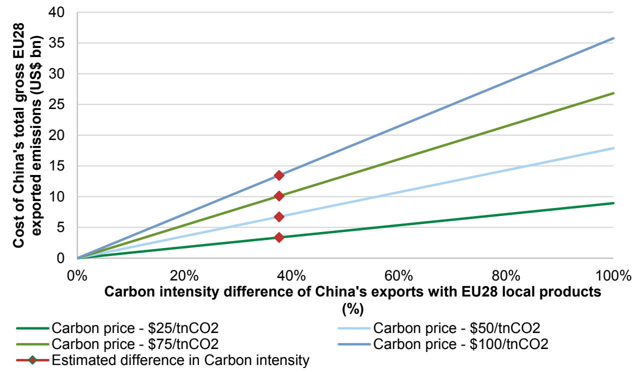
Cost of China's annual gross globally exported emissions (US$ bn)



Source: Goldman Sachs Global Investment Research

Exhibit 135: ...and when we look at the EU in particular, the cost could be as high as US$35 bn pa

Cost of China's annual gross exported emissions to the EU (US$ bn)



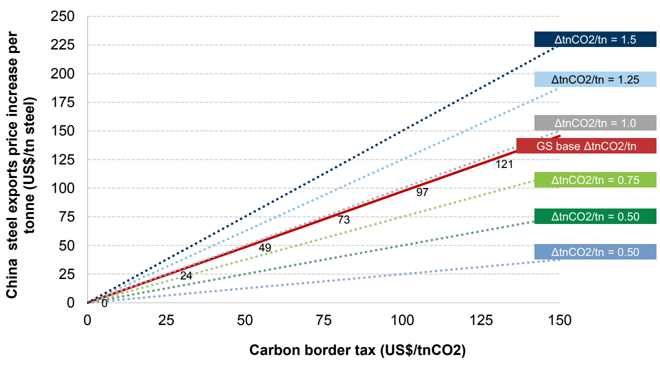
Source: Goldman Sachs Global Investment Research

Case study: Examining the impact of a carbon border adjustment tax on Chinese steel exports to the EU

To illustrate the potential impact of a carbon border tax adjustment implemented by the EU, we consider the example of China's steel exports into the region. Depending on the difference in the carbon intensity of producing steel in the EU compared with China, a carbon tax will have differing impacts on steel export prices. Using the current carbon intensity of producing steel in China under a coal blast furnace BF-BOF process (2.1 $tnCO_2eq$/tn steel) and comparing it to the average carbon intensity of steel produced in the EU using a natural gas-based DRI-EAF process (1.1 $tnCO_2eq$/tn steel with grid electricity), we can determine the incremental cost for steel exports on the basis of the difference in carbon intensity. As illustrated in Exhibit 136, the results indicate that a US\$100/$tnCO_2$ carbon price could result in an increase in China's steel export cost of c.US\$100/tn steel. Alternatively, if the average steel produced in the EU relies on net zero electricity, then a natural gas DRI-EAF process will have a carbon intensity of 0.6$tnCO_2$/tn steel, meaning the case illustrated in Exhibit 137 would result in an increase in the price of steel exported from China of US\$150/tn steel. Assuming a steel price of US\$500/tn, such a price increase would be equivalent to c.30% inflation in China steel export costs.

Exhibit 136: Comparing the standard coal blast furnace process used in China for steel production with an average natural gas DRI-EAF process used in the EU, a carbon border adjusted tax could lead to a price increase of US$100/tn steel for Chinese exports....

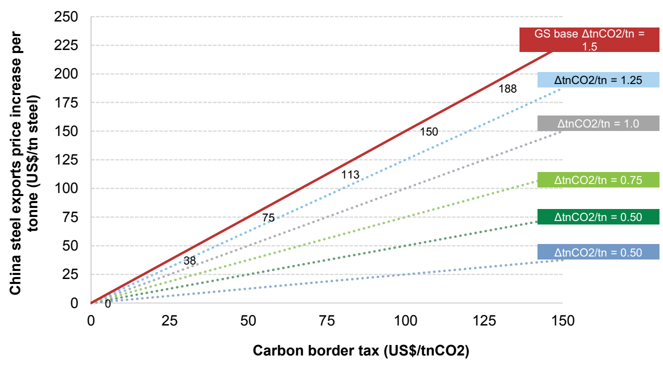
Increase in China's exported steel prices at different carbon border tax and carbon intensity levels



Source: Goldman Sachs Global Investment Research

Exhibit 137: ...which could be as high as US$150/tn steel if net zero electricity is used in the steel manufacturing process in the EU, at a carbon tax of US$100/tnCO2

Increase in China's exported steel prices at different carbon border tax and carbon intensity levels



Source: Goldman Sachs Global Investment Research

China net zero: What have banks done to address China's goal for carbon neutrality?

