



CHINA 2050: A FULLY DEVELOPED RICH ZERO-CARBON ECONOMY



THE ENERGY TRANSITIONS COMMISSION

The Energy Transitions Commission (ETC) is a global coalition of leaders from across the energy landscape (energy producers, energy-intensive industries, technology providers, finance players, environmental NGOs) committed to achieving the Paris climate objective of limiting global warming to well below 2°C and ideally as close as possible to 1.5°C. Our work combines analysis to define how that objective can be achieved, and engagement with public policymakers, industry initiatives, and individual companies, to encourage and energize action which will ensure change pathways are implemented and targets achieved. The ETC is co-chaired by Lord Adair Turner and Dr. Ajay Mathur. Our Commissioners are listed on the next page.

In China, the ETC partners closely with the Rocky Mountain Institute (RMI)'s Beijing office, which acts as the ETC China secretariat. RMI is an independent, non-partisan non-profit, whose mission is to transform global energy use to create a clean, prosperous, and secure low-carbon future. It is a member of the ETC.

The "*China 2050: A Fully Developed Rich Zero-Carbon Economy*" report was developed by the Commissioners with the support of the ETC and RMI China teams. It draws upon previous analyses from the ETC and

broader literature review. It also integrates feedback from several rounds of consultation with representatives of Chinese companies, academia and institutions as well as global companies and institutions operating in China. We warmly thank them for their contributions.

This report constitutes a collective view of the Energy Transitions Commission. Members of the ETC endorse the general thrust of the arguments made in this report, but should not be taken as agreeing with every finding or recommendation. The institutions with which the Commissioners are affiliated have not been asked to formally endorse the report.

The ETC Commissioners agree that it is vital that China has a strategy to achieve net-zero emissions by mid-century for the world to deliver the Paris climate objectives, that achieving this goal is technically and economically feasible, and that this transition would benefit the Chinese economy. This agreement between leaders from companies and organizations with different perspectives on and interests in the energy system should give Chinese decision-makers confidence that it is possible simultaneously to grow the Chinese economy and to limit global warming to well below 2°C, and that many of the key actions to achieve these goals are clear and can be pursued without delay.

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EXECUTIVE SUMMARY

China 2050: A Fully Developed Rich Zero-Carbon Economy

Global climate change threatens major harm to human society across the world. A November 2018 report from the Intergovernmental Panel on Climate Change (IPCC) argued that to avoid extreme harm, the world must limit global warming to less than 1.5°C¹. But this is only possible if the whole world achieves net zero greenhouse gas emissions by around mid-century.

The good news, as the global Energy Transitions Commission (ETC) has described in two reports—*Better Energy, Greater Prosperity* (2017) and *Mission Possible* (2018)—is that the technologies exist to make this objective attainable, and at a very small cost to economic growth and consumer living standards. This is true even for “harder-to-abate” sectors of the economy—

heavy industry and heavy-duty/long-distance transport—which could be decarbonized at a cost to the economy of less than 0.6% of GDP, and with only a minor impact on consumer prices.

China’s welfare is threatened by climate change as much as other nations. And China’s energy-intensive development mode for decades has made it a major emitter of greenhouse gases. In per capita terms, China’s emissions are in line with the rich developed economies of Europe, although only 45% of the United States’ extremely high level. But China’s sheer scale makes it in absolute terms the world’s largest emitter, with 9.8 gigatonnes of CO₂ per annum accounting for 28% of the global total. For the whole world and for China itself, it is therefore vital that China has a strategy to achieve net zero emissions by mid-century.

1. IPCC (2018), *Global warming of 1.5 °C*

This report shows that it is technically and economically feasible to achieve that objective, that the investment required can easily be affordable given China's high savings and investment rate, and that the impact on China's GDP per capita in 2050 will be minimal. Far from constraining China's ability to meet its objective of being "a fully developed rich economy" by 2050, committing to achieve zero emissions by 2050 will spur investment and innovation that could accelerate progress. It will also deliver large improvements in local air quality and create huge opportunities for Chinese technological leadership in multiple industries.

To achieve net zero emissions will require the total decarbonization of electricity generation and the massive expansion of electricity use, electrifying as much of the economy as possible. It will also require an over threefold increase in the production and use of hydrogen, together with important but more limited roles for increased bioenergy production and for carbon capture and either storage or use. China's natural resources, technological prowess, and savings and investment rates make it possible for these different technologies to deliver a zero-carbon economy, even while China enjoys rapid growth of energy-based services such as transport and residential heating and cooling.

Key sectoral actions to achieve a zero-carbon economy include:

- **Total electrification of surface transport (road and rail services) while supporting a threefold increase in transport use.** Within light duty sectors (autos and vans), electric vehicles (EVs) will soon be economically superior to internal combustion engines, whereas hydrogen fuel cell vehicles (FCEVs) likely will eventually dominate heavy-duty road transport. China's huge high-speed rail network and its extensive subway systems will help to somewhat constrain the growth of road

traffic and significantly constrain domestic aviation. All rail travel should be electrified well before 2050. Electrification in these surface transport sectors will result in a decline in final energy demand due to the inherently higher energy efficiency of electric versus internal combustion engines. And decarbonization in these sectors will increase rather than decrease attainable GDP per capita, due to EVs' inherent long-term cost advantage.

- **The use of biofuels, synthetic fuels, hydrogen, or ammonia to drive decarbonization of long-distance international aviation and shipping,** combined with the use of battery electric hydrogen and hybrid options over short distances. These fuels likely will be more expensive than existing fossil fuels, implying somewhat higher international freight rates and airline tickets. However, technological progress and economies of scale could drive substantial cost reductions over time.

- **A shift toward a more circular economy, with far more efficient use and greater recycling of key materials** such as steel, cement, fertilizers, and plastics. Total needs for primary steel and cement production to support construction will inevitably fall as China's population stabilizes and then falls, and as urbanization reaches completion. As a result, steel production from recycled scrap steel would take up 60% of total production compared to its share of less than 10% today. In cement, recycling opportunities are more limited, but improved building design and material quality could reduce total demand by nearly 50% compared with the business-as-usual (BAU) level. Demand for fertilizers could be cut by one-third through much higher but feasible fertilizer use efficiency. And 52% of China's plastics use could come from recycled plastic, with extensive development of both mechanical and chemical recycling.

- **The use of electrification, hydrogen, carbon capture**

and storage (CCS), and bioenergy to achieve full decarbonization of heavy industries such as steel, cement, and chemicals (ammonia, methanol, and high-value chemicals [HVCs]). Direct electrification would be most applicable for industrial processes with a low to medium temperature requirement, while hydrogen and bioenergy can be used to meet intense heat demands. Hydrogen would also be used as a reduction agent for steel and as a feedstock in chemicals production. Biomass could be another important feedstock for chemicals. CCS would play a role in dealing with industrial process emissions and those from remaining fossil fuel use.

• **The wider deployment of advanced heat pump technologies plus state-of-the-art building insulation to deliver heating and cooling to houses and offices in a zero-carbon fashion, with long-distance industrial waste heat transportation and biomass also playing a role in specific circumstances.** By 2050, energy efficiency in China’s building sector would be significantly improved to ensure economical and effective use of energy in the face of a growing service level, and by then 75%

of building heating and cooling would be delivered by electricity. Electrification combined with heat pumps would in turn reduce the final energy demand, given the inherent efficiency benefits of heat pumps, which even today can deliver 4 kWh of heat for each kilowatt-hour of input electricity, with further significant improvement in this “coefficient of performance” likely to be achieved over time.

The combination of reduced demand for steel and cement, more circular use of all materials—including, in particular, plastics—and the inherent energy efficiency advantages achieved by the electrification of both surface transport and building heating will enable China to enjoy a GDP per capita and standard of living of three times the current levels while reducing final energy demand from 88 EJ today (24,000 terawatt-hours [TWh]) to 64 EJ (17,800 TWh) in 2050. Within this, the industry would experience the most significant reduction (minus 30%) but would continue to account for 60% of final energy demand in 2050 (see Exhibit A).

This energy demand could be met in a zero-carbon

Under our scenario, China would be able to reduce final energy demand from 88 EJ in 2016 to 64 EJ in 2050, where industry would experience the most significant reduction (minus 30%) but would continue to account for 60% of final energy demand.

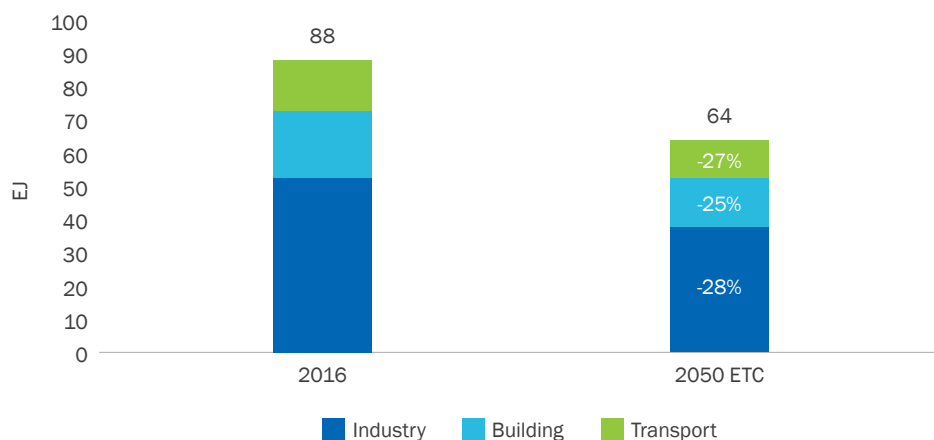


Exhibit A: China’s final energy demand by sector (industry, building, and transport)

Source: China Statistics Yearbook;
Rocky Mountain Institute analysis for ETC China

fashion through the use of four technologies: electricity, which can be made zero carbon if it derives from renewable or nuclear sources; hydrogen, which can be produced in zero-carbon fashion via electrolysis using zero-carbon electricity, and which can also be used in the form of ammonia; bioenergy, which can be used as zero-carbon fuel and feedstock; and the continued use of some fossil fuels, if combined with carbon capture and either storage or use. Exhibit B sets out the different energy mixes that could be used in each sector of the economy in 2050.

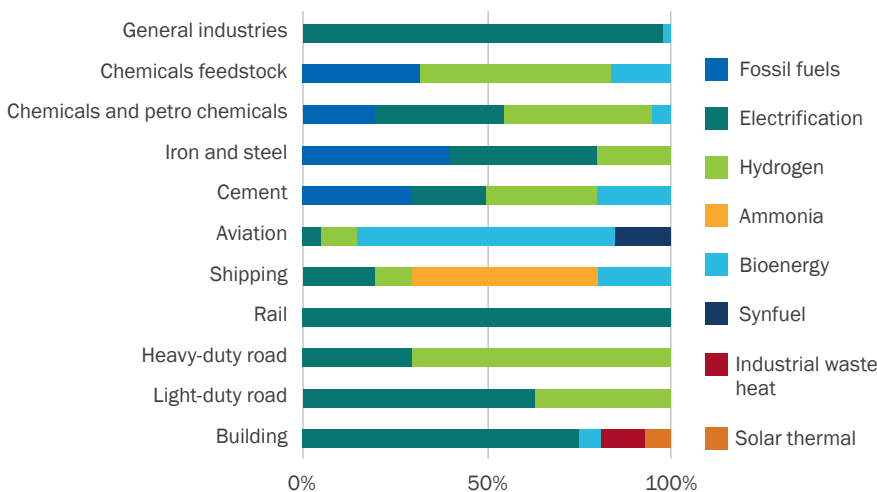
Electricity will play the most important role, either used directly or to produce hydrogen, ammonia, or other synthetic fuels. In aggregate, achieving a zero-carbon economy will require an increase in electricity generation from today's 7,000 TWh to something around 15,000 TWh in 2050 (see Exhibit C). In addition, hydrogen use will need to rise from today's 25 million tonnes per annum to more than 81 million tonnes. Making this electricity in a zero-carbon fashion could be

achieved with 2,500 GW of solar capacity, 2,400 GW of wind, 230 GW of nuclear, and 550 GW of hydro power. This is technically feasible given China's wind, solar, and hydro resources and the number of coastal sites already identified as suitable for nuclear power plants.

While places with rich solar resources cover two-thirds of its total land area, China would need to devote less than 1% of its land mass to deliver the 2,500 GW of solar energy required within the total mix, and China's estimated wind capacity resources, at 3,400 GW onshore plus 500 GW offshore, exceed the required amount.

Building the required capacity will require a dramatic increase in the annual pace of investment (twice today's rate for solar and three to four times for wind) but the financial cost of this investment would still be less than 0.4% of China's GDP. This is clearly economically feasible in an economy currently investing over 40% of GDP, some of which is wasted on excessive investments

Final energy consumption by sectors and by energy carriers



Total electricity would reach 15,000 TWh in 2050.

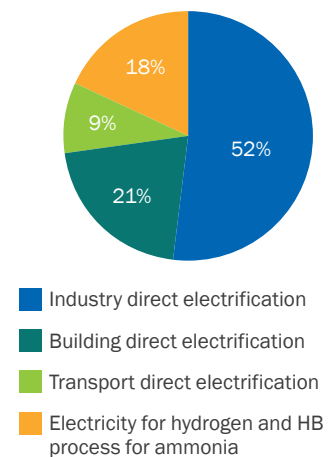


Exhibit B. Snapshot of final energy consumption by sectors and energy carriers in China 2050

Note: HB process = Haber-Bosch process.
Source: Rocky Mountain Institute analysis for ETC China

in unoccupied real estate, and which will face declining real estate and non-energy infrastructure investment needs as the population stabilizes and urbanization reaches completion.

As Exhibit C shows, the resulting electricity system would derive nearly 70% of its electricity from wind and solar resources, which vary with weather conditions. But a portfolio of grid flexibility and storage options will make it possible to balance supply and demand. A total of 142 GW of pumped hydro storage (PHS) could provide longer duration seasonal backup. Battery storage could grow from today's trivial levels to reach 510 GW in 2050, with costs likely to fall dramatically over time. Production of hydrogen from excess electricity could serve as an effective demand response mechanism, with at least 100 GW of capacity in place. Various categories of demand response—in both the

industrial and residential sectors—could play a major role provided that appropriate software systems and market incentives are in place. Thermal plants, powered either by biomass or by fossil fuels with carbon capture applied, will play a limited but still vital role, providing short-term backup while running only a small number of hours per annum.

In addition to electricity and hydrogen, achieving a zero-carbon economy will require the production of about 13 EJ per annum of bioenergy, compared with only 1 EJ today. Achieving this bioenergy supply in a sustainable fashion will prove a major challenge, but in principle China could develop sustainable bioenergy on the scale of 12 EJ to 25 EJ. Given its limited bioenergy resource, China would need to prioritize its use on those sectors where alternative decarbonization options are not available. Aviation is likely a priority sector; trucking is not.

In aggregate achieving a zero-carbon economy will require an increase in electricity generation from 6,000 TWh in 2016 to something around 15,000 TWh in 2050.

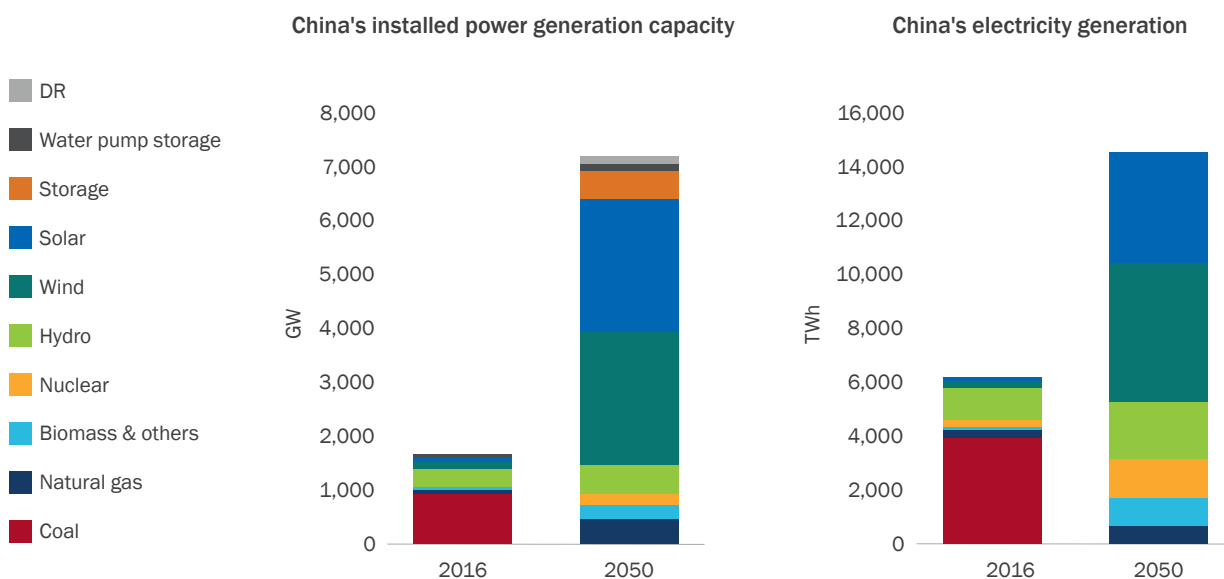


Exhibit C. China's installed power generation capacity and electricity generation mix

Note: HB process = Haber-Bosch process.
Source: Rocky Mountain Institute analysis for ETC China

There would also be a limited but still vital need to apply carbon capture to several industrial processes, with the CO₂ either utilized in applications that achieve permanent sequestration (such as new forms of concrete curing) or transported and stored. China’s geological capacity for CO₂ storage far exceeds the 1 gigatonne per annum which will be required, and there is sufficient matching between the location of carbon emissions and the location of storage to minimize the requirement for very long distance (greater than 250 km) transport of CO₂.

Given both the reduced final energy demand described in Exhibit A and the switch to the zero-carbon energy mix shown in Exhibits B and C, total primary energy demand could fall by 45% from 132 EJ today to 73 EJ in 2050. This larger fall in primary energy demand than in final energy demand (minus 30%) largely reflects the elimination of the energy losses involved in today’s thermal electricity production system. Within this reduced total, there would be a dramatic change in the

sources of energy, with fossil fuel demand falling over 90% while non-fossil energy would expand by 3.4 times (see Exhibit D).