Achieving the government's long-term climate goals of a carbon peak by 2030 and carbon neutrality by 2060 will require a fundamental transformation of China's entire social and economic systems, with the financial system playing a crucial role. As the key financial intermediary, banks are the primary financial institutions for the development of green finance in China. While there are opportunities for banks to actively respond to China's national carbon neutral goal, there are challenges that will need to be taken into consideration.

On January 6, 2020, the PBOC proposed implementing major decisions it had taken about the carbon peak and carbon neutrality as a key mission in 2021, to improve China's green financial policy framework and to act as an incentive mechanism. As far as we are aware, this was the first time the central bank has included carbon issues in its working pipeline together with monetary policies and financial stability. The PBOC will guide financial resources with a tilt towards green development, enhancing the financial system's ability to manage climate change-related risks, and to promote the establishment of a carbon emissions trading market to set a reasonable price for carbon emissions. We believe that these policies could gradually improve the green finance standard system, clarify regulatory and information disclosure requirements, and improve green financial products and market systems.

Based on PBOC data, the balance of green loans was Rmb11.6 tn as of 3Q2020, an increase of 16% from the beginning of the year and up 17% yoy, four percentage points higher than the growth rate of total loans over the same period. The total balance of green bonds was Rmb1.1 tn as of end-2020, a 32% increase from a year ago, the growth rate of which slowed vs. 2019's 77%.

In the meantime, the structure of the green bond market has undergone significant changes: banks were previously the major issuers of green bonds for capital raising, but starting from 2019, banks have helped underwrite more green bonds issued by non-financial corporates than they have issued themselves.

A Carrot and Stick approach: Policy plays an important role in carbon neutrality

We believe that China moved much earlier than most market participants expected in adopting a market-driven carbon exchange market:

- **2011:** two local carbon exchanges were established to test the water. This was supported by the NDRC, a government agency in China for economic planning.
- **2017:** a national carbon exchange was announced as a further step to unify and integrate the nationwide carbon exchange market.
- Since then, the government has announced more policies and procedures regarding carbon trading, clearing and accounting, suggesting further progress towards a fully-fledged carbon exchange.

In terms of the financial sector, in 2018 the PBOC issued guidelines that established a framework to evaluate the performance of banks with respect to green finance, including:

- the growth of green finance
- non-performing loans (NPL)
- green finance evaluation to be part of banks' macro-prudential assessment (MPA)
- green finance bonds to be regarded as qualified collateral for a medium liquidity facility (MLF) from the PBOC.

To achieve the goal of a carbon peak by 2030 and carbon neutrality by 2060, we would expect more changes to the regulatory indicators of green finance, with the potential to further increase the assessment of green finance in banks' MPA in 2021.

What do banks say? NPLs matter most for healthy growth of green finance

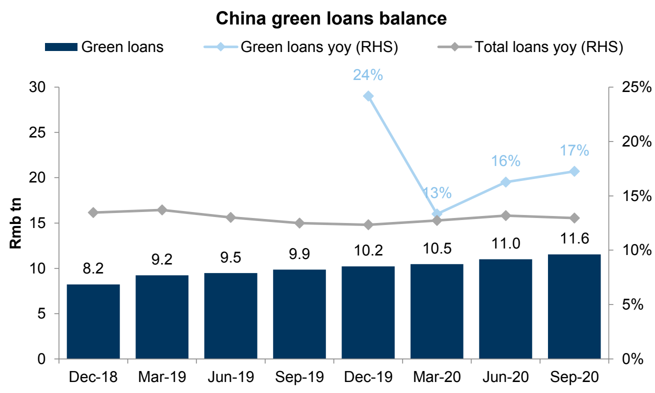
On the one hand, more green bonds issued by non-financial corporates than the banks themselves should drive new business growth. However, a number of factors need to be taken into consideration:

- the low margin of green bond underwriting, though this could be partially offset with the PBOC pledging green bonds to the central bank for cheaper liquidity
- the NPL cycle cannot be smoothed out in the green sector, given the fluctuating nature of business cycles
- more green finance potentially means less non-green finance. Old economy sectors such as materials and other traditional industries could face more challenges in terms of new financing and cash flows.

Carbon exchanges can function to discipline carbon emissions as a price is charged, with obtaining a quota for carbon emissions posing additional costs to corporates, particularly those in the old economy. From the point of view of banks, to achieve carbon neutrality, NPLs will matter most: they will not only determine the sustainability and healthy growth of green finance, but also the orderly exit of non-green finance.

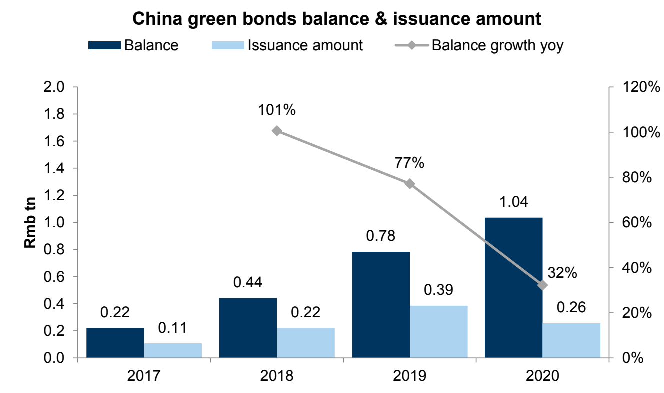
We believe this will pose challenges for China's banks, but not necessarily threats, as the government's "Carrot and Stick" policy stance, that aims to drive carbon neutrality, is consistent with the PBOC's financial deleverage campaign (started in 2017) to abate systemic risk and encourage an appropriate risk pricing mechanism.

Exhibit 138: China green loans balance was Rmb11.6 tn as of 3Q20, a 17% increase vs. a year ago
China green loans balance



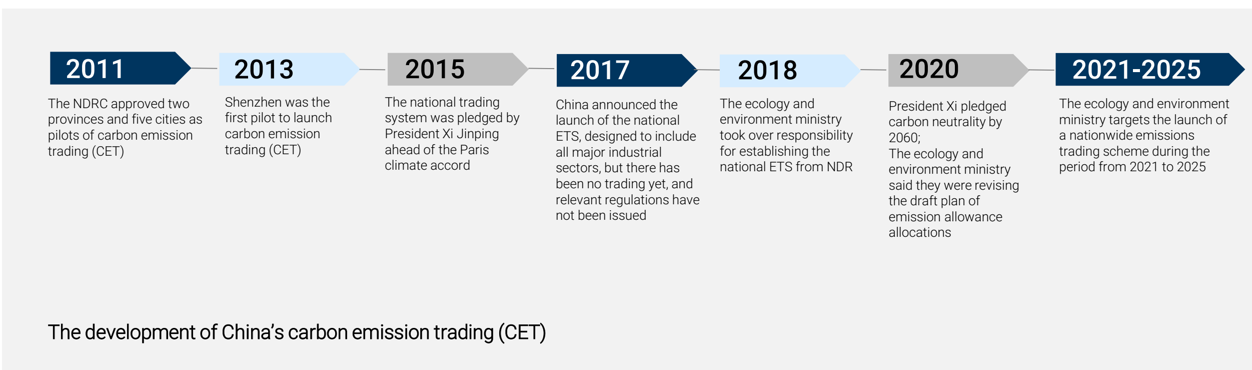
Source: PBOC.

Exhibit 139: China green bond balance growth slowed in 2020 but still at a 32% high growth rate
China green bonds balance and issuance



Source: Wind.

Exhibit 140: After nearly a decade of pilot testing and discussion, China may officially launch the nationwide emissions trading system in 2021-2025



Source: Xinhua, Reuters.

** This chapter was contributed by Shuo Yang, Ph.D. (China Financials analyst).*

China ETS: Getting closer to the implementation of the world's largest national emissions trading scheme

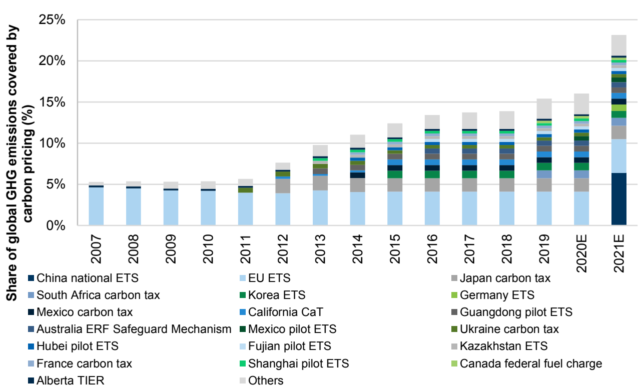
Carbon pricing a key ingredient for de-carbonization, with China's proposed national ETS the largest globally...

We believe that carbon pricing will be a critical part of any effort to move to net zero emissions, while incentivizing technological innovation and progress in de-carbonization technologies. The very steep carbon abatement cost curve for China calls for growing technological innovation, sequestration technologies deployment and effective carbon pricing. The two approaches to de-carbonization, conservation and sequestration, are both vital in achieving net zero carbon emissions, as emissions continue to overshoot the path associated with the more benign global warming paths. In the short term, we believe that carbon prices should be sufficiently high to incentivize innovation and healthy competition between conservation and sequestration technologies, while in the longer term, the equilibrium price of carbon is likely to decline on the back of technological innovation and economies of scale.

At present, 64 carbon pricing initiatives have been implemented (or are scheduled for implementation), covering 46 national jurisdictions worldwide, according to the World Bank Group, mostly through cap-and-trade systems. These initiatives are gaining momentum, with the **People's Republic of China in 2017 announcing the implementation of a national emissions trading scheme.** This would be the **world's largest national emissions trading scheme** and according to the World Bank Group, combining all of these initiatives (including China) will cover 12GtCO2eq, representing c.23% of the world's total GHG emissions.