The precise balance between different decarbonization routes and energy supply options will need to reflect evolving technological possibilities and economic developments over time. But the scenario presented here shows that it is possible to achieve zero emissions at a very small cost, with the impact on China’s GDP per capita and living standards in 2050 unlikely to exceed 1%.

This cost could indeed be lower still, or even negative, if the very fact of committing to a zero-emissions target induced technological advances and cost reductions not assumed in our calculations.

But this feasible path to a zero-carbon economy will not be achieved without clear targets and forceful public policies. Setting a clear national objective to reach zero emissions by 2050 is essential to provide a framework

Total primary energy demand could fall by 45% from 132 EJ today to 73 EJ in 2050, with fossil fuel demand falling over 90% and non-fossil energy expanding by 3.4 times.

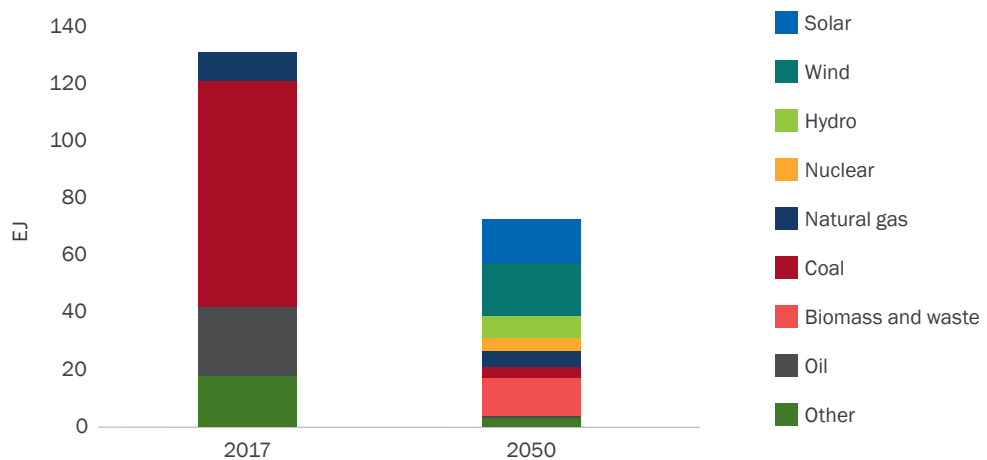


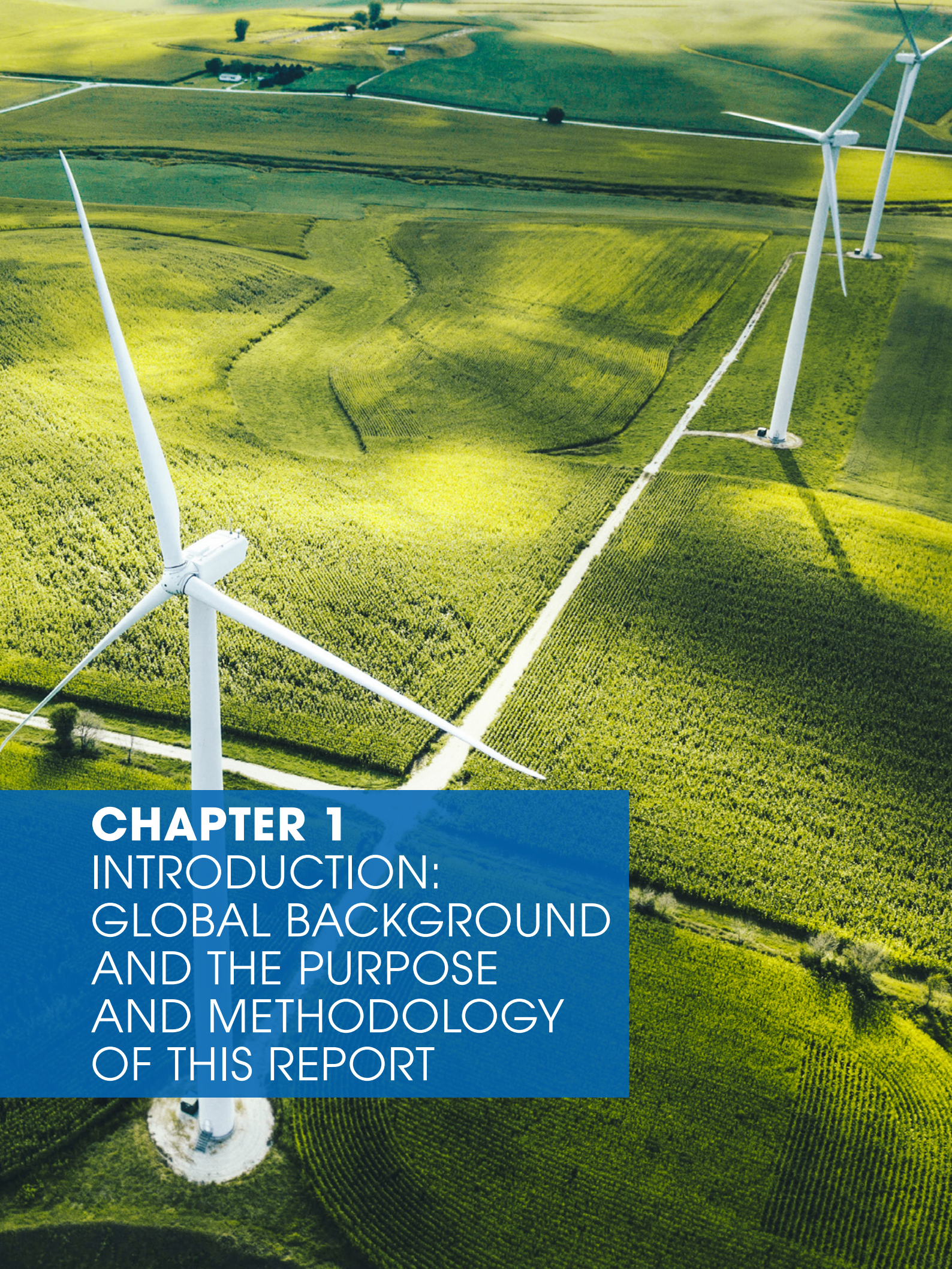
Exhibit D. China’s primary energy demand by energy carrier

Source: China Statistical Yearbook; Rocky Mountain Institute analysis for ETC China

within which state-owned and private enterprises can make the investments required. But this long-term objective must be supported by short-term targets and investment plans—such as those set out in China’s forthcoming 14th Five Year Plan—and by strong policies. These should include:

- Clear policies to support increased investment in zero-carbon electricity system, including generation, transmission, distribution and energy storage systems;
- A national carbon price system to drive decarbonization across the whole economy and particularly in heavy industry;
- Strong regulations to drive the electrification of surface transport and building heating, and to ensure ever improving standards of building insulation;
- Regulations and incentives to support an increasingly circular economy of materials recycling and reuse, particularly in the plastics sector;
- And public support for the development and early deployment of the new technologies required to build a zero-carbon economy;

China’s political and economic system, which combines market incentives with strong state ability to define long-term objectives and support long-term investments, makes it well placed to put these policies in place, to achieve net zero emissions by 2050, and to gain the economic and environmental advantages which would result.



CHAPTER 1
INTRODUCTION:
GLOBAL BACKGROUND
AND THE PURPOSE
AND METHODOLOGY
OF THIS REPORT

The Paris Climate Agreement committed the world to limit global warming to well below 2°C and keep it as close as possible to 1.5°C above preindustrial levels. Human-induced global warming has already caused major negative impacts in multiple areas. The latest Intergovernmental Panel on Climate Change (IPCC) report has warned the world of the even more drastic consequences of 2°C global warming, including severe adverse impacts on water resources, land use, food production, and human health. It therefore urged that the world commit to limiting global warming to 1.5°C.

The Energy Transitions Commission (ETC) is a global coalition of companies and institutions from across the energy landscape: energy producers, energy users, equipment suppliers, investors, non-profit organizations and academics. All of our members, whose names are set out on page II, support the objective of limiting global warming ideally to 1.5°C, and at the very least to well below 2°C.

To achieve that climate objective, the world economy will need to reach net zero emissions sometime around mid-century. The ETC believes that the specific objective should be for all fully developed economies to reach net zero emissions by 2050 and developing countries by 2060. We have set out how that can be achieved in two major reports:

- In *Better Energy, Greater Prosperity*, published in April 2017, we described the overall path to decarbonizing the global economy and showed that it is now possible to build electricity systems that are as much as 85% dependent on variable renewables at costs that are fully competitive with fossil fuel generation. The world can build zero-carbon power systems much faster and cheaper than seemed likely 10 years ago.

- In *Mission Possible*, published in November 2018, we showed it was also possible to decarbonize the so-called hard-to-abate sectors of the economy, such as heavy industry (in particular, steel, cement and petrochemicals) and long-distance transport (trucking, aviation, and shipping).

Together, these two reports illustrate not only that it is technically possible to build zero-carbon economies but that achieving that objective by mid-century will have only a very small (about 1%) impact on growth and consumer living standards, provided that forceful policies are now put in place. In December 2019, the ETC will publish an updated overview of the path to a global zero-carbon economy, integrating the findings of our two reports.

The ETC is now working across the world to identify and encourage the detailed public policy actions and private investments required to achieve the feasible goal of net zero emissions by mid-century. We have substantial work underway in the European Union (EU) and India, a newly launched initiative in Australia, and specific initiatives working with each of the hard-to-abate sectors at a global level. In China, the ETC started work in April 2019 and is committed to building a significant Chinese membership and to making a major contribution to debates about China's energy transition.

Surpassing the EU in 2003 and the United States in 2006, China has become the world's largest emitter of CO₂, with total 2018 emissions of 9.2 gigatonnes (Gt) making up 28% of the world's total. This of course reflects China's large population, but it also reflects China's extraordinary economic success over the last 30 years, which has both delivered huge increases in the Chinese people's standard of living and made China a major net exporter to the rest of the world. As a result, while China's emissions per capita are

only 45% of the US's extremely high level, they are now similar to EU levels on a production basis and approaching European levels on a consumption basis². Unless China achieves the net zero emissions required for all fully developed rich economies, eliminating carbon inputs both from the goods it consumes and from those it exports, it will be impossible to limit global warming to well below 2°C, let alone to 1.5°C.

The Chinese government has already made commitments within its nationally determined contributions to the Paris Agreement to reduce the carbon intensity of Chinese growth and to ensure that carbon emissions peak around 2030. More ambitious targets are now being discussed and additional actions taken. But these commitments have not focused on the required objective for 2050, and they fall far short of both what is necessary to limit the global temperature rise to well below 2°C and what is technologically achievable at a low cost.

The ETC therefore decided to begin our work in China by developing an overview of what would be required for China to achieve net zero emissions by 2050. To do that, we have worked in close partnership with the Beijing office of Rocky Mountain Institute; RMI is a member of the ETC and led the analytical work.

This report - *China 2050: A Fully Developed Rich Zero-Carbon Economy* – sets out the key conclusion: it is technically and economically possible for China to achieve net zero emissions by 2050, at a very small economic cost to growth and consumer living standards, and China is well placed to gain technological competitive advantage from the transition to net zero emissions. But the report also highlights, in Chapter 11, that this feasible transition to a zero carbon economy

will not be achieved without strong policies.

The report reflects just six months of work and covers all sectors of the Chinese economy. It has not therefore been possible in that time to conduct detailed analysis of the technical abatement options and costs relevant in each specific sector of the Chinese economy. To enable us to rapidly develop an overview analysis, we have therefore drawn heavily on the two existing global ETC reports, but with a specific focus on those areas where distinctive Chinese characteristics may make global conclusions inapplicable. In particular:

- Our starting-point assumption has been that technical decarbonization options that can work at a global level are also applicable in China; that the costs of cutting emissions, and the drivers of relative cost between different options, will be similar in China to elsewhere; and that the overall mix of technology that will be used to achieve decarbonization (electricity, hydrogen, bioenergy, and carbon capture) will be somewhat similar in China to elsewhere.
- But we then looked carefully at distinctive Chinese factors in respect to (1) the likely evolution of energy demand—for instance, the far greater role in the Chinese economy of infrastructure investment, and thus of steel and cement production; (2) the existing production base—for instance, the far greater role that coal plays as a feedstock in China's chemical industry than in other countries; (3) China's natural resource availability, whether in terms of wind, solar, or hydro resources, bioenergy or carbon storage capacity; and (4) existing policies and trends—for instance, the more rapid progress being made in China toward road transport electrification, and the far greater role of high-speed rail.

2. On the standard "production" basis used in UNFCCC accounting, national emissions include all emissions resulting from production within an economy, irrespective of whether the goods and services are consumed within the country or exported. The alternative "consumption" basis deducts emissions arising from production of exported goods and adds emissions arising from production of imports.

As a result, our conclusion that China can achieve zero emissions by 2050 is rooted in careful analysis of China's distinctive national characteristics.

However, it is important to understand what this report does not yet cover. Our focus here is on the feasibility of the endpoint in 2050, but we do not describe the decade by decade transition path from today to that point, nor define what has to be achieved by when to make the 2050 objective attainable. Our analysis makes us certain that the end point can be achieved with forceful policies, but in the next stage of ETC China's work we will focus on how to get there and on the short-term actions now needed.

The report sets out in turn:

- An overview (Chapter 2) of how China's economy is likely to develop in the face of demographic and structural change to become a fully developed rich economy by 2050.
- Analysis in Chapters 3 to 5 of the future demand for energy for the industry, transport, and building sectors, which is then pulled together into an overview of China's 2050 energy demand in Chapter 6.
- Analysis of the technical and economic feasibility of delivering the massively increased supply of zero-carbon electricity (Chapter 7) and hydrogen (Chapter 8) and the significant quantities of bioenergy and carbon storage capacity (Chapter 9) that will be required to meet that energy demand in a zero-carbon fashion.
- An integrated picture of the economic implications of total decarbonization for growth, investment, and consumer living standards (Chapter 10).
- A summary of the key public policies and technological developments required to drive progress toward a zero-

carbon economy (Chapter 11).

The ETC and RMI look forward to engaging with sectors, companies, and public policy experts in discussion of the report's conclusions and its supporting analysis.



CHAPTER 2
CHINA IN 2050:
A FULLY DEVELOPED
ECONOMY

China's current GDP per capita is still only 25% of the US level in PPP terms (and 15% in MER terms), but would catch up towards rich economy levels by 2050.

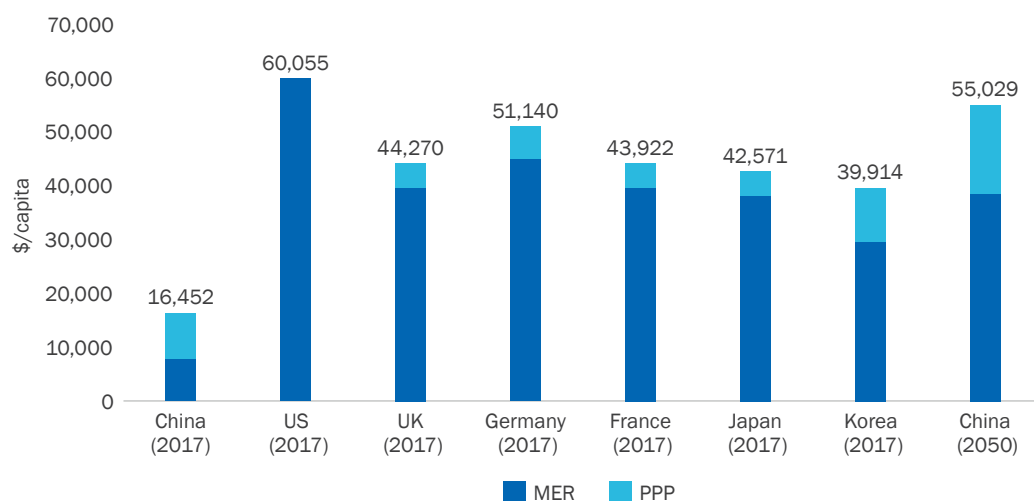


Exhibit 2-1. Comparison of GDP per capita across countries

Note: MER = market exchange rate; PPP = purchasing power parity

Source: IMF (2019), World Economic Outlook; UNESDA (2015), World Population Prospects: The 2015 Revision

China's economic performance over the past 30 years has been remarkable, with real annual GDP growing by 9.5% in the past three decades to 2018. But because GDP per capita is still only 25% of the US level in purchasing power parity terms (and 15% in market exchange rate terms), as shown in Exhibit 2-1, there is still great potential for rapid growth, catching up toward rich economy levels of productivity and living standard.

Looking forward, China's stated long-term development goals include:

- By 2035, to basically realize socialist modernization, with GDP per capita equal to 60% of the US level.
- By 2050, to become a "fully developed rich economy", completing modernization with GDP per capita reaching 70% of the 2017 US level. Given that China's population is about four times that of the United States, this would imply that the Chinese economy will by then be about 2.5 to 3 times larger than the US economy.

These economic goals are highly credible, and the resulting growth in Chinese living standards and consumer expenditure will have important implications for future demand for energy-intensive goods and services. Road, rail, and air transport demand will grow rapidly, and Chinese people will increasingly demand rich developed country standards of residential heat and cooling comfort. The implications of this for energy demand are considered in Chapter 4 and 5.