Exhibit 141: With the addition of China's national ETS, the total global emissions covered by carbon pricing initiatives should reach c.23%...

Carbon pricing initiatives' share of global GHG emissions covered (%)

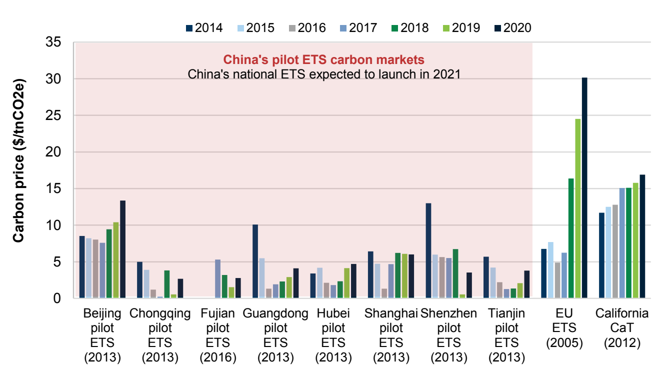


EU includes the UK.

Source: World Bank Group.

Exhibit 142: ...with China currently operating several regional pilot ETS

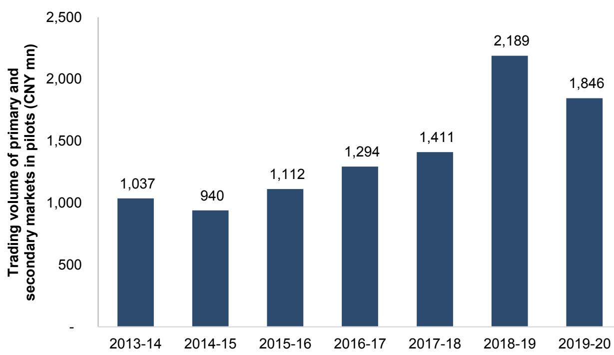
Carbon price for several operating ETS ($/tnCO2eq)



EU includes the UK.

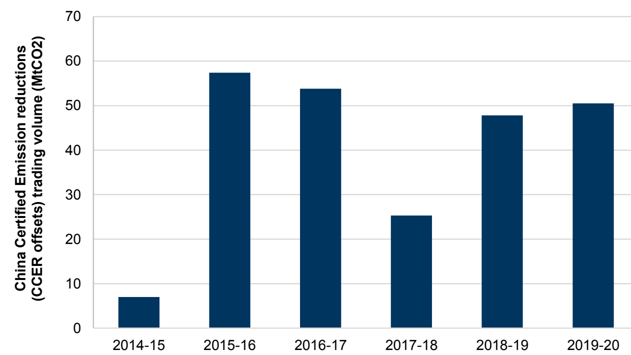
Source: World Bank Group.

Exhibit 143: Trading volumes have increased on China's pilot ETS and the national ETS could be a step function upward...
Trading volume of primary and secondary pilot ETS markets in China (CNY mn)



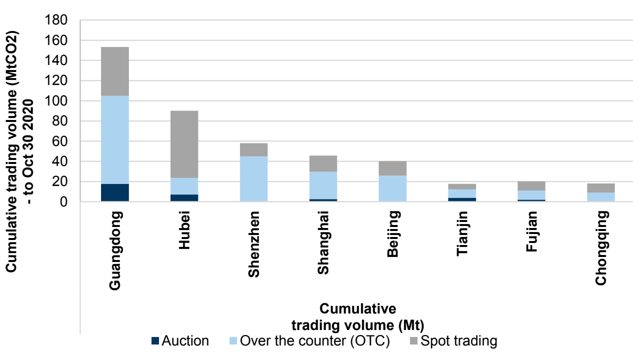
Source: 2020 China Carbon Pricing Survey.

Exhibit 144: ...and so have the number of projects registered for CCER with 256 mn tonnes cumulative of CCER traded in primary & secondary markets
China Certified Emission Reduction (CCER) offsets volume (MtCO2)



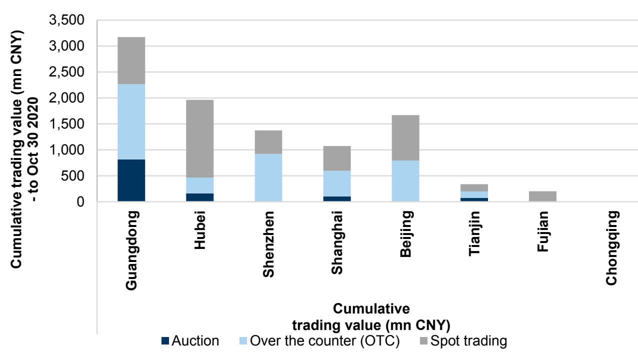
Source: 2020 China Carbon Pricing Survey.

Exhibit 145: Guangdong is currently the largest pilot regional ETS operating in China in terms of trading volume...
Cumulative trading volume of China's pilot ETS (to October 30, 2020)



Source: 2020 China Carbon Pricing Survey.

Exhibit 146: ...and trading value
Cumulative trading value of China's pilot ETS (to October 30, 2020)



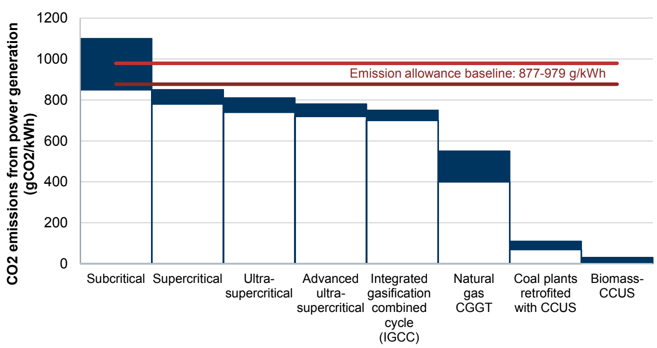
Source: 2020 China Carbon Pricing Survey.

...and getting closer to implementation with numerous recent announcements on its progress

The Ministry of Ecology and Environment (MEE) hosted a media conference on January 5, 2021, confirming that the first compliance cycle of China's national ETS was effectively rolled out on January 1, 2021. **The ETS will initially cover power generation plants**. It will allocate allowances (also known as permits), based on the plant's generation output, with emission benchmarks for each fuel and technology. China's ETS, **set to expand to seven other sectors (aviation, non-ferrous metals, steel, construction materials, chemicals, petrochemicals, paper manufacturing) will be the world's largest globally**.

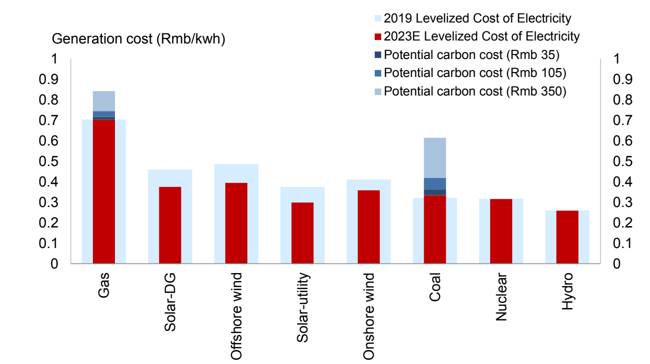
Ultimately, benefits from China's national ETS will come from either **surplus allowances for companies operating below the baseline threshold** (e.g. "clean" coal utilities) or **companies that are able to issue CCERs** (e.g. renewable operators). The latter could also drive demand for renewable projects, which could lead to growth in demand for renewable equipment, benefiting upstream players. Among coal operators, the suggested benchmark is likely to drive asymmetric risk exposure, with some potentially benefiting from the ETS. We base this view on the proposed thresholds and where industry intensity currently stands. The current proposed carbon emission allowance baseline is 0.877-0.979 kg/kWh for conventional coal units, depending on their installed capacity, which will likely affect subcritical coal plants, which have a lower thermal efficiency and a higher emission intensity.

Exhibit 147: China's ETS' proposed carbon emission allowance baseline could potentially benefit in the near term, lower-carbon, more efficient coal power plant operators, with subcritical plants the least favoured...
Range of CO2 emissions from different power generation plants (gCO2/kWh)



Source: IEA, Company data, Goldman Sachs Global Investment Research.

Exhibit 148: ...as well as benefiting renewable energy producers (carbon credits might also render solar and wind more financially attractive), with longer-term cost implications for fossil fuel power generation companies
Generation LCOE (Rmb/kWh)



Source: Goldman Sachs Global Investment Research.

The timeline laid out by the Ministry of Ecology and Environment (MEE) would imply that the first batch of 2,225 entities in the power sector will have until December 31, 2021, to comply with the scheme for their 2019-2020 emissions. This follows two key legislative documents released by the MEE (i.e. the Measures for the Administration of National Carbon Emission Trading (Trial) and the 2019-2020 Implementation Plan for National Carbon Emission Trading Total Allowances Setting and Allocation (Power Generation Industry)). Following this announcement, the MEE plans to expedite building the registration and trading system for the ETS. Our China Clean Energy analyst believes Chinese upstream clean energy manufacturers are positioned well to benefit from the new de-carbonization target (including 25% non-fossil energy by 2030, up from 20%) announced by President Xi on December 12, 2020, at the Climate Ambition Summit.

Our GS SUSTAIN team outlines the key details from these releases below, building on their previous work:

- The **power generation sector has been identified as the first sector to be included in the first compliance cycle of China's ETS**, starting from January 1, 2021, and has until December 31, 2021, to meet its compliance obligations for their 2019 and 2020 emissions.