On the production and investment side, however, the Chinese economy will inevitably change significantly, including in some ways that will reduce energy demand. In particular:

- Given the long-term impact of the one-child policy, China's population, currently about 1.42 billion, is likely to reach a peak of about 1.44 billion in the late 2020s, and is then projected to decline slowly to 1.36 billion in 2050.⁽¹⁾ This will inevitably mean that in the long term, investment in new construction of buildings and

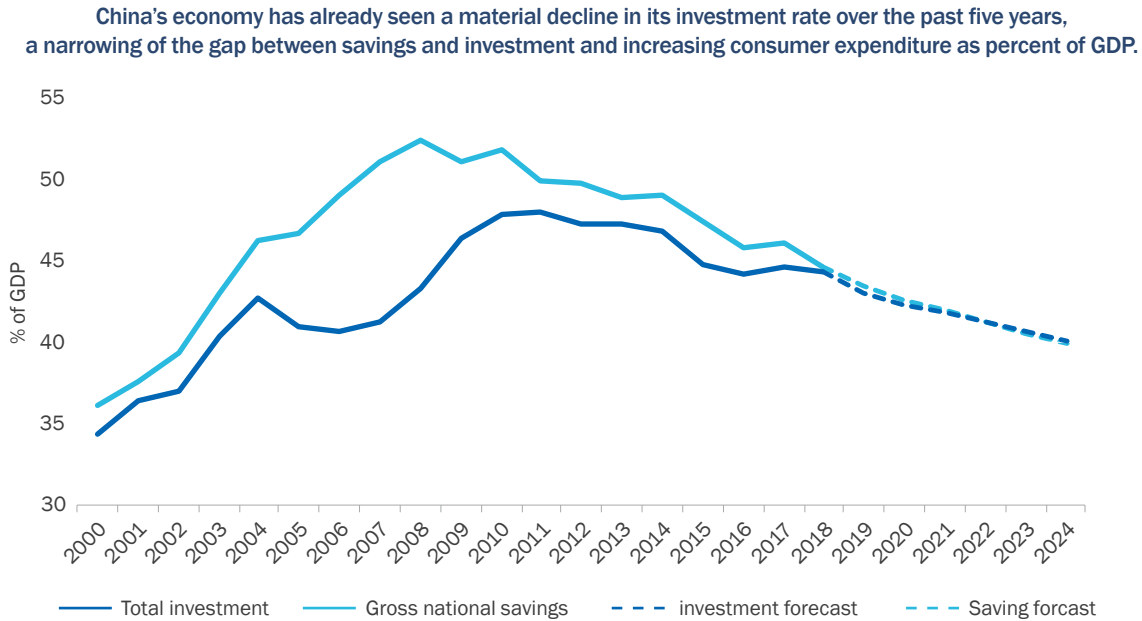


Exhibit 2-2. China's national savings and investment from 2000 to 2020

Note: The dotted line represents forecasting data.
Source: IMF (2019), World Economic Outlook Database

infrastructure will decline significantly, as it has in Japan over the past 30 years.

- For the next 10 to 15 years, such investment will continue to be underpinned by the continuing process of urbanization. But by the mid-2030s, this process will be approaching completion. From 50% in 2010, the urban population share has already reached 60% in 2019 (a year ahead of the 2020 target) and is projected to reach 70% by 2030 at the latest, and typical developed country levels of 75%–80% during the 2030s. As the pace of urbanization slows down, demand for steel and cement will inevitably fall.

- Meanwhile, China's ability to run a large current-account surplus, with the manufacturing sector significantly larger than required to satisfy domestic demand, will inevitably decline as the Chinese economy accounts for a larger share of the global total. Relatively small economies can run very large current surpluses as a percent of GDP; continental scale economies simply cannot.

Reflecting these long-term structural changes, China's economy has already seen a material decline in its investment rate over the past five years, a narrowing of the gap between savings and investment (which is equal to the current-account surplus) and increasing consumer expenditure as percent of GDP (Exhibit 2-2). But with the investment rate still over 40% of GDP—which is far higher than in most developing countries, let alone developed economies—there remains a large potential for further decline in the coming decades.

One key determinant of both the total quantity and the nature of China's future energy demand will be the extent to which China's economy continues to be skewed toward industry. As Exhibit 2-3 shows, industry (which includes heavy industry, general manufacturing, and construction) accounted in 2016 for 39.9% of the total value added of the Chinese economy, which is well above the 28%–29% share seen in the export-oriented economies of Germany and Japan, let alone the 18%–20% seen in the UK and the US.

China starts with a heavily industry-focused economy and forecasts assumed the share of industry significantly more industry-focused than Japan or Germany today.

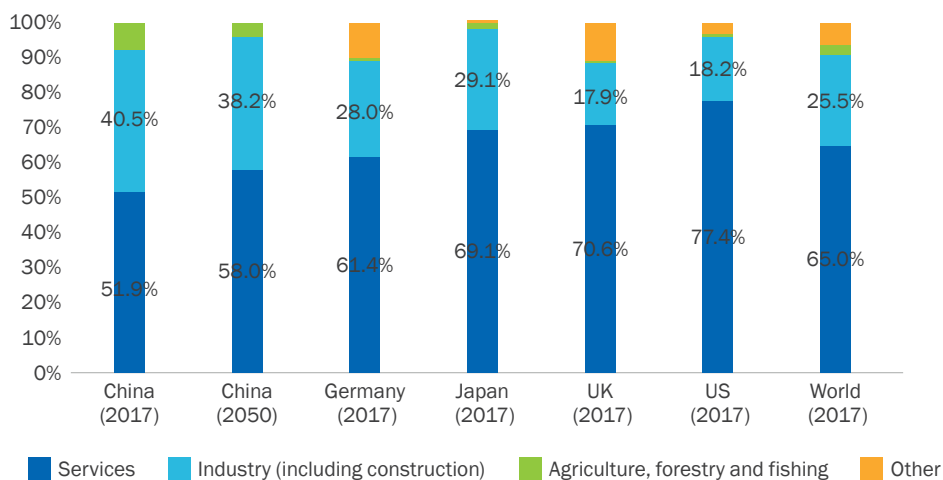


Exhibit 2-3. Value added by sectors across different countries

Note: "Other" represents the remaining part other than agriculture, industry, and services to make the sum 100%, according to the World Bank Database.
 Source: All 2017 data from World Bank Database. Data for China in 2050 estimated by Energy Research Institute of China National Development and Reform Commission

Several forecasters have assumed that the share of industry will continue to be about 38% in 2050, and forecasts of energy demand sometimes reflect this assumption. But there are strong reasons for believing that the percentage will decline to or even below Japanese and German levels, given that:

- There is no reason to believe that domestic demand should be more skewed towards manufacturing goods and construction (as against services) in China in 2050 than it is in Japan and Germany today.
- It will not be possible for China, as a continental scale economy, to maintain a current-account surplus as a share of GDP as high as the 8% which Germany currently runs.

The longer-term tendency must therefore be for industry to decline significantly as a percent of GDP. Over the short and medium term, this tendency may be delayed if large Belt and Road Initiative infrastructure investments

are supported by heavy industry exports from China. But once China becomes a fully developed rich economy, it is almost inevitable that its economic structure will look similar to that of rich developed countries today.

The inevitable decline in infrastructure investment will have important implications for energy demand deriving from heavy industry sectors such as steel and cement; these are discussed in Chapter 3. General manufacturing will continue to grow to meet growing consumption demands but will be increasingly focused toward higher-value-added products, whose production tends to create demand for electricity rather than for the intense heat required in some heavy industrial processes. Information and communications technology will also play an ever-increasing role in China's economy, again creating huge additional demands for electricity.

The implications of this overall picture for energy demand sector by sector are described in the next three chapters.



CHAPTER 3
DECARBONIZING
INDUSTRY

Decarbonizing Steel

China's steel production currently results in about 15% of China's total CO₂ emissions in 2017.⁽²⁾ These will fall naturally once China's urbanization reaches completion, demand for construction steel therefore declines, and an increased share of steel comes from recycled sources. In addition, there are further opportunities to drive energy efficiency improvement while continuing to use existing blast furnace production technology. But to achieve zero-carbon emissions, China will also need to apply more radical decarbonization technologies to primary steel production.

Background: China's current steel production and consumption

China is the world's largest steel-producing and consuming country. Data from the World Steel Association shows 2015 production at 804 million tonnes and consumption at 672 million tonnes, accounting respectively for 48% and 45% of the global total. Exports in 2015 were 112 million tonnes and imports were 15 million tonnes, with net exports thus 97 million tonnes.

Urbanization and industrialization have driven rapid expansion of Chinese steel consumption. Almost

Building and infrastructure take the majority of China's steel consumption currently.

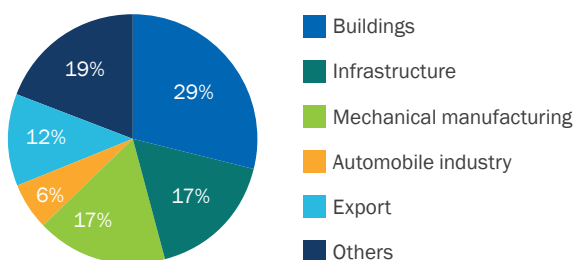


Exhibit 3-1. China's steel use in 2015

Source: China Iron and Steel Association; World Steel Association

half (48%) of steel is used either in buildings or in infrastructure, such as railways and highways. The auto industry accounts for the largest share of manufacturing use (see Exhibit 3-1).

China's production has increased in line with this growth of consumption, growing from only 66 million tonnes in 1990 (just 9% of the global total) to over 800 million tonnes today. Of this total, over 90% is primary steel production using the blast furnace (basic oxygen furnace, or BOF) production route. Electric arc furnace production (EAF) using scrap steel and electricity accounts for only 9% of production and is primarily used to produce high-end special steel products.

This low recycling share—against, for instance, the 60% EAF share within total US production—is typical of a country at the early stages of development, with steel stocks per capita still growing and limited supplies of scrap steel available relative to demand.

Consumption outlooks and the primary/secondary production balance

Fully developed economies typically reach a point where steel stocks per capita are stable at about 10 to 15 tonnes (see Exhibit 3-2). Despite rapid growth, China has not yet reached this level, with an estimated stock in 2019 of almost 8 tonnes per capita.

But at current production and consumption rates, China will reach typical developed country levels within 10–15 years. And as China's urbanization rate, currently about 60%, approaches the planned level of 70% by 2030, demand for construction steel for both property and new infrastructure is bound to decline.

Our modelling suggests that by 2050, China's total steel consumption could fall to around 475 million tonnes, in line with the International Energy Agency (IEA) estimate

China's steel stock per capita is around 7 tonne/capita now and will reach maturity in early 2030s.

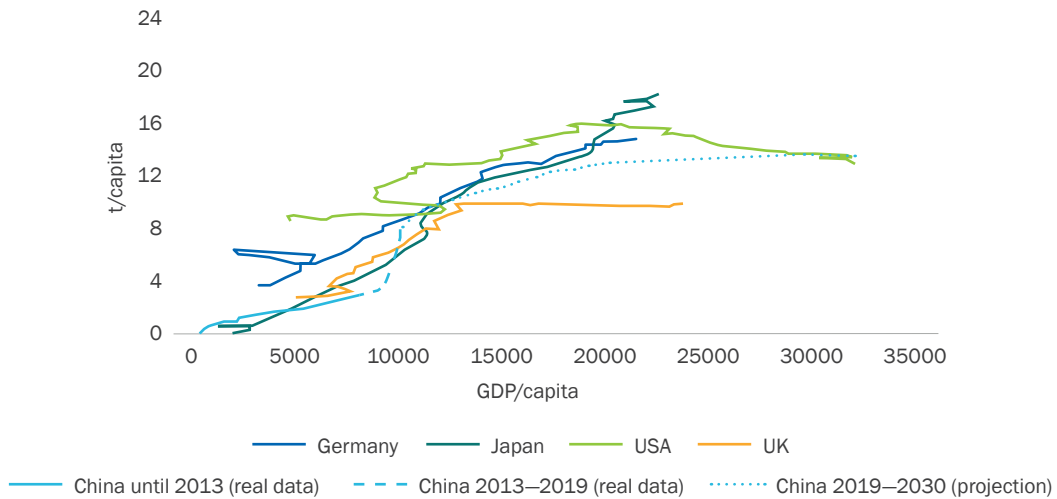


Exhibit 3-2. Steel stock per capita across countries

Source: Bleischwitz, R. et al. (2018) Extrapolation or saturation - Revisiting growth patterns, development stages and decoupling. *Global Environmental Change*. 48:86-96; Rocky Mountain Institute analysis for ETC China

in the 2°C Scenario (2DS). Moreover, an increasing proportion of steel could then come from recycling and EAF production; scrap supply is expected to grow at 10% per annum, and scrap prices will likely fall significantly as an increasing number of buildings, autos, and other equipment items reach end of life.

We estimate that by 2050, recycled steel could account for 60% of total Chinese production, and it is essential that public policies are designed to ensure maximum high-quality steel recycling.³ Primary steel production could therefore fall from 760 million tonnes today to about 190 million tonnes per annum by 2050.

However, some other estimates of China's total and primary steel production in 2050 suggest significantly higher figures. This reflects major uncertainties related to:

- How large China's direct steel exports will be. Our base case scenario assumes 2050 exports at about 70

million tonnes, will be in line with current level⁴, but it is possible that declining domestic demand will be offset by increasing exports to support infrastructure in investment and growth in developing countries;

- How large will be its indirect exports incorporated in manufactured products, and in particular whether China could become a major exporter of automobile, buses and trucks.

Given these uncertainties, we also consider the implication for energy demand (and either hydrogen or CCS capacity) of a scenario in which total China steel production in 2050 is 700 million tonnes, with primary production equal to 280 million tonnes. CCS demand also increase by 95 million tonnes if fossil fuel route takes up 50% of primary steel production.

In the next stage of the China ETC work we will explore the different scenarios in more detail and adjust our

3.The main challenges of steel recycling in China are the lack of an effective collection, sorting, and distribution system and the resulting high cost of scrap.

4.China's steel export in 2018 was 69 million tonnes.

projection as appropriate⁵.

Energy efficiency improvement

In 2015, China's steel industry consumed 18% of total coal consumption and 15% of total Chinese energy consumption (640 Mtce). The energy intensity of production was 573 kgce equivalent per tonne of steel produced.

China has already significantly improved energy efficiency of steel production, and the latest plans aim for a further intensity reduction to 560 kg of coal equivalent per tonne by 2020.

There are multiple further opportunities to improve energy efficiency toward best available practice. These could include capturing high-pressure gas leaving the furnace and using it to power other equipment, such as deploying

top pressure recovery turbines to blast furnace, or high-grade coke dry quenching. Other emerging technologies include Jet BOF, which could reduce electricity consumption by 60%, coke gas consumption by 37%, and coal consumption by 16% on average globally.

It is vital to continue to pursue energy efficiency improvement as aggressively as possible. But given the fairly high level of efficiency already achieved, further improvements are unlikely to reduce energy consumption and emissions per tonne of steel by more than about 15%–20%. To achieve net zero emissions, China will also need to apply radical new approaches to primary steel production.

Decarbonizing steel production

The increasing share of EAF production will automatically

Scrap recycling and DRI with zero-carbon electricity would help China's steel production reach decarbonization.

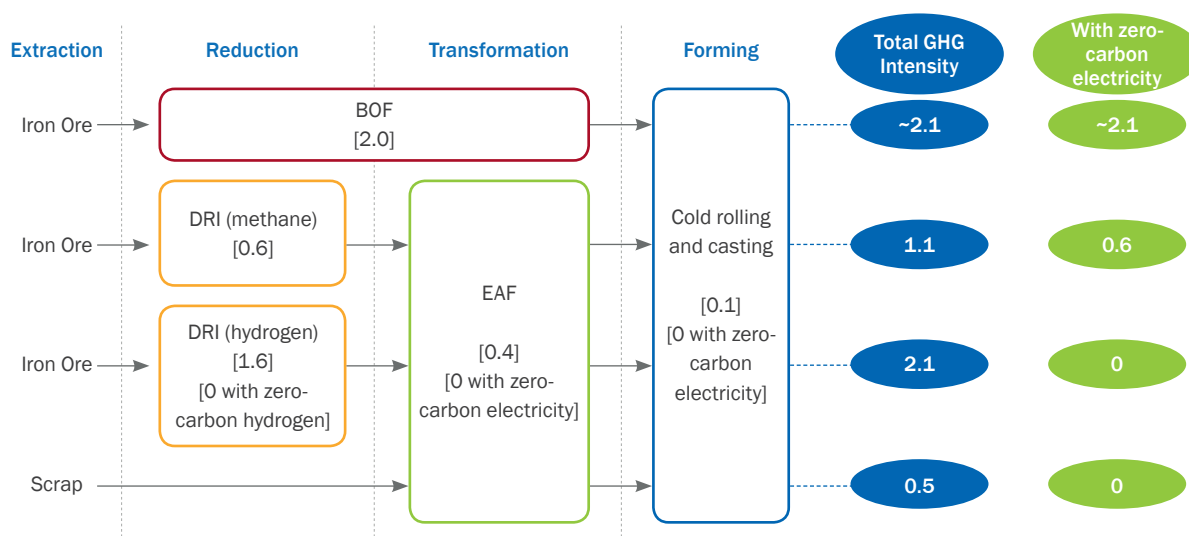


Exhibit 3-3. Greenhouse gas (GHG) intensity of main steel routes

Note: DRI is short for direct reduced iron.

Source: Rocky Mountain Institute analysis for ETC China

5. Some industry analysts also believe that China's starting point of steel production today may be higher than the 800 million tonnes figure used here (which is taken from World Steel Association statistics). This reflects observation of the significant upward revisions made to some past year estimates of total China steel production. In our next steps we will engage closely with leading Chinese iron and steel experts to ensure as robust an understanding as possible of the starting position.

reduce the average carbon intensity of steel production, given the much lower carbon intensity of EAF compared to blast furnace production. Even given the current carbon intensity of Chinese electricity (an average of about 596 grams of CO₂ per kWh), the carbon intensity of scrap-based EAF production route is about 0.5 tonnes of CO₂ per tonne of steel, compared with 2.1 tonnes for the BOF production route, and, as electricity is decarbonized, the carbon intensity of EAF production will decline toward zero (see Exhibit 3-3).

The most important policy to support decarbonization of Chinese steel is therefore the rapid expansion of zero-carbon electricity generation from renewable and nuclear sources. By 2050, under ETC's scenario, EAF production of 333 million tonnes of secondary steel could require about 160 TWh of zero-carbon electricity input.

It is also vital to develop an effective scrap recycling system through policy support and appropriate market design. Many researches have predicted that there would be 300-400 million tonnes domestic scrap supply per annum by 2050 in China, which would be sufficient for secondary steelmaking under our scenario. ^{(3),(4)}

In addition, however, China will need to decarbonize its remaining primary steel production. There are four main technology options:

Hydrogen-based direct reduction iron (DRI). This is a zero-carbon technology if the hydrogen itself is produced in a zero-carbon fashion, whether via electrolysis of water or by applying carbon capture and storage (CCS) to gas-based (steam methane reforming, SMR) or coal-based production. The Swedish steel company SSAB has begun construction of a pilot plant and plans to become a zero-carbon steel producer using hydrogen direct reduced iron (DRI) by the early 2040s, as also does the German steel company Salzgitter. ArcelorMittal is also considering this technology. In China, the biggest

steelmaking company, Baowu Steel, has started collaborations on hydrogen for steelmaking with China National Nuclear Corporation and Tsinghua University, and on low-carbon metallurgical innovation with Rio Tinto in 2019.