- In the December 30 Implementation Plan, the MEE confirmed that the first batch of 2,225 entities in the power sector, including those with coal-fired units, will be included in the first cycle. An initial look at the draft list of 2,267 companies released on November 20, suggests that while the majority of the assets are within the power sector, the list also extends to other industries such as chemicals and paper that have on-site installations.
- The December 30 Implementation Plan confirmed a carbon emission allowance baseline between **0.877-0.979 tCO2/MWh for conventional coal units and 1.146 tCO2/MWh for unconventional coal units** (e.g. plants using coal gangue or coal water slurry).
- The new baseline for conventional coal units is more stringent than the initial proposed baseline, but our view on the asymmetric risk exposure among coal operators remains unchanged. We see **more efficient operators potentially benefiting from the ETS as they may have surplus allowances to monetize,** while a smaller portion of less efficient players could see greater costs to comply.
- On January 5, 2021, the MEE announced that Measures for the Administration of National Carbon Emission Trading (Trial) will become effective on February 1, 2021 (link). As discussed in our previous note, this establishes stronger transparency and governance measures for emissions disclosures by introducing legal liabilities for corporates. Our China Clean Energy analyst continues to believe that Chinese upstream clean energy manufacturers are positioned well to benefit from the scheme based on this announcement.
- The provincial departments of Ecology and Environment will decide on quotas to be allocated for each company by January 29, 2021.

Source: Goldman Sachs Global Investment Research.

We further note that there are a number of low-carbon pilot cities and provinces that have proposed peak emission target years:

- This initiative started in 2010, led by NCSC (National Center for Climate Change Strategy and International Cooperation).
- Following China's commitment at COP25 to reach peak emissions by 2030, cities have announced their emission peak targets, most with a target year before 2025.
- As of 2020, NCSC reported that 82 pilot cities and provinces have proposed peak emission target years, with 18 targeting 2020 and 42 targeting pre-2025.

Appendix: China de-carbonization cost curve details

Exhibit 150: China de-carbonization cost curve with the carbon abatement price range (US$/tnCO2eq) and abatement potential (GtCO2eq) split by industry