CCS. Carbon capture can be applied to the CO₂ produced by a blast furnace. Some steelmaking technologies such as HIsarna technology (which uses a powdered coal input, and recycles the concentrated top CO₂ gas), which Tata Steel is developing, could enable more efficient CCS application, with reduced energy use and more complete CO₂ capture. The feasibility of this route depends on the availability and location of carbon storage capacity.

Direct electrolysis. The direct use of electricity to reduce iron via electrolysis is also technically feasible and may become economically viable in the long term. A few steel makers, such as ArcelorMittal and Boston Metal, have begun to develop this technology to process raw iron ore.

Use of biomass. It is possible to use charcoal rather than coking coal as both the fuel source and reduction agent within a blast furnace. This technique is used in Brazil, where large timber resources have made it economic. It is only zero carbon, however, if the wood is produced from continually regenerated forests, and its feasibility depends on local supplies of biomass and alternative demands on that supply. In addition, it is technically possible for bioenergy to play a role in steel decarbonization in the form of waste, agricultural and forest residues and animal depositions to produce bio-coals, bio-fuels and bio-gases.

Relative costs and China's specific considerations

The relative costs of hydrogen DRI versus CCS depend

crucially on the price at which zero-carbon electricity is available to support the zero-carbon production of hydrogen. As Exhibit 3-4 shows, hydrogen DRI-EAF will be a cheaper route than greenfield BOF facilities equipped with CCS if zero-carbon electricity is available for below \$45 per MWh. In the brownfield case (i.e. where a plant already exists and must therefore either be replaced or retrofitted, electricity prices would have to be below \$25 per MWh to make the hydrogen route cheaper than CCS.

This suggests that CCS will likely be the cheaper route for brown field sites in the short term: and given China's large existing steel capacity, and our projection of gradual future demand decline, the brownfield case will often be the relevant one. But it is possible that in some locations China's excellent renewable electricity resource will make zero-carbon electricity available at less than \$25 per MWh well before 2050, as suggested in Chapter 7.

The relative cost position shown in Exhibit 3.4 reflects some important assumptions about future cost trends. In particular:

- The forecast for hydrogen cost which underlies Exhibit 3-4 assumes that hydrogen electrolysis equipment costs could be dramatically reduced over time – from

today's \$850 per kW to as low as \$200 per kW since susceptible to the economy of scale and learning curve effects often observed when equipment can be mass produced. Such a reduction would not only reduce the capital cost elements within hydrogen production cost but would make it economic to run electrolyzers for only a small proportion of the year and therefore to use cheap electricity which might otherwise be curtailed in a variable electricity system.

- Conversely our base case assumes that the costs of CCS will be less susceptible to dramatic cost reduction, since the plants are more likely to require somewhat bespoke engineering, with less potential for mass manufacture.

It is however possible that hydrogen costs might not fall so rapidly, and that CCS costs can be significantly reduced. If so, this would imply that the optimal path to zero carbon steel would entail a greater role for CCS and smaller role for hydrogen direct reduction than Exhibit 3.4 implies.

The biomass route is unlikely to play a major role in China given its more limited forest cover, and the other significant demands on biomass resources—for instance, from the aviation and chemical industry sectors.

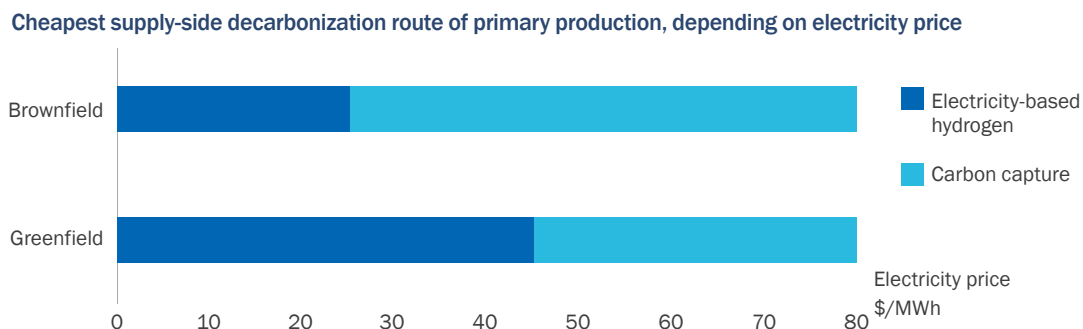


Exhibit 3-4. Cost of supply-side decarbonization route of steel production

Source: McKinsey & Company (2018). Decarbonization of the industrial sectors: the next frontier

The economics of direct electrolysis relative to CCS will also depend on the price of zero-carbon electricity.

If in 2050 China used hydrogen-based DRI to meet all the projected primary steel production of 190 million tonnes, this would require 675 TWh of zero carbon electricity. If all such primary steel production were made zero carbon by the application of CCS, CO₂ storage capacity of about 400 million tonnes per annum would be required. These figures would increase to about 1000TWh (for entirely hydrogen-based primary production) and about 600 million tonnes of CO₂ storage, (for an entirely CCS-based system) if primary production were as high as 280 million tonnes.

Our base case scenario presented in Chapter 6 reflects a 50/50 hydrogen/CCS split of 190 million tonnes of primary steel production, but China has enough renewable energy and carbon storage capacity to support decarbonization even if one technology dominates, and even if total production is in line with our higher alternative scenario.

Decarbonizing Cement

The cement industry in China was responsible for 1.2 gigatonnes of CO₂ emissions in 2017, roughly half the total from the world's cement sector. With already much higher levels of per-capita cement stock and consumption compared to its international counterparts, China is likely to see a decline in future cement production as its construction boom comes to an end. While China already compares well in terms of the energy efficiency of its cement production, there remain significant opportunities for further improvement. But to achieve full decarbonization, will require more fundamental change to decarbonize heat inputs, and to apply CCS/U to the process emissions which inevitably result from the chemical process of producing limestone-based cement.

Background: China's current cement production and consumption

China produces more cement than the rest of the world combined, accounting for 53% of world's total cement

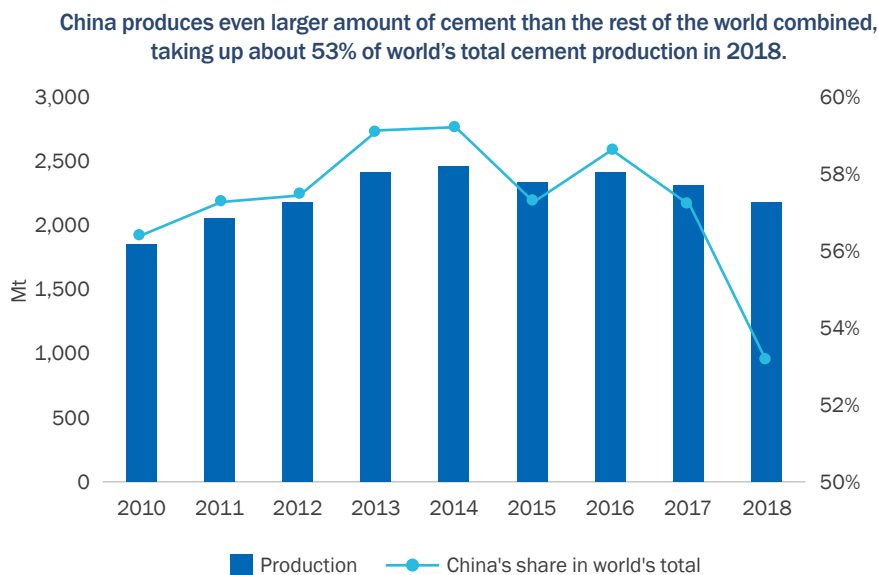


Exhibit 3-5. China's cement production from 2010 to 2018

Source: Data for China is from China Statistical Yearbook; Data for the world is from Statista database

production in 2018. After years of growth, China’s cement production reached its highest level of 2,480 million tonnes in 2014, and then decreased to reach 2,400 million tonnes in 2016, and 2,180 million tonnes in 2018 (see Exhibit 3-5).⁽⁵⁾ However this is still about 10 times the level of India,⁽⁶⁾ the second largest cement producers in the world. Due to the relatively high cost of transportation compared with its production cost, the import and export amount of cement is quite small. In 2018, China imported 14 million tonnes of cement, and exported just 5 million tonnes.⁽⁷⁾

Rapid urbanization and industrialization have been the main drivers of China’s construction boom, which in turn boosted domestic cement demand, with China’s cement consumption growing 33% from 2010 to 2014. Infrastructure and real estate are responsible for 55% of total demand (see Exhibit 3-6).

If China’s cement sector were assumed to be complete economy, it would rank as the third largest CO₂ emitter in the world. Not only is CO₂ produced from the fuel combustion to heat cement kilns to above 1,600°C, but the chemical reaction which turns limestone (CaCO₃) into Calcium Oxide (CaO) itself generates CO₂ emissions with these process emissions responsible for about 60% of total CO₂ emission. Apart from these two activities, a very small share of CO₂ emission comes from the electricity required to grind the feedstock and clinker.

Consumption outlooks and opportunities of higher resource efficiency

China’s per capita cement consumption peaked in 2014, at a level of 1.8 tonnes, far above the peak levels seen in other developed countries, which ranged from 0.4 tonnes per capita in the UK (in 1973) to 1.3 tonnes per capita in Korea (in 1997) (see Exhibit 3-7) . Looking forward, consumption per capita is certain to decline. China’s Ministry of Industry and Information Technology (MIIT) have come up with

guidelines to eliminate outdated cement production capacity, targeting at least 500 million tonnes of low-grade capacity to be phased out; and the IEA forecasts a decline in consumption from 2,400 million tonnes to 1,700 million tonnes in 2050 under its 2°C scenario.

Our analysis of China’s cement stock per capita, compared with the levels seen in fully developed rich economies, suggests that a still more dramatic fall in cement consumption and production is likely to occur. Developed economies typically have stocks of cement per capita no higher than 25 tonnes, but China had already reached that level by 2017 (see Exhibit 3-8). And even if annual consumption fell immediately to the IEA’s projected per capita level in 2050 (1.2 tonnes per capita) China would accumulate a stock of cement of 50 tonnes per capita in 2050, which no other country has ever come anywhere near.

Infrastructure and real estates were responsible for 55% of China's total cement demand.

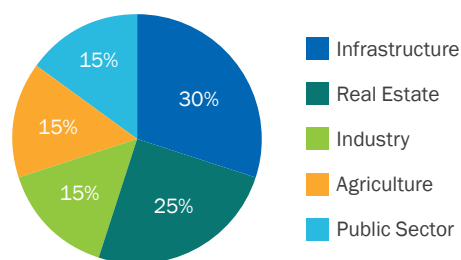


Exhibit 3-6. China's cement consumption by sector

Source: Public data from China Industrial Information webpage

Exhibit 3-7. Peak values of per-capita cement consumption across countries.

Country	Year	Peak value of per capita cement consumption (t)
China	2014	1.81
US	1974	0.41
UK	1973	0.40
Japan	1980	0.83
Korea	1997	1.28

Source: Dianqing Xu and Ying Liu (2018), Understanding China's Overcapacity.

Developed countries have seen cement stocks per capita no higher than 25 tonne, where China has already exceeded.

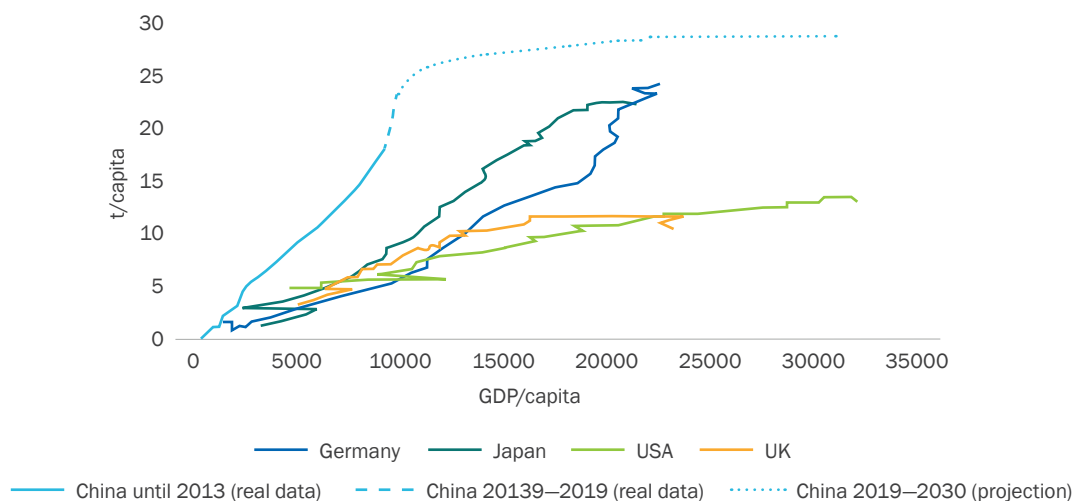


Exhibit 3-8. Cement stock per capita across countries

Source: Raimund Bleischwitz et al. (2018), “Extrapolation or Saturation—Revisiting Growth Patterns, Development Stages and Decoupling,” *Global Environmental Change*, 48: 86–96.

The waning of the construction boom will in itself lead to a significant fall in concrete and thus cement demand. In addition, demand could be reduced by:

- Increasing the lifetime of Chinese buildings, which currently have a notoriously short lifetime of only 25–30 years, compared to 80 years for US buildings, 85 years in France, and 130 years in the UK.⁽⁸⁾
- Reducing the extremely high unoccupied rate of buildings⁽⁹⁾ (20%–30%, compared to only 5%–10% in developed countries). Estimates suggest that better urban planning and management could reduce the required scale of construction by 20%.⁽¹⁰⁾
- Utilization of high-performance concrete to improve resource efficiency. Expert studies have suggested that by improving concrete strength, China could save up to 10%–40% of concrete, depending on different structures. With the proper mixture of materials like fly ash, steel slag powder, zeolite powder, silicon powder, further demand reduction of cement could also be achieved. In terms of

cost, high-performance concrete is actually even more attractive. For the same strength level, the cost per m³ of high-performance concrete is lower by \$4.7–\$8.4 than ordinary concrete.⁽¹¹⁾

- The use of alternative building materials, such as cross laminate timber (CLT) and other types of cement with a lower carbon footprint, which could be

While the IEA sees cement production falling to 1,700 Mt per annum in 2050, ETC projection suggests a fall to 800 Mt.

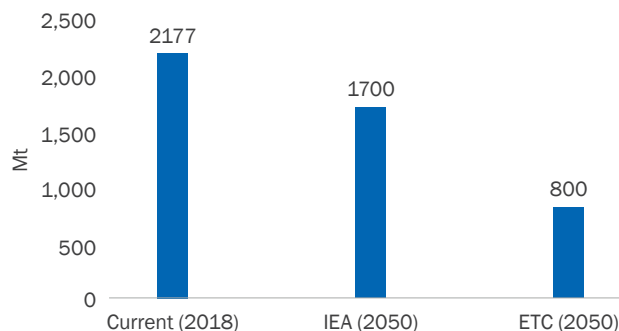


Exhibit 3-9. China's current and 2050 cement production

Source: China Statistical Yearbook; IEA (2017), *Energy Technology Perspectives*; Rocky Mountain Institute analysis for ETC China

China is already in good position as a pioneer of cement producer with high energy efficiency, with unit clinker heat consumption only ~85% of world's level and even further 13.6% reduction by 2050.

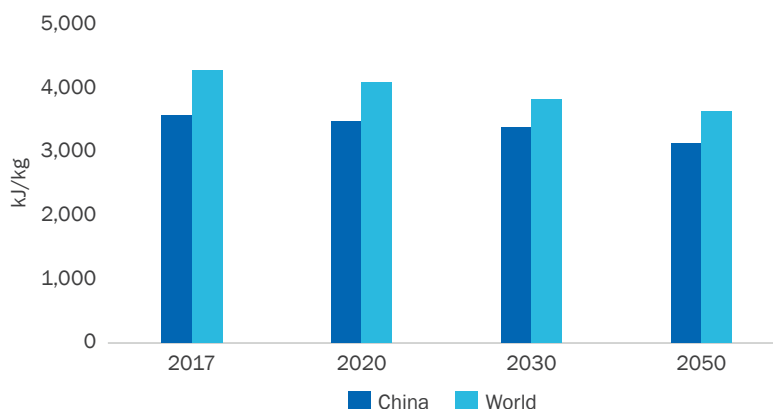


Exhibit 3-10. China and the world's thermal energy intensity of clinker for cement production

Source: Changming Gao (2019), World and China's Cement Industry Development Outlook

Also, China's unit cement general electricity demand is lower than world's level, with even further 16.7% reduction by 2050.

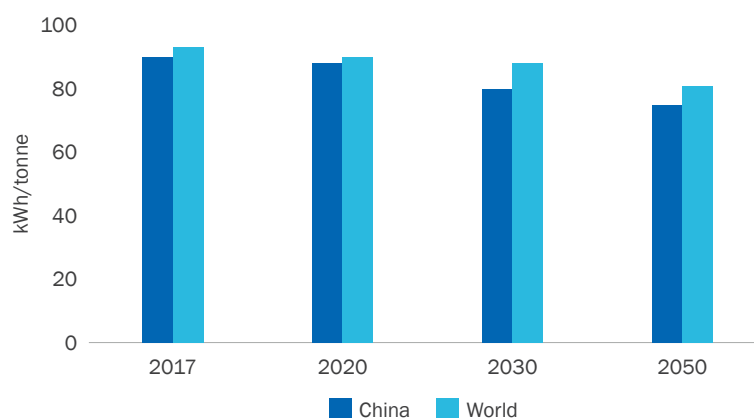


Exhibit 3-11. China and the world's electricity intensity of cement

Source: Changming Gao (2019), World and China's Cement Industry Development Outlook

encouraged by policies relating to building codes and material standards.

Taking all these factors into consideration, our projection suggests that China's cement production could decrease to 800 million tonnes in 2050 (see Exhibit 3-9).