Conservation carbon abatement routes	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
Power generation		(US$/tnCO2 eq)	(US$/tnCO2 eq)	(US$/tnCO2 eq)	(GtCO2eq)
Hydroelectric power, low cost scenario, high coal price	Power generation	-16	-19	-13	0.00
Nuclear power, low cost scenario, high coal price	Power generation	-14	-17	-11	0.03
Hydroelectric power, high cost scenario, high coal price	Power generation	-11	-13	-9	0.00
Hydroelectric power, low cost scenario, base coal price	Power generation	-10	-11	-8	0.00
Nuclear power, low cost scenario, base coal price	Power generation	-8	-9	-6	0.06
Hydroelectric power, high cost scenario, base coal price	Power generation	-4	-5	-3	0.00
Solar power, low cost scenario, high coal price	Power generation	-4	-5	-3	0.15
Hydroelectric power, low cost scenario, low coal price	Power generation	-2	-3	-2	0.00
Onshore wind power, low cost scenario, high coal price	Power generation	-2	-2	-2	0.08
Nuclear power, high cost scenario, high coal price	Power generation	-1	-1	-1	0.03
Nuclear power, low cost scenario, low coal price	Power generation	-1	0	-1	0.03
Solar power, low cost scenario, base coal price	Power generation	3	2	3	0.31
Hydroelectric power, high cost scenario, low coal price	Power generation	3	2	4	0.00
Onshore wind power, low cost scenario, base coal price	Power generation	5	4	6	0.16
Nuclear power, high cost scenario, base coal price	Power generation	6	5	7	0.06
Solar power, medium cost scenario, high coal price	Power generation	10	8	11	0.15
Solar power, low cost scenario, loq coal price	Power generation	10	8	12	0.15
Onshore wind power, low cost scenario, low coal price	Power generation	12	10	14	0.08
Nuclear power, high cost scenario, low coal price	Power generation	13	10	16	0.03
Onshore wind power, base cost scenario, high coal price	Power generation	16	13	19	0.08
Solar power, medium cost scenario, base coal price	Power generation	16	13	19	0.31
Solar power, high cost scenario, high coal price	Power generation	21	17	25	0.15
Onshore wind power, base cost scenario, base coal price	Power generation	23	18	27	0.16
Solar power, medium cost scenario, low coal price	Power generation	23	19	28	0.15
Solar power with battery storage, low cost scenario, high coal price	Power generation	26	21	31	0.03
Solar power, high cost scenario, base coal price	Power generation	28	22	33	0.31
Wind power with battery storage, low cost scenario, high coal price	Power generation	28	23	34	0.02
Offshore wind power, low cost scenario, high coal price	Power generation	29	19	40	0.05
Onshore wind power, base cost scenario, low coal price	Power generation	30	19	40	0.08
Solar power with battery storage, low cost scenario, base coal price	Power generation	33	21	44	0.05
Onshore wind power, high cost scenario, high coal price	Power generation	34	22	45	0.08
Wind power with battery storage, low cost scenario, base coal price	Power generation	35	23	47	0.04
Solar power, high cost scenario, low coal price	Power generation	35	23	47	0.15
Offshore wind power, low cost scenario, base coal price	Power generation	36	23	48	0.11
Solar power with battery storage, low cost scenario, low coal price	Power generation	40	26	54	0.03
Onshore wind power, high cost scenario, base coal price	Power generation	40	26	54	0.16
Wind power with battery storage, low cost scenario, low coal price	Power generation	42	27	57	0.02
Offshore wind power, low cost scenario, low coal price	Power generation	43	28	58	0.05
Onshore wind power, high cost scenario, low coal price	Power generation	47	31	64	0.08
Coal power CCUS	Power generation	60	39	81	0.22
Offshore wind power, high cost scenario, high coal price	Power generation	67	44	91	0.05
Offshore wind power, high cost scenario, base coal price	Power generation	74	48	100	0.11
Offshore wind power, high cost scenario, low coal price	Power generation	81	53	109	0.05
Solar power with battery storage, high cost scenario, high coal price	Power generation	87	57	118	0.03
Hydrogen CGGT, switch from low gas price	Power generation	92	60	125	0.03
Solar power with battery storage, high cost scenario, base coal price	Power generation	94	61	127	0.05
Wind power with battery storage, high cost scenario, high coal price	Power generation	100	65	135	0.02
Solar power with battery storage, high cost scenario, low coal price	Power generation	101	66	137	0.03
Wind power with battery storage, high cost scenario, base coal price	Power generation	106	69	144	0.04
Wind power with battery storage, high cost scenario, low coal price	Power generation	114	74	153	0.02
Hydrogen CGGT, switch from base gas price	Power generation	116	75	157	0.03
Solar power with hydrogen storage, low cost scenario, high coal price	Power generation	117	76	157	0.03
Onshore wind power with hydrogen storage, low cost scenario, high coal price	Power generation	119	77	160	0.02
Solar power with hydrogen storage, low cost scenario, base coal price	Power generation	123	80	166	0.05
Onshore wind power with hydrogen storage, low cost scenario, base coal price	Power generation	125	81	169	0.04
Solar power with hydrogen storage, low cost scenario, low coal price	Power generation	130	85	176	0.03
Onshore wind power with hydrogen storage, low cost scenario, low coal price	Power generation	132	86	179	0.02
Hydrogen CGGT, switch from high gas price	Power generation	140	91	189	0.07
Solar power with hydrogen storage, high cost scenario, high coal price	Power generation	202	131	272	0.03
Solar power with hydrogen storage, high cost scenario, base coal price	Power generation	208	135	281	0.05
Onshore wind power with hydrogen storage, high cost scenario, high coal price	Power generation	214	139	289	0.02
Solar power with hydrogen storage, high cost scenario, low coal price	Power generation	216	140	291	0.03
Onshore wind power with hydrogen storage, high cost scenario, base coal price	Power generation	221	144	298	0.04
Onshore wind power with hydrogen storage, high cost scenario, low coal price	Power generation	228	148	308	0.02
Transport					
Switch aircraft to one of highest efficiency	Transport	40	6	91	0.01
LNG in shipping	Transport	68	21	115	0.01
Hydrogen FCEV truck, long-haul	Transport	219	164	273	0.11
Marine biofuels	Transport	235	215	254	0.00
Biofuels on road transport	Transport	268	179	357	0.01
City Buses to electric buses	Transport	299	260	324	0.07
Clean ammonia fuel-run ships	Transport	319	250	393	0.02
Truck to electric, short-haul	Transport	428	389	454	0.14
Truck to electric, medium-haul	Transport	454	415	480	0.02
Switch to hydrogen FCE train	Transport	474	232	717	0.03
Aviation biofuels	Transport	564	498	630	0.06
Gasoline vehicle to EV, urban	Transport	967	720	1,226	0.34
Gasoline vehicle to EV, rural	Transport	1,170	776	1,721	0.14