Energy efficiency improvement

After 40 years of continuous technological innovation

efforts the energy efficiency of Chinese cement production compares well with other countries. Most cement plants are equipped with advanced dry kilns rather than energy-intensive wet ones. Currently, China's thermal energy intensity of clinker is 3,600 kJ/kg, about 15% below the world average level (see Exhibit 3-10). The electricity intensity is also lower at 90 kWh per t of cement produced (see Exhibit 3-11). Nevertheless, there is still an incremental possibility to increase energy efficiency by 13%–16% by 2050,⁽¹²⁾ as China has targeted.

One major area of potential lies in the use of waste heat to generate power. Already 80% of kilns in China use waste heat for power generation, with a total capacity of 4,950 MW, contributing to 35 TWh electricity recovered per annum. This prevents 2.6 million tonnes CO₂ emissions, nearly one-third of indirect emissions from the cement industry. The efficiency boundary can be pushed further. FLSmidth, an engineering company from Denmark, has demonstrated breakthroughs of 40 kWh electricity generation per tonne of clinker and China is aiming for 56–60 kWh/tonne clinker by 2050, twice as much as today's level, leading rest of the world. Even by 2035, China is targeting zero electricity demand from outside in clinker production. Mature business models (e.g., Design-Bid-Build, Engineering Procurement Construction, Build-Operate-Transfer) are already in place to make this happen.

Coprocessing with alternative energy rather than fossil fuel is another opportunity. Currently, thermal substitution rates (TSRs)⁶ for Germany and the Netherlands are as high as 70% and 90% respectively, and some major developed countries are now aiming for a 100% TSR. Despite a low TSR of 1.2% as a starting point, China is committed to realizing a 15% TSR by 2020, and researchers see 70% by 2050 as definitely achievable.⁽¹³⁾ China could even reach higher TSRs of 90%–100%, and parallel with strong players of the cement industry, with high TSRs of 90%–100%. However, it is important to note that if coprocessing uses an energy source that is itself originally derived from fossil fuels—such as waste tires, engine oil, or plastics—then this cannot be a route to true zero carbon.

Decarbonizing cement production

While energy efficiency improvements of the sort discussed above can somewhat reduce emissions, more radical changes in production method will be

needed to achieve full decarbonization. The options include using zero-carbon energy sources for heat input, applying CCS to both combustion and process emissions, and using alternative feedstocks other than limestone or clinker.

Zero-carbon energy source as a heat input. Replacing fossil fuels with biogas or biomass is already a mature technology, with only a modest retrofit of the kiln required. Hydrogen as fuel is also an option but would require redesign of the furnace and extensive retrofitting of existing sites. Direct electrification for heat input is also possible, and will become a zero carbon approach once electricity itself is fully decarbonized. However electric kilns for cement production are not yet commercially available, and significantly high capital cost will be required for their application.

CCS. As long as cement is made from limestone, CCS/U will be essential to capture the process emissions – which amount to around 330 kgCO₂/tonne of clinker for Portland cement). Applying carbon capture to the exhaust gases of cement kilns would capture the CO₂ emissions resulting from both fuel combustion and limestone calcination. Technologies can be applied which increase the concentration of CO₂ stream and as a result lower the capture cost. One good example is the innovative kiln design (known as LEILAC) that separates exhaust gas from fuel combustion (low in CO₂) from that of calcination (nearly pure CO₂). Oxy fuel combustion is another option. However, CCS can be used only at cement sites close to carbon-storage locations; in addition, however there may be options to use rather simply store the captured CO₂.

Alternative feedstocks. Using alternative minerals to replace limestone or clinker can help reduce CO₂ emissions from the chemical process. Substitutes like fly ash and slag are widely in use; however, with some

6.TSR is the substitution rate of thermal energy provided by alternative energy rather than fossil fuels.

Cheapest supply-side decarbonization route of primary production depending on electricity price

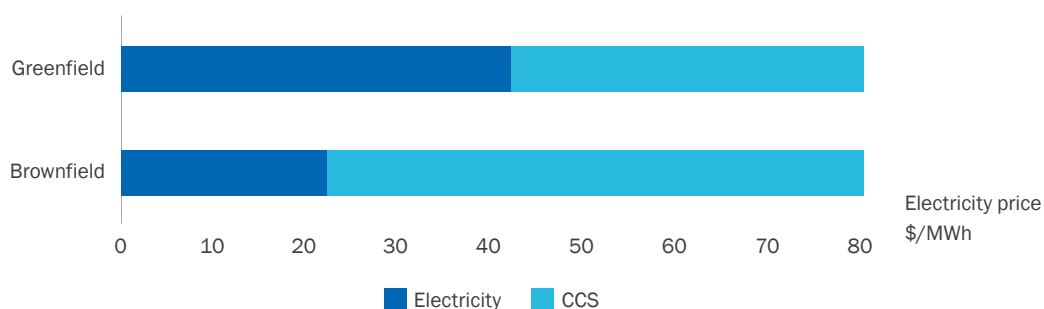


Exhibit 3-12. Cost of decarbonization route of cement production

Source: McKinsey & Company (2018), Decarbonization of the industrial sectors: the next frontier

steel production potentially moving out of the BOF route and the phase-out of coal power plants, there would be less fly ash and slag available. Other new cement chemistries, which use magnesium oxide and alkali/geopolymer binders, are promising but still being tested, and in some cases will be constrained by local mineral supplies.

Relative costs and China’s specific considerations

ETC’s global analysis by its knowledge partner McKinsey & Company suggests that using biomass for heat plus carbon capture of the CO₂ emissions will in many cases be the lowest-cost route to decarbonize cement production. However, if zero-carbon electricity were available below US\$22/MWh for a brownfield project or US\$42/MWh for greenfield, electrification for heat plus CCS for process emissions could be a better choice than applying CCS to capture emissions both from heat and process (see Exhibit 3-12).

Given the large number of existing cement plants in China, and the projected fall in future demand, the “brownfield” case will usually be the more relevant one in China. But in the long run, China’s excellent renewable energy resource may make zero-carbon electricity

available in some locations at below US\$22/MWh.

For China, using biomass as fuel for cement production is currently the most probable route towards decarbonization since it is not only likely to be the most cost-effective in the short term, but also has the most policy support. In 2016, led by China’s Ministry of Industry and Information Technology, six ministries jointly announced that they were piloting coprocessing cement with municipal waste as fuel. This also contributes to dealing with China’s municipal waste, which grows by 8%–10% annually.

However, the use of biomass is subject to resource scarcity and local availability. Moreover, there are other significant sectors which may need to use bioenergy in order to decarbonize (in particular aviation) limiting the supply of sustainable biomass available to the cement industry. Other solutions will therefore also need to play a role.

Our analysis of CO₂ storage capacity, set out later in Chapter 9, shows that there is sufficient storage capacity to meet the need for carbon emission capture and storage. The full value chain CCS cost for cement industry ranges between \$40 and \$100 per tonne of CO₂ at 90% capture rate.⁽¹⁴⁾

Decarbonizing Chemicals

China's chemicals and petrochemicals sector accounts for 28% of industrial energy consumption in 2016,⁽¹⁵⁾ and the IEA's 2DS scenario still expects it to account for 23% in 2050.⁽¹⁶⁾ For this sector, there are significant opportunities to reduce demand for virgin materials below business as usual levels via improved materials efficiency and greater reuse or recycling of materials in a more "circular" economy. But achieving full decarbonization will also require the adoption of zero-carbon production routes.

Given the major role which coal currently plays as an energy source and feedstock within China's chemical industry, coal-based routes would still play a significant role in 2050: but our projections suggest a much smaller one than existing plans assume, and it is essential that CCS is applied to all coal-based production. Emerging routes to decarbonization such as power-to-X and biomass-based routes also need to be developed to play significant role.

Background: Current status of China's chemicals sector

Products from the chemicals sector are everywhere and are integral to modern societies. As a result, this sector has become one of the most rapidly growing sources of energy consumption throughout the entire economy. In 2016, the chemicals sector was responsible for 28% of industrial energy consumption in China, and the IEA still expects 23% in 2050 under its 2DS scenario.

There are thousands of products in the chemicals sector, but three groups of primary chemicals — ammonia, methanol, and High Value Chemicals (HVCs, which includes light olefins and aromatics) — account for about three-quarters of the sector's total final energy consumption.⁽¹⁷⁾ These primary chemicals provide key

China starts with a chemical industry which is far more dependent on coal than typical elsewhere.

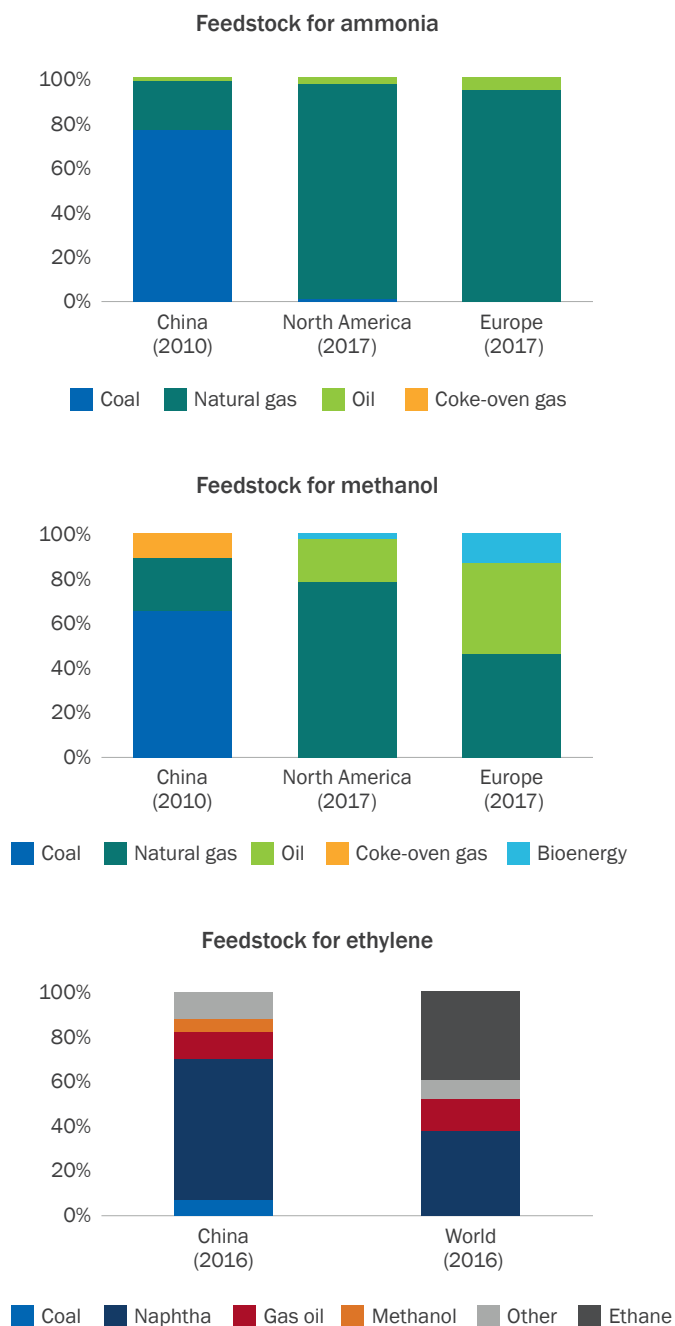


Exhibit 3-13. Comparison of major chemical feedstocks between China and the rest of the world

Source: Data from National Institute of Clean-and-Low-Carbon Energy; IEA (2019), The Future of Petrochemicals

China currently uses 45 kg of plastics per person per year, which would possibly increase to a level of 100 kg, making total plastic consumption of 135 Mt.

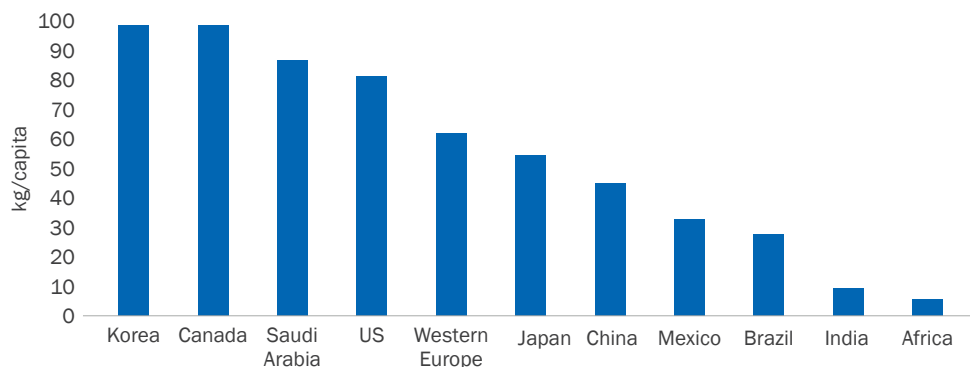


Exhibit 3-14. Per capita demand for major plastics in 2015

Source: IEA (2019), The Future of Petrochemicals

building blocks that support the production of multiple end products.

China is the world's largest ammonia producer, with 49 million tonnes of ammonia produced in 2017, most of which was converted to fertilizer. After the increasing trend at a yearly growth rate of 2.4% from 2010 and the peak of 49.8 million tonnes in 2015, China's fertilizer consumption fell slightly to 47.8 million tonnes in 2016. This domestic use takes up the majority of production. Even with excess capacity, China's ammonia export amount is only around thousand tonnes, and imports are of the magnitude of 10 thousand tonnes, which are quite small compared to the production.

Plastics are a key driver of demand for methanol and HVCs. Methanol is a major intermediate input into the production of HVCs, which are reactive compounds in turn used to produce polymers to manufacture plastics. In most of the world HVCs are primarily produced by applying catalytic cracking and reforming to ethane or naphtha inputs, but in China, while naphtha is the main feedstock now, the methanol-to-olefins (MTO) and methanol-to-aromatics (MTA) processes are starting to play a more and more important role, given its increasing cost-competitiveness and China's concern

on energy security. For ammonia and methanol, unlike other parts of the world, coal is already the dominating feedstock: this reflects China's abundant and cheap coal resources and the resulting use of coal as feedstock input (Exhibit 3-13).

In 2017, China's plastic production reached 75 million tonnes, making up more than a quarter of the global total. Consumption is 53 million tonnes per annum, reflecting a current per capita use of 45 kg of plastics per year. If this increased to the 100 kg per capita seen in some developed countries (see Exhibit 3-14), China's total plastic consumption would reach 135 million tonnes.⁽¹⁸⁾

Consumption outlooks and opportunities of higher efficiency and circularity

Higher fertilizer use efficiency and demand reduction of ammonia

By 2050 ammonia may be used in significant new applications (in particular in the shipping industry – see Chapter 4), but its most important use will still be in fertilizer. As China's population first stabilises and then slowly declines, China's domestic fertilizer consumption will tend to flatten, but in addition China's currently high

China's fertilizer average application rate is among highest in the world, twice as high as developed countries.

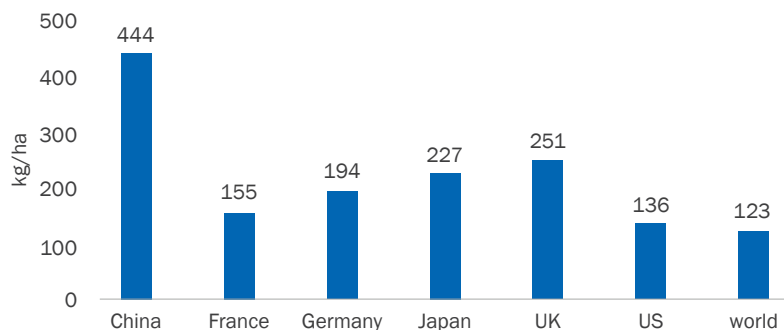


Exhibit 3-15. Fertilizer average application rates of China and major developed countries (2016)

Source: Data Food and Agriculture Organization of the United Nations

average fertilizer application rate indicates large room for fertilizer demand reduction.

In 2016, China's fertilizer use per unit area of arable land was 444 kg/ha,⁽¹⁹⁾ which was among the highest in the world, and about twice the level of major developed countries (see Exhibit 3-15). In 2017, the fertilizer efficiency in China was only 35%, as a result of notorious overuse of fertilizer, compared to 52% in the United States and 68% in Europe.⁽²⁰⁾ As a result, China consumes over 30% of global fertilizer while accounting for only 7% of global arable land.

There is therefore a major opportunity to improve China's fertilizer use efficiency. Some studies suggest that fertiliser use could be reduced by 30%–50% without reducing crop yields⁽²¹⁾: another study⁽²²⁾ has argued that even if China's nitrogen use efficiency (NUE) will not fully reach the United States level due to the unique crop mix and suboptimal farming practices, China can still double its NUE compared with today. Indeed, China has already implemented a series of policies to encourage efficient use of fertilizers, including the Action Plan for Zero Increase of Fertilizer Use launched in 2015.

Reflecting these factors, our projection assumes that:

- Under a BAU scenario, Chinese fertilizer consumption would increase by 1% per annum from 48 million tonnes in 2016 to reach 57 million tonnes per annum in 2050;
- But with higher efficiency, this could be cut by 20 million tonnes, a reduction of over one third;
- This in turn would mean that ammonia production would be cut from a BAU level of 67 million tonnes to 43 million tonnes (see Exhibit 3-16).

Greater circularity of plastics and demand reduction of HVCs and methanol

The way that plastics are used, recycled, and dealt has a major impact on the need for primary plastics production. Analysis by Material Economics for the global ETC⁽²³⁾ indicated that in Europe a combination of reuse and recycling could provide 62% of the plastics demand by 2050, cutting CO₂ emissions by half. For the EU, this would reduce the annual plastics demand by 13 million tonnes by 2050.⁽²⁴⁾ The IEA suggested a similar 43% global recycling rate in its Clean Technology Scenario (CTS)⁽²⁵⁾; compared with the 2050 BAU figure this would

7. Calculated as the nitrogen output divided by sum of nitrogen inputs.

Greater fertilizer use efficiency and plastics circularity would dramatically drive demand reduction by 35% for ammonia, 38% for HVCs and 18% reduction for methanol, compared to what IEA RTS scenario suggested.

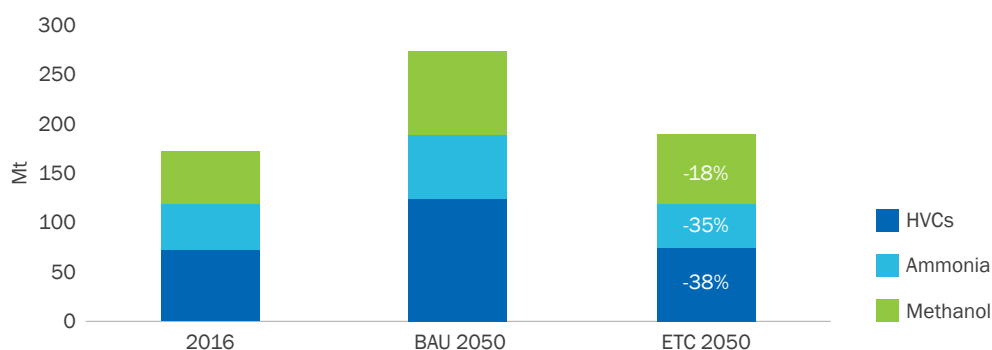


Exhibit 3-16. Production of primary chemicals in China

Source: IEA (2019), *The Future of Petrochemicals*; Rocky Mountain Institute analysis for ETC China

imply a doubling of secondary plastic production from recycled resins, resulting in a 70 million tonnes reduction in the need for primary chemical production.

At present, China’s plastics collection rate is close to 50%, but due to large losses in the recycling process, the overall recycling rate is still very low. By 2050 however, and indeed well before, plastics recycling could reach and exceed the levels observed in the best practice developed countries today. Our model assumes that 52% of plastics used in China in 2050 could come from recycled plastics. As a result, primary plastics production would be 65 million tonnes, which is 45% lower than it would be if the recycling rate stayed the same as in the IEA’s RTS scenario. This would in turn reduce HVC demand by 38% and methanol demand by 18%, compared to the IEA RTS scenario (see Exhibit 3-16).

Plastics can be recycled in a “mechanical” or a “chemical” fashion, with the latter requiring significant energy inputs.⁸ As a result, Material Economics’ analysis suggests that plastics recycling is financially challenging today but can be made economically attractive.⁽²⁶⁾ Costs can be reduced by 16% through cleaner flows of materials and product

design, increased production scale, specialization of markets, and technological improvement. Meanwhile, a 71% increase in revenues could be achieved given higher product quality and increased yields.

To achieve this more circular plastics system, policy action is required to raise the cost of virgin material inputs and to establish standards and regulations which require maximum feasible collection and recycling.

Energy efficiency improvement

Aiming at reaching the world’s advanced level by the end of 2020, China has made continuous improvement in energy efficiency in chemicals production. In 2018, the energy intensity per unit of GDP of China’s chemicals and petrochemicals sector fell by 10%,⁽²⁷⁾ with most major products consuming less energy in their production processes.

Some pilot projects in China have already equalled or even outpaced their international counterparts in terms of energy efficiency. For example, energy intensity of 31 GJ/tonne is now achievable for China’s ammonia production,

8. Our model of total required energy supply presented in Chapter 6 does not yet reflect these energy input needs for chemical recycling, which we will investigate in more detail in the next stage of our analysis.

and 33 GJ/tonne for methanol and 22 GJ/tonne for ethylene. However, with a highly uneven level of energy efficiency throughout the industry, there is still be much room for improvement.

At the global level, analysis by ETC's knowledge partner, McKinsey & Company, suggests that further energy efficiency improvements in monomer production (a key input to plastics) could reach 15%–20%;⁽²⁸⁾ and while the energy use per tonne of ammonia has decreased by 30% over the past three decades, adopting the best available technology could still deliver a further reduction of 20%–25%.⁽²⁹⁾ Continuing improvements in energy efficiency therefore remain a key priority.

Decarbonizing chemicals production

Even ambitious efficiency improvement and recycling as described above cannot eliminate all CO₂ emissions. To fully decarbonize, new production routes for chemicals must therefore also be put in place, eliminating or capturing both the CO₂ which results from the use of fossil fuel chemical feedstocks and those which result from energy use in production.

One way is to achieve this is to rely on electricity, hydrogen, and biomass as the major energy or feedstock inputs. But in China in particular, there should also be an important role for CCS, both on production and on plastics waste incineration, given that China probably continue to use coal as significant feedstock and energy source.

Fossil fuel-based routes with CCU/S. China starts with a chemicals industry that is far more dependent on coal than is typical elsewhere, and our scenario for energy demand assumes that coal will continue to play a significant role in chemicals production. It will therefore be essential for China to use CCU/S to capture use and

either store or use the CO₂ emission which coal based chemicals production will inevitably generate.

The economics of applying CCU/S to coal based chemical production, may be favourable because of the relatively high purity of the CO₂ streams produced (70%–98%), which are higher than in some other industrial processes. Existing pilot CCU/S examples include the Shenhua Ordos CCU/S project, which is reported to achieve 51 million m³ CO₂ reduction annually, and the Xinjiang Qinghua coal-to-gas project, which uses CO₂ to provide pressure in production⁹. However, it should be noted that the coal-to-gas project itself is actually carbon-intensive and does not fit in with a zero-carbon future.

CO₂ captured from chemical production processes (whether based on coal or on ethane or naphtha) could be either stored or in turn used as an input to produce non fuel products: provided these are in turn either recycled or combusted but with CCS applied, the total system can be zero carbon.

Power-to-X routes. The chemical industry is based on transformation processes, with hydrogen and carbon as building elements. Reactions with mixtures of hydrogen, CO, and CO₂ can build up all major chemicals in the value chain. “Power-to-X” production routes use hydrogen from zero-carbon electricity and CO₂ as feedstocks. CO₂ from flue gas, industrial process, or carbon capture sources can be utilized as a reactant.

For ammonia production, zero-carbon hydrogen can be made from electrolysis of water if the electricity in turn comes from zero carbon sources, and can then be used in the Haber-Bosch process, in which hydrogen and nitrogen are synthesized. Calculations by DECHEMA⁽³⁰⁾ indicate electricity demand of 9.1 MWh for the 178 kg of hydrogen required per tonne of ammonia. Also, an additional 1.4

9. Coal-to-gas process produces more carbon emissions than burning coal directly and therefore is not endorsed by ETC.

MWh is estimated for compressors as well as 0.33 MWh required by other utilities per tonne of ammonia.

For methanol, catalysts are already commercially available for hydrogenation of CO₂ as a carbon source, and a number of pilot plants are in operation. Carbon Recycling International is an Iceland-based plant currently producing 4,000 tonnes of zero-carbon methanol per year, with a planned expansion to 40,000 tonnes. The CO₂ feedstock comes from a geothermal power plant, and the 5 MW water electrolysis for hydrogen is also powered by geothermal. Mitsui Chemicals (Japan) also has a pilot plant for synthesizing methanol from hydrogen and CO₂ and has investigated the feasibility of industrial-scale production.

For HVCs production, although there is no existing process at high TRL (Technology Readiness Level) which directly turns hydrogen and CO₂ into olefins and BTX (benzene, toluene and xylenes), there are commercial operations which use methanol as feedstock – known as MTO (methanol-to-olefins) or MTP (methanol-to-propylene) and MTA (methanol-to-aromatics). The methanol feedstock here refers to that described above from zero-carbon hydrogen and CO₂. Energy consumption of MTO/MTP

plants with best practicable technology is 5 GJ/tonne product, and a similar level for MTA; China could achieve these best practicable technology levels well before 2050.

Biomass-based routes. Another route to achieve zero-carbon production is to use biomass as a feedstock, and zero-carbon sources to provide process energy. Anaerobic digestion and gasification are two options to produce conventional plastics from biomass. A Chinese company in Ningbo, Zhejiang province, has developed a corn-made plastic that can be further made into tableware, toys, packages, and so on. Annual production has reached 1,000 tonnes, and products are exported to US and EU markets. Hainan Province has announced a policy to ban the production, consumption, and use of nondegradable plastic products by 2025. Government, companies, and academia are working together with the focus on starch and cellulose conversion, bio-based polymer materials, and so on. However, given the constraints on the supply of sustainable biomass in China which we discuss in Chapter 9, it would not be safe to assume that China could base a large share of its plastics production on biomass. Also, the process energy requirement of bio-based production routes is much higher than conventional fossil fuel routes.

Hydrogen could serve as major feedstocks (52%) while electricity (35%) and hydrogen (40%) are the main source of process energy for China's chemicals sector in 2050.

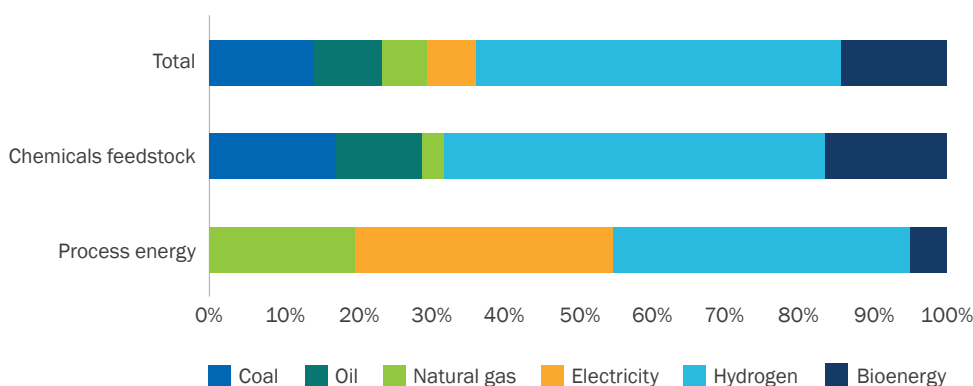


Exhibit 3-17. Energy carrier portfolio for China's chemicals sector in 2050

Source: Rocky Mountain Institute analysis for ETC China

Relative costs and China's specific considerations

For primary chemicals, costs of materials usually represent 60%–70% of total production costs.⁽³¹⁾ The ETC's global analysis indicated that electrification of the heat input to monomer production for plastics could be cheaper than CCS if electricity costs are less than US\$25/MWh for a greenfield plant and US\$15/MWh for brownfield.⁽³²⁾ Using biodiesel as a feedstock would be at a very high cost of US\$1,000 per tonne of CO₂ saved if calculated based on production emissions only, but would represent a much lower cost of US\$200 if end-of-life emissions were also considered.

However, it should be noted that the actual costs of bio-based plants are very much related to plant setups, capacity scale, and local situations; as a result, the low-end and high-end costs of the same route can differ by as much as 5 times.

Generally speaking, the costs of the new routes (such as power-to-X and biomass-based options) would be higher

than conventional ones; extensive policy support will therefore be needed to bring them to scale. With no time to lose before 2050, the new business case needs to span the entire value chain, from product design to end-of-life disposal.

In the Chinese context, unless power-to-X and biomass-based routes enjoy obvious economic advantages (resulting for instance from very cheap electricity or biomass supplies in specific circumstances), coal-based routes would still dominate for many years. "Clean" use of coal in the chemical industry is indeed already an official strategic policy, with projections assuming very significant scale up.

However, our analysis suggests that the scale of the coal chemical industry would need to be much smaller than existing plans assume, not only for carbon emission related reasons but also due to water and air quality concerns. Out of the seven provinces (Shanxi, Henan, Shaanxi, Inner Mongolia, Xinjiang, Qinghai, and Ningxia) where the coal chemical industry is under development, six are caught with water shortage or even severe water

China's chemicals sector would be responsible for 40% of total coal consumption in 2050, distinguishing itself as even more challenging in controlling coal use than the power sector.

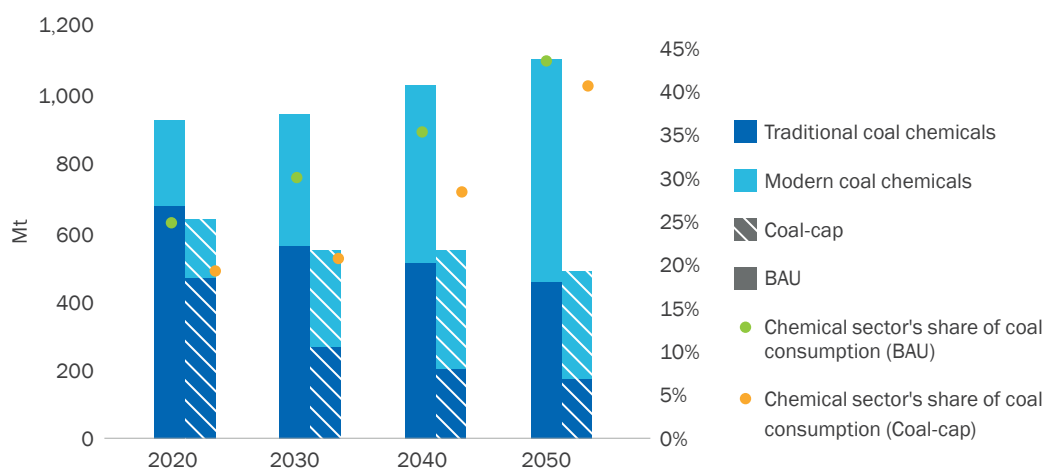


Exhibit 3-18. Coal consumption by China's chemicals sector

Source: Natural Resources Defense Council

shortage. Also, all seven provinces with a coal chemical industry fail to reach air quality standards.

Analysis by the Natural Resources Defense Council⁽³³⁾ indicated that even under a coal-cap scenario in which a series of measures is taken to control coal use, coal consumption by the coal chemical industry in 2050, while reduced by 56% of 1,091 million tonnes than BAU, would still be as high as 482 million tonnes. Our own assumption set out in Chapter 6, total coal consumption of Chinese economy could reduce to 145 million tonnes. It might be even more challenging to keep coal use under control in the chemical sector than in the power sector, and this would be an extended task rather than a short-term practice.



CHAPTER 4
DECARBONIZING
TRANSPORT

In 2014, transport accounted for 17.2% of Chinese energy demand and 8.5% of total emissions (870 million tonnes of CO₂), but per capita travel stayed well below developed economy levels. Given current demand growth trends and using existing technologies, transport emissions could grow to over 3.3 billion tonnes by 2050, and could then account for 30% of China's total emissions. It is quite possible, however, for China to meet rapidly growing demand for transport services while also achieving zero emissions by 2050. This will require total electrification of surface transport, which China is well-placed to achieve earlier than any other major country. In aviation and shipping, achieving zero-carbon emissions will require a combination of electrification for short distances and the use of new zero-carbon fuels for longer-distance travel.

Background – China's current transport activity level and energy consumption

Over the last 40 years, China has invested heavily in transport infrastructure construction. A major cross-country highway network has been constructed, whose total mileage surpassed the United States in 2014 and reached 143,000 km in 2018. Per-thousand-capita

highway mileage of 0.1 km, however, is still only 33% of that in the United States.⁽³⁴⁾ Passenger vehicle sales have also soared, with annual sales now higher than in the United States, and a total vehicle stock of over 240 million (of which 220 million are passenger cars) in 2018.⁽³⁵⁾

The growth of the rail network has made China the clear world leader in high-speed rail.⁽³⁶⁾ Data from the China Railroad Bureau shows that in 2018, the commercial railroad mileage surpassed 130,000 km, within which 29,000 km is high-speed rail. There has also been very large investments in urban subway systems. In 2018, China's total subway length reached 5,700 km, leading Germany by 2,600 km to be the world leader.⁽³⁷⁾

As a result, China's passenger and freight volume has experienced tremendous growth. Exhibit 4-1 and 4-2 show the official figures for each of the different transport modes in 1978, 2000 and 2018: passenger travel is measured in passenger km and freight in tonne km. These show an incomplete picture of the growth since they exclude private autos and some urban bus services, But even on this incomplete basis, the passenger km have increased by 17.6 times and freight tonne-km by 18 times since 1978.⁽³⁸⁾

Exhibit 4-1 China Passenger Volume by Modes in 1978, 2000 and 2018 (Bn Passenger-km)

Year	1978	2000	2018
Road ¹⁰	55	616	927
Rail	115	395	1415
Domestic Aviation	1.9	41	789
International Aviation	0.1	41	282
Shipping	12	11	8
Total	184	1104	3421

Source: Year 1978 and 2000 data are from China Energy Research Institute, LBNL, RMI. (2017). Reinventing Fire: China; Year 2018 data are from China Ministry of Transport. (2019). Statistical Communique of China's Transport Development in 2018.

Exhibit 4-2 China Freight Volume by Modes in 1978, 2000 and 2018 (Bn Tonne-km)

Year	1978	2000	2018
Road	50	627	7125
Rail	574	1303	2882
Aviation	0	5	27
Shipping	425	2263	9905
Total	1049	4198	19939

Source: Year 1978 and 2000 data are from China Energy Research Institute, LBNL, RMI. (2017). Reinventing Fire:China; Year 2018 data are from China Ministry of Transport. (2019). Statistical Communique of China's Transport Development in 2018.

10.All passenger activity level (passenger-km) in official statistics books are not including private cars.

China's vehicle ownership and road travel distance per capita are much lower than developed countries.

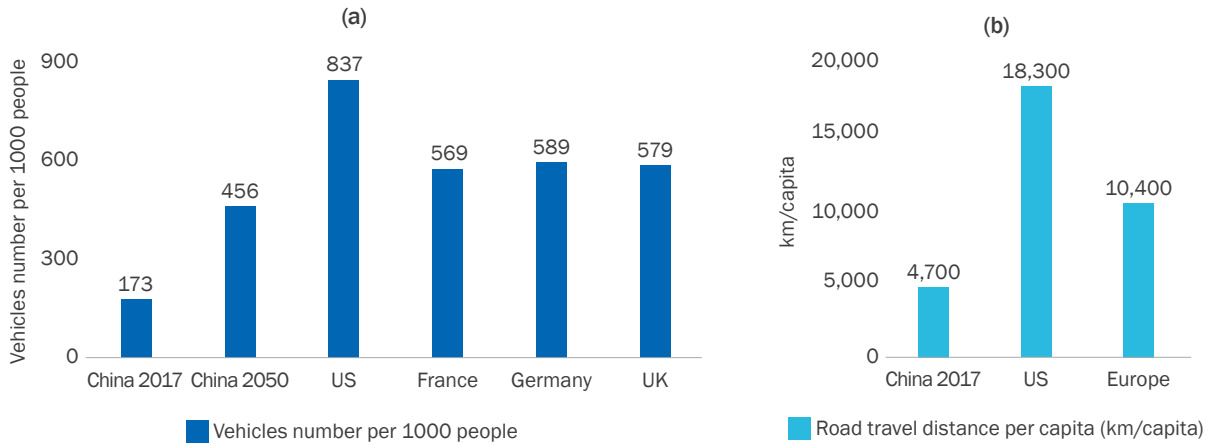


Exhibit 4-3. Vehicles number per 1000 people, road travel distance per capita (km/capita)

Source: World Bank, Autohome.com

Despite this growth, China's per capita use of transport services is still much lower than in fully developed rich economies. Vehicle ownership (including all vehicle types) stands at 170 per 1,000 people versus about 840 in the United States, and 500 to 600 in European countries (see Exhibit 4-3 (a)). Road passenger km per person is about 4,700 km⁽³⁹⁾ versus 18,300 km in the United States and 10,400 km in Europe (see Exhibit 4-3 (b)).⁽⁴⁰⁾ And despite significant growth in outbound tourism, flight km per capita stands at 770 km versus 1,330 km in Europe and 3,400 km in the United States.⁽⁴¹⁾

Freight volumes per capita, however, are more comparable with other rich countries, reflecting China's major manufacturing role. China's road freight tonne-km per capita reaches 5,100 tonne-km compared with 9,000 tonne-km in the United States and 3,900 tonne-km in Europe;⁽⁴²⁾ and shipping freight tonne-km per capita for China is 7,100 tonne-km, whereas the number is 2,300 tonne-km in Europe (see Exhibit 4-4).