Source: Goldman Sachs Global Investment Research

Conservation carbon abatement routes	Industry	Carbon abatement price - base case	Carbon abatement price - low case	Carbon abatement price - high case	Carbon abatement potential
Industry & industrial waste					
Non-ferrous metals secondary production through scrap/recycling	Industry & waste	-121	-146	-97	0.23
Efficiency gains and circular economy (plastics recycling) in chemicals	Industry & waste	-58	-70	-46	0.09
Switch from coal to natural gas+CCUS based process in ammonia	Industry & waste	39	31	47	0.04
Textiles manufacturing efficiency gains	Industry & waste	45	32	59	0.40
Swicth from coal to natural gas+CCUS processes in chemicals (HVCs, methanol)	Industry & waste	52	41	62	0.03
Efficiency gains and waste reduction in manufacturing processes (low cost)	Industry & waste	58	41	75	0.19
Inert anodes for non-ferrous metals processing	Industry & waste	68	55	82	0.03
Switch from BF-BOF (coal) to natural gas DRI-EAF (with zero carbon electricity) in s	Industry & waste	79	63	94	0.22
Fuel switch to biomass & waste in cement	Industry & waste	81	65	97	0.35
Other industrial CCUS	Industry & waste	90	60	130	0.32
Retrofit BF-BOF (coal) with charcoal/biomass furnace for fuel/feedstock in steel	Industry & waste	91	73	110	0.06
Switch from BF-BOF (coal) to scrap-EAF process in steel	Industry & waste	102	81	122	0.85
Swicth to electroysis hydrogen process in chemicals (HVCs, methanol)	Industry & waste	127	102	153	0.13
CCUS in cement	Industry & waste	130	104	156	0.70
Non-ferrous metals CCUS	Industry & waste	140	98	182	0.12
Electrification of heat in industrial processes	Industry & waste	145	75	345	0.39
Efficiency gains and waste reduction in manufacturing processes (medium cost)	Industry & waste	170	119	221	0.19
Switch to electrolysis hydrogen process in ammonia	Industry & waste	205	123	287	0.07
Switch from BF-BOF (coal) to hydrogen DRI-EAF process in steel	Industry & waste	220	176	264	0.85
Efficiency gains and waste reduction in manufacturing processes (high cost)	Industry & waste	350	245	455	0.19
Reducing clinker to cement in cement process	Industry & waste	363	290	435	0.10
Switch to biogas/biomass fuel and feedstock in ammonia	Industry & waste	427	341	512	0.03
Swicth to biogas/biomass for fuel and feedstock in chemicals (HVCs, methanol)	Industry & waste	523	419	628	0.18
Buildings					
LED and increased efficiency, commercial buildings	Buildings	-77	-96	-58	0.03
LED and increased efficiency, residential	Buildings	-67	-83	-50	0.05
Insulation (cavity and wall), commercial buildings	Buildings	-58	-72	-43	0.02
Insulation (cavity and wall), new build	Buildings	-50	-63	-38	0.02
HVAC Systems/thermostat & smart meters efficiency gains, commercial buildings	Buildings	-48	-60	-36	0.01
HVAC Systems/thermostat & smart meters efficiency gains, new builds	Buildings	-42	-52	-31	0.01
HVAC Systems/thermostat & smart meters efficiency gains, retrofit	Buildings	-32	-40	-24	0.01
Insulation (cavity and wall), retrofit	Buildings	-20	-25	-15	0.02
Solar thermal renewable heat, commercial buildings	Buildings	38	29	48	0.01
Solar thermal renewable heat	Buildings	45	34	56	0.10
BACS systems/efficiency gains/BAT appliances residential	Buildings	159	120	199	0.11
BACS systems/efficiency gains/BAT appliances commercial	Buildings	183	138	229	0.02
Switch from coal boiler to natural gas boiler, retrofit	Buildings	232	174	290	0.04
Switch from coal boiler to natural gas boiler, commercial buildings	Buildings	239	179	299	0.02
Switch from coal boiler to natural gas boiler, new build	Buildings	281	211	352	0.02
Heat pumps for water heating (ground source), commercial buildings	Buildings	317	238	396	0.00
Heat pumps for water heating (ground source)	Buildings	373	280	466	0.00
Switch from coal boiler to hydrogen boiler, commercial buildings	Buildings	497	373	622	0.05
Switch from coal boiler to heat pump (renewabe electricity), commercial buildings	Buildings	538	404	673	0.03
Switch from coal boiler to hydrogen boiler, new build	Buildings	585	439	731	0.05
Switch from coal boiler to hydrogen boiler, retrofit	Buildings	593	444	741	0.10
Switch from coal boiler to heat pump (renewabe electricity), new build	Buildings	633	475	791	0.03
Switch from coal boiler to heat pump (renewabe electricity), retrofit	Buildings	749	562	936	0.02
Agriculture, Forestry and Other Land uses (AFOLU)					
Fire & disaster improved mannagement practices	Agriculture, forestry & other land uses	10	6	14	0.04
Reduced soil erosion, salinization and compaction	Agriculture, forestry & other land uses	35	21	49	0.34
Improved cropland management practices	Agriculture, forestry & other land uses	42	25	59	0.10
Improved grazing land management practices	Agriculture, forestry & other land uses	58	35	81	0.02
Improved livestock management practices	Agriculture, forestry & other land uses	120	72	168	0.25

Source: Goldman Sachs Global Investment Research

Disclosure Appendix

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