As in all countries, the vast majority (98%) of all current road transport is powered by internal combustion engines, and aviation is powered almost exclusively by fossil fuel-

based jet fuel and shipping by heavy fuel oil. But forceful government policies have already made China a leader in new energy vehicles. In 2018, 984,000 electric vehicles (EVs) were sold in China⁽⁴³⁾, accounting for about 50% of global total EV sales.⁽⁴⁴⁾ Specifically, China contributed 99% of the sales of global electric buses and more than 90% of the sales of electric urban delivery trucks.⁽⁴⁵⁾

China's e Energy Saving and New Energy Vehicles Industry Development Plan sets a clear target of 5 million total cumulative sales of new energy vehicles (NEVs) by 2020. To support such a target, both national and local governments have set up comprehensive subsidy and road right preference policies to accelerate the adoption of NEVs, which as a result increased the EV stock to 2.1 million by the end of 2018.⁽⁴⁶⁾

Demand outlooks and opportunities to moderate demand growth

As China develops to become a fully developed rich economy, its per capita use of transport services is bound to increase significantly. But China's leadership position in high-speed rail and subway systems, and its ability to

China's freight volumes per capita are more comparable with developed countries.

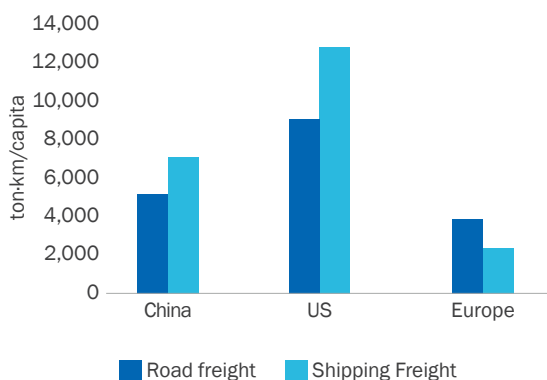


Figure 4-4. Freight activity per capita across countries

Source: China Ministry of Public Security

Under ETC analysis, road and rail will respectively take 50% and 40% of total passenger activity by 2050.

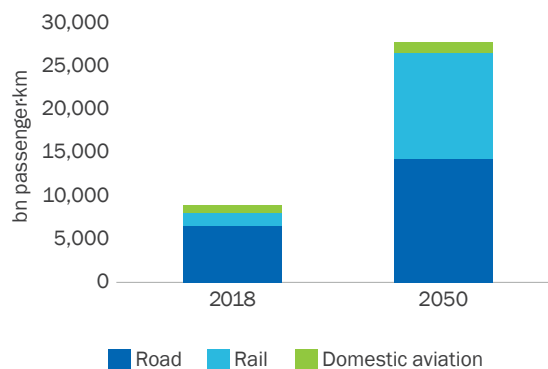


Exhibit 4-5. China total domestic passenger activity level 2018 and 2050

Source: Rocky Mountain Institute analysis for ETC China

implement optimal urban planning, could enable it to deliver rich country standards of mobility services with significantly less road transport and domestic aviation transport than seen in today's rich countries.

Exhibit 4-5 sets our forecast for the growth of total domestic passenger traffic between now and 2050, with passenger km travelled by either road, rail or domestic aviation increasing by 3 times from 9 trillion to 28 trillion passenger km. Within this total rail is likely to take a higher percentage than in many other developed economies. The total increase represents growth in line with real GDP.

Passenger traffic – road and rail

Compared with road aviation, rail is an inherently energy efficient mode of transport, and China's heavy investments in both high-speed rail and subway systems will therefore help to reduce China's total transportation energy need.

From 29,000 km today, the high speed rail network is targeted to grow to 30,000 km by 2025 and 45,000 km by 2030, and travelling by high speed rail is likely to be more convenient than air travel for all distances

shorter than 1,000 km. Continued investment in subway systems will also ensure that much inner-city travel in major cities is done by rail. Overall we assume that subway travel will account for 20% of China's total urban passenger transport activity in 2050, and that in total rail will account 40% of total passenger activity, with 12 trillion passenger km travelled by rail.⁽⁴⁷⁾

This expanded road for rail will be partly at the expense of domestic aviation which is considered in the aviation section below. But it will also help to moderate the growth of total road transport. Our model therefore assumes that China's vehicle number per 1000 people in 2050, at about 460 will still fall slightly short of current European figures of around 550, and will be far behind the US's current figure of around 840.⁽⁴⁸⁾

However this still significant growth of vehicle ownership will drive major growth in total road passenger volumes. Smart city planning, coordinated industrialization and urbanization, and ICT could help to limit annual vehicle mileage to 12,000 km versus 22,000 in the US today, but road passenger traffic would still increase by 120% to reach 14 trillion passenger-km.

Freight traffic: road and rail

On the freight side, rail and intermodal freight is already supported by national and local government (e.g through the Three-Year Action Plan for Winning the Blue Sky Protection) and rail freight will in many cases be more economic than road freight. Thus, our model assumes that rail will take up 25% of the total freight activity by 2050 (Exhibit 4-6).⁽⁴⁹⁾

This growth in rail freight will help moderate the growth in road freight, but economic growth would still drive a 3-time increase in total road freight volume from 7 trillion tonne-km today to 29 trillion tonne-km 2050.

Aviation: domestic and international

As in all countries, aviation in China is dominated by passenger travel, with domestic passenger travel of 570 km per capita in 2018 and international travel still at a low level of 340 km per capita (Exhibit 4-7). As incomes per capita grow, and people have more money to spend on leisure and travel, passenger flights for leisure

purposes will grow significantly and business travel will also tend to increase. China has recently been investing heavily on airports and related infrastructure (at a pace of about 70–80 billion RMB per annum) and there has been approximately 12% growth in both passenger aviation volume and the number of airline routes.⁽⁵¹⁾

On the domestic side, however, the very extensive high speed rail network will provide an attractive alternative for travel of up to 1,000 km. As a result, we estimate that China’s domestic per capita aviation will always stay far below today’s US level of about 3,600 km per person, with an estimated Chinese figure of about 860km per person in 2050. (see Exhibit 4-7) Total domestic passenger travel would therefore reach about 1,200 billion km.

On the international side, however, once China will become a rich developed country we expect China’s per capita passenger international aviation volume to reach the United States’ 2018 level of around 1860 passenger-km. This would imply total Chinese international passenger km of about 2.5 trillion passenger-km 2050.

Under ETC analysis, road and rail will respectively take 60% and 25% of total freight activity by 2050.⁽⁵⁰⁾

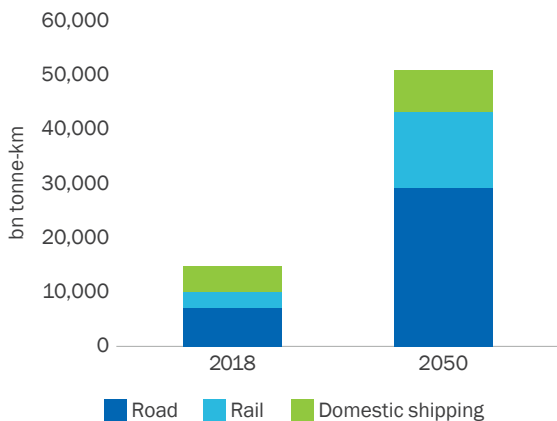


Exhibit 4-6. China total domestic freight activity level 2018 and 2050

Source: Rocky Mountain Institute analysis for ETC China

In 2050, China's domestic per capita aviation will still be lower than current US level, but international aviation activities will parallel.

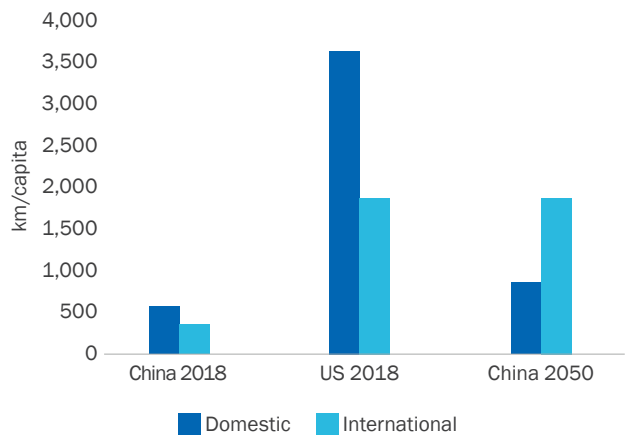


Exhibit 4-7. Aviation activity per capita across countries

Source: Rocky Mountain Institute analysis for ETC China

Shipping

Shipping serves as a critical freight transport channel, especially for import and export, and in 2018, China's freight shipping volume reached 9.9 trillion tonne-km, within which inland waterway, coastal and overseas account for 16%, 32%, and 52%, respectively.⁽⁵²⁾

Within domestic freight, China has introduced policies to encourage shifts from road to waterways and coastal freight where possible. International freight volumes are however unlikely to grow significantly, since while China's GDP will triple and China will remain a major manufacturing and trading country, the growth will be primarily in terms of the value of goods, rather than tonnage. Our model therefore assumes that China's per capita overseas shipping volume will remain at about 3.7 tonne-km per person. And the total shipping activity would be about 13 trillion tonne-km.

Decarbonizing transport

Faced with significant growth on overall transport

volumes, it is vital to improve energy efficiency as much as possible. But energy efficiency improvements using unchanged engines and fuels cannot deliver zero emission and would not even offset the impact of rising demand. Full decarbonization would therefore require complete electrification of surface transport and a switch to zero-carbon fuels for long-distance aviation and shipping. The former is highly likely to save costs in the long term; the latter might still impose moderate but acceptable costs.

Exhibit 4-8 sets out our projected energy mix by transport for a zero emission transport system in 2050. China's transport sector would consume 11.2 EJ (about 3,111TWh) of energy in total, with no gasoline, diesel, or natural gas. Electricity used directly in the rail system, or used to charge road vehicle batteries would grow from nearly zero in 2014 to 4.8 EJ (about 1,100 TWh). Hydrogen would provide 3.1 EJ (about 861TWh) of energy, primarily in the heavy-duty trucking sector, but also for autos which are used for longer distance journeys. In the meantime, biofuel and ammonia would account for 1.9 EJ (about 528TWh) and 1.4

Snapshot of China 2050 transport's final energy demand by sub-sector and by energy carrier under ETC decarbonization scenario

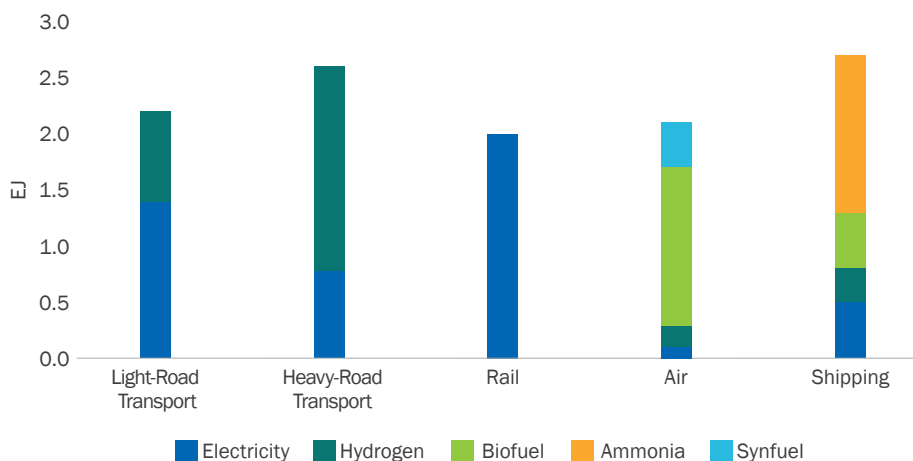


Exhibit 4-8. China 2050 transport's final energy demand by sub-sector and by energy carrier

Source: Rocky Mountain Institute analysis for ETC China

EJ (about 389TWh), respectively. Hydrogen used directly and in the form of ammonia might in turn be produced from electricity, as discussed in Chapter 8. The decarbonization of electricity, discussed in Chapter 7 is therefore essential if transport is to become zero carbon.

The sections below discuss the details and feasibility of this zero-carbon system by transport mode.

Full electrification of surface transport – via BEVs or FCEVs

The global ETC Mission Possible report suggests that future surface transport systems should and will become entirely electric – either in battery electric vehicle (BEV) or fuel cell electric vehicle (FCEV) form. This reflects the inherent energy efficiency and cost advantages of electric engines. China is well-placed to achieve this transition to complete electrification faster than other developed countries.

Electric engines are inherently more efficient than internal combustion engine (ICE) vehicles, which turn 60%-80% of the energy used into wasted heat rather than kinetic energy to drive the vehicle. As a result, electrification could enable China to meet rapidly increasing demand for road and rail travel services while reducing final energy demand in the surface transport sector. Given China's current electricity mix, which delivers electricity at an average 590g of CO₂ per kilowatt hour using BEVs rather than ICE vehicles could cut EV vehicle emissions by approximately 20%-33%.^{11,(53),(54)}

With strong policy support, China is already the global leader in EV development and use. Cities like Shenzhen and Taiyuan have already accomplished 100%

electrification of taxis and urban buses. China's two-wheeler vehicle fleet is electrifying rapidly, far ahead of any other country. Major Chinese companies are leaders in electric auto and bus manufacturing, and in battery manufacturing and R&D.

Given this starting point and pace of progress, our model assumes that China's light duty road system will be 100% electrified by 2050 (and probably well before) and that China will gain major competitive advantage from its leadership position in this technology. The vast majority of light-duty vehicles will be BEV rather than FCEV, but the latter may be favoured by users who have frequent long-distance road travel requirements, and could therefore count for as much as 35% of total energy demand even if for only 20% of all light-duty vehicles.

China's high-speed rail is already fully electrified and will play a major role in electrifying surface transport as the network expands to 45,000 km. Slower-speed passenger trains are also being progressively electrified. Our model assumes that by 2050 all passenger rail traffic and most freight rail traffic will be electrified, though there may be a role for hydrogen powered trains as an alternative on very long distance freight routes where line electrification would impose significant capital costs.

Hydrogen will also probably play a major role in long-distance trucking and intercity bus services. The precise balance between BEVs and FCEVs cannot and does not need to be predicted in advance. It is possible that improvements in battery density and charging speed will eventually make BEVs the favoured solution for even the longest trucking applications;⁽⁵⁵⁾ but it is also possible that rapid falls in the cost of electrolysis

11. Note however that further decarbonization from today's generation mix is required before the use of hydrogen fuel cell vehicles would reduce emissions. A carbon intensity below about 440 grams per kWh (according to Mission Impossible report) is required before hydrogen FCEVs produce lower emissions than ICE vehicles (assuming that the hydrogen is made from electrolysis. This lower "carbon intensity break-even point" reflects the energy losses within hydrogen production.

and fuel cell equipment could make hydrogen FCEVs competitive with BEVs over medium as well as long distance ranges. It is moreover important to note that (i) both BEVs and FCEVs use electric engines not ICEs, and (ii) if the hydrogen used in FCEVs is produced via electrolysis, then FCEVs as well BEVs create increased electricity demand (the economics of alternative routes to zero-carbon hydrogen production are discussed in Chapter 8).

Our current assumption however is that hydrogen will dominate the longest-distance trucking sectors, and China already has significant plans in place to develop FCEVs. Starting in 2018, Beijing, Rugao, and Foshan actively began pilots of hydrogen trucks and buses. During the 2022 Winter Olympic Games, about 5,000 hydrogen FCEVs will be used to transport athletes, audiences, and goods. According to MIIT's Energy Saving and New Energy Vehicles Technology Roadmap, China plans to have 5,000 FCEVs on the road and 100 charging stations by 2020, 50,000 FCEVs and 300 charging stations by 2025, and 1 million FCEVs with 1,000 charging stations by 2030.⁽⁵⁶⁾ In addition, the China Hydrogen Industry Infrastructure Development Blue Book 2016 announced a 10 million FCV stock target by 2050.⁽⁵⁷⁾ This compares with a total current truck fleet of around 24 million.⁽⁵⁸⁾

Balancing these considerations, our estimates for transport energy demand set out on Exhibit 4-8, assume that BEVs dominate the market for shorter-and-middle-distance trucks, while FCEVs dominate longer-distance very heavy trucks and account for 70% of intercity buses. As a result, about 70% of total final energy demand from heavy duty vehicles would come from hydrogen FCEVs.

Fuel alternatives for shipping and aviation

By 2050, as Exhibit 4-8 shows, Chinese aviation and

shipping could account for as much energy use as the road transport sectors (light-duty and heavy-duty combined), whereas in 2014 they account for only 30% as much. This reflects the more limited opportunity in these sectors to gain the inherent efficiency advantage of electric engines.

In both aviation and shipping it will increasingly possible to electrify shorter distance journeys, but decarbonizing long-distance shipping and aviation will almost certainly require the use of zero-carbon "drop-in" fuels which can be used in largely unchanged engines.

Many major aircraft companies and smaller start-ups are developing electric aircraft, powered either by batteries or hydrogen fuel cells, and by the 2030s these are likely to play a major role in very short distance small aircraft flight. Some technological optimists believe that it might be possible to electrify flights up to 500 kilometres by planes up to 100 seats in size. But until and unless there are dramatic breakthroughs in battery energy density (e.g. around 6 to 8 times) it will not be feasible to use batteries to power international flight, which is likely in China's case to account for around 70% of all passenger kilometres travelled (see Exhibit 4-7).

The decarbonization of long-distance aviation is therefore almost certain to require the use of "sustainable aviation fuels" (SAFs) which are the close chemical equivalent of conventional jet fuel, but made from either bioenergy inputs or from the synthesis of hydrogen and CO₂ using zero-carbon electricity inputs. At the global level, ETC contact with aircraft and engine manufacturers has confirmed that it is either already technically possible, or soon will be, to use such fuels in existing engines in a 100% fuel mix; and in China, a partnership between Chinese oil companies (including Sinopec), China-based Hainan Airlines, and Boeing successfully flew test flights using fuel made from waste oil from Haikou to Shanghai in 2015.

The key issues are therefore not the technical feasibility but rather (i) the cost at which bio or synthetic fuel can be produced; (ii) the total amount of biofuel which can be sourced on a sustainable basis. On these:

- ETC global analysis suggests that biofuels or synthetic fuels will probably always be significantly more expensive than conventional jet fuel, but the price premium will fall over time through learning curve and economy of scale effects as volumes grow, and the total impact on consumer standards of living of paying a premium price for air travel will be trivial (see Chapter 10) ;


- In China as across the world, there is enough biofuel to support the decarbonization of aviation, but only if aviation is made a priority sector for the use of such sustainable biofuel, with total electrification of surface transport removing the need to use any biofuels in the trucking sector (see Chapter 9). China's more limited biomass resources than in other countries, and its abundant renewable energy resources (described in Chapter 7) may however favour the synthetic fuel route in China.

In shipping too there are major opportunities to use electric engines (whether powered by batteries or fuel cells) to decarbonize river and coastal shipping which currently account for about 50% of China's tonne-kms of shipping transport. But unless there are major technological breakthroughs it is unlikely to be possible to electrify long-distance tanker, bulk and container shipping since (i) the required batteries would be too heavy, and (ii) while hydrogen has a much higher gravimetric energy density than marine fuel oil (so that the required hydrogen fuel would weigh much less) its very low volumetric density means that required hydrogen storage would take up a significant amount of cargo capacity.

It is however technically possible to decarbonize long

distance shipping by using either biofuels or ammonia in modified marine engines, and the largest container shipping company in the world, Maersk, has therefore felt confident enough to commit to achieving zero emission shipping by 2050. Modelling by the University Maritime Advisory Service (UMAS) for the ETC, reported in the *Mission Possible* report, shows that ammonia powered ships will add significantly to total freight costs, but that, as Chapter 10 will discuss, the impact of higher freight costs on consumer living standards will be trivial.

Our model of future Chinese energy demand therefore assumes that Chinese shipping would be decarbonized by the mix of electricity, hydrogen, biofuel and ammonia routes illustrated in Exhibit 4-8. Both the hydrogen and the ammonia routes will in turn create large demands for zero-carbon electricity, the feasibility of which is discussed in Chapter 7.

A low-angle, upward-looking photograph of two modern skyscrapers with glass facades. The buildings are set against a clear blue sky with a few wispy clouds. The perspective makes the buildings appear to converge towards the top of the frame. The foreground shows the dark, grid-like structure of a window frame, suggesting the viewer is looking out from a high vantage point.

CHAPTER 5 DECARBONIZING BUILDING

China's building sector currently results in 2.13 gigatonnes of CO₂ emissions annually, which is about 20% of the total. These will fall significantly with the implementation of more energy efficient building technologies, such as heat pumps, light-emitting diodes (LEDs), efficient air conditioners (ACs), and passive houses. In addition, the building electrification rate will increase gradually to 75% in 2050. Given complete decarbonization of the electricity together with the utilization of solar thermal, biomass, waste heat, and geothermal, China's building sector will therefore be able to achieve zero emissions by mid-century.

Background: China's current building energy consumption

With heating and cooling as major energy consumers in the building sector, China is officially divided into five major climate zones according to different thermal design requirements (see Exhibit 5-1). These thermal design codes apply to specific climate zones and rural/urban areas. North China requires space heating in the winter, and the space heating systems vary between urban and rural areas due to difference in building density per hectare. In urban areas with high building density, the district heating system serves as the major heating system, whereas in rural areas, individual heating systems dominate. Cooling is required across the whole country. Although individual air conditioners (ACs) are common in residential buildings, building/district cooling systems are often used for commercial buildings.

China's building energy consumption has increased quickly over the past decade. Data from Tsinghua University shows that in 2017 China's building sector consumed 19.9 EJ energy in total.⁽⁵⁹⁾ Exhibit 5-2 shows the breakdown of energy use by building type. Northern district heating is shown separately due to its large energy consumption.

China consists five climate zones with different building heating and cooling patterns.

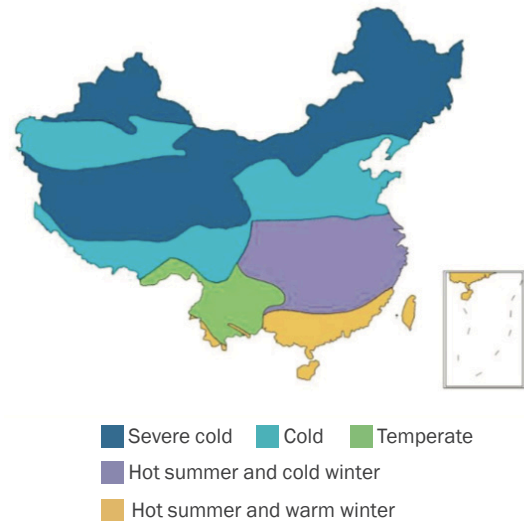


Exhibit 5-1. China's major climate zones

Source: Tsinghua Building Energy Research Center. (2019). China Building Energy Annual Report

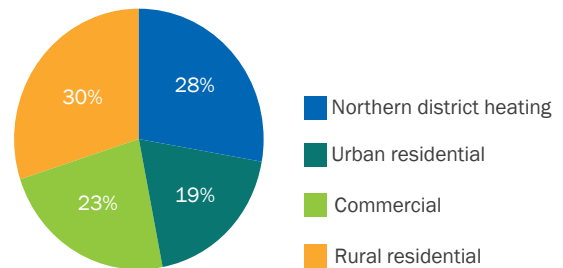


Exhibit 5-2. China's building sector energy consumption by source in 2017

Source: Tsinghua Building Energy Research Center. (2019). China Building Energy Annual Report

Fast urbanization is the primary driver for building sector development. Since 2001, more than 1.5 billion square meters of new buildings have been constructed every year.⁽⁶⁰⁾ As a result, China's average residential floor area per capita has already caught up with typical levels in European developed countries, though it remains significantly below US levels as Exhibit 5-3 shows; average commercial building floor area per

Under ETC analysis, China's average residential floor area per capita would increase by 2050 to a slightly higher level than those of Europe.

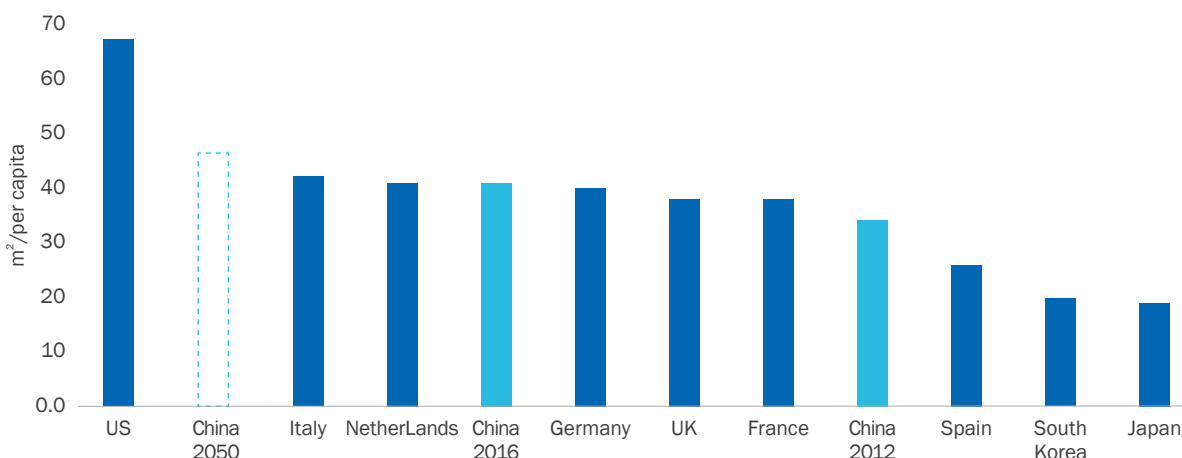


Exhibit 5-3. Residential floor area per capita in major countries

Source: IMF; Reinventing Fire: China; National Bureau of Statistics

China's average commercial building floor area per capita remains low at 1/3 of US and 50%–60% of UK /France /Japan level.

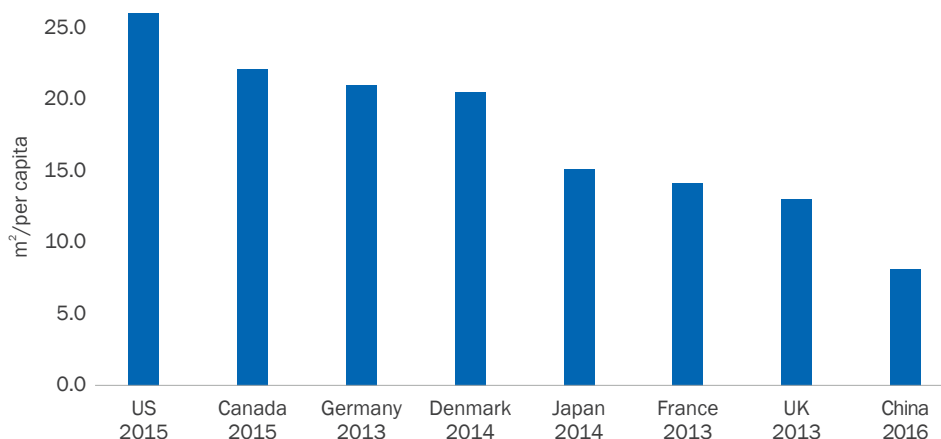


Exhibit 5-4. Average commercial building floor area across countries

Source: Tsinghua Building Energy Research Center, China building energy annual report 2018

capita by contrast is still only 50%–60% of the UK/ France/ Japan level and one third that of the US. (See Exhibit 5-4).

Currently, China's per capita building energy demand is only about one-quarter of the US level and one-third of the EU's level. Nearly 60% of the sector's final energy consumption comes from space heating and cooling.

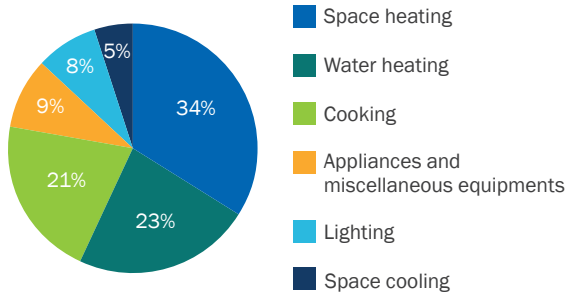
Fossil fuel is the largest energy source, accounting for 40% of total final energy; electricity currently accounts for only 28% of final building energy use (Exhibit 5-5).

Demand outlooks and better buildings in accelerated urbanization

The key drivers of China's building sector demand are

60% of China's building energy consumption comes from space heating and cooling, and fossil fuel is the largest energy source now.

China building sector energy consumption



China's building sector energy consumption by energy carrier

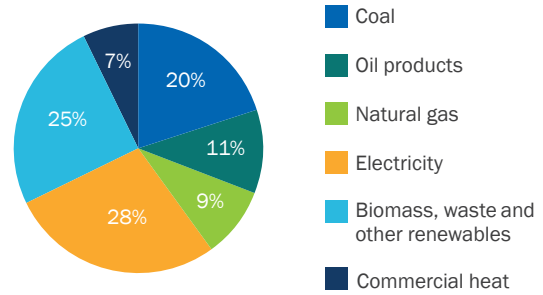


Exhibit 5-5. China's building energy consumption by activity and by energy

Source: IEA (2017), Energy technology perspectives

accelerated urbanization and the increased demand for better buildings. According to Tsinghua University's research⁽⁶¹⁾, China's urbanization rate will increase to 75% in 2050 compared with 58% in 2017; but recent trends suggest that the official target of 70% by 2030 may be achieved before that date, making it possible that urbanisation will be effectively complete significantly before 2050.

With accelerated urbanization, people are moving from rural areas to urban areas, which will lead to more new buildings in cities. As China has already caught up with European developed countries in 2016, we estimate that by 2050 China's average residential floor area per capita could increase to a slightly higher level (see Exhibit 5-3).

With the development of urbanization and economy, the floor area of commercial buildings—including offices, shopping centers, hotels, schools, hospitals, museums, libraries, stadiums, airports, and railway stations—will increase sharply. We estimate that by 2050 China's average floor area of service buildings per capita will catch up with the developed countries' level. We estimated that by 2050, China's total building floor area, including

commercial and residential, would be 85 billion m².

Meanwhile, with the growing demand for a better life, Chinese people will demand better buildings with more comfortable, healthier and safer building environments. Currently, people who live south of the Yangtze River in the hot summer and cold winter area do not have enough heating service even when the outdoor temperature falls below 5 °C in January and February. However, in 2050, with significantly improved life quality, the residential buildings in this area will have adequate heating service. Exhibit 5-6 shows our assumptions on the growth of the building energy service coverage rate from 2019 to 2050.

However, it is possible that China's culture will continue to display more frugal practices than those seen in other developed countries. According to a survey on the cooling behavior in urban Chinese households⁽⁶²⁾, most households turn on ACs in only one or two rooms when it is hot and typically use their ACs only when the room is occupied (see Exhibit 5-7). Chinese people may therefore be able to enjoy developed country levels of building heating and cooling comfort while wasting less energy.

Exhibit 5-6. Building energy service cover rate in 2019 and 2050.

Building type	End-use type	Service cover rate		
		2019	2050	
Residential	Cooling	Severe cold area, cold area, and mild—Urban	100%	100%
		Severe cold area, cold area, and mild—Rural	10%	100%
		Hot summer and cold winter—Urban	100%	100%
		Hot summer and cold winter—Rural	50%	100%
		Hot summer and warm winter—Urban	100%	100%
		Hot summer and warm winter—Rural	80%	100%
	Heating	Severe cold area and cold area	100%	100%
		Hot summer and cold winter	30%	100%
		Hot summer and warm winter; mild	5%	10%
	Appliances and miscellaneous equipment	Refrigerator—Rural	80%	100%
		Kitchen ventilator—Rural	20%	100%
		Refrigerator—Urban	100%	100%
		Kitchen ventilator—Urban	100%	100%
Commercial	Heating	Severe cold area and cold area	100%	100%
		Hot summer and cold winter	70%	100%
		Hot summer and warm winter; mild	5%	10%
	Cooling	Severe cold area, cold area, and mild	100%	100%
		Hot summer and cold winter	100%	100%
		Hot summer and warm winter	100%	100%

Source: Rocky Mountain Institute analysis for ETC China

Chinese share frugality practices in urban residential households.

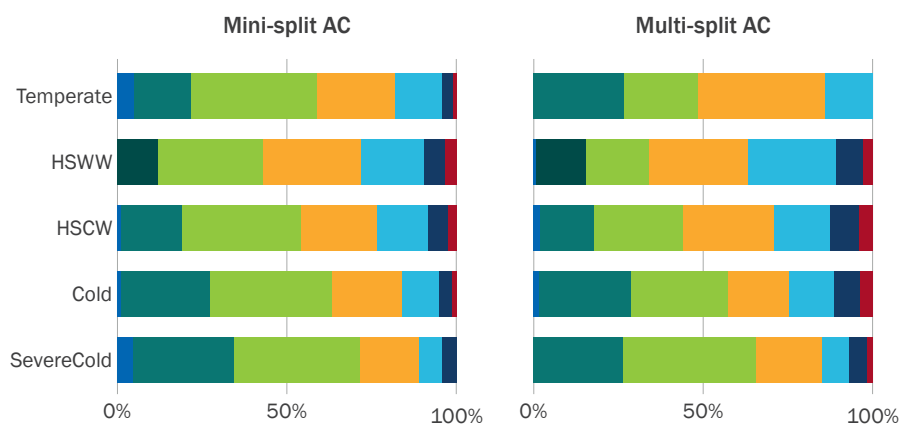


Exhibit 5-7. Cooling behavior in urban Chinese households

Note: HSWW = hot summer and warm winter; HSCW = hot summer and cold winter. The sample quantity includes 6,225 mini-split ACs and 608 multi-split ACs. The sample shares are weighted by provincial population within the climate zones. Central HVAC, which represents a small number of units, typically had B4-7 behavior. B1: never use AC; B2: turn on when extremely hot and turn off before sleep; B3: turn on when extremely hot and turn off when leaving room; B4: turn on when hot and turn off when leaving room; B5: turn on when occupied and turn off when leaving room; B6: turn on for whole apartment and turn off when leaving; B7: turn on throughout the summer

Source: Hu et al. (2017). A survey on energy consumption and energy usage behavior of households and residential building in urban China. Energy and Building. (148) 366-378

Building energy efficiency improvement

China's policies on energy efficiency have played an important role in building energy efficiency improvements, especially in space heating. China has improved space heating energy efficiency in urban northern China through implementing mandatory standards, subsidy policies and government-sponsored housing retrofits, and the energy intensity of district heating has fallen from 187 kWh/m² to 114 kWh/m². But further improvement opportunities remain.

Since the 1980s, China's building energy efficiency design standards have significantly raised the insulation requirement of building envelopes in the urban area, but there is further potential to progress toward best available practice. These could include the passive house and integrated design solution, which could lead to near-/net-zero energy building. Additionally, these standards could be applied to rural areas as well.

Since 2017, China's clean heating policy has forcefully banned the use of individual coal furnaces and promoted gas boilers and heat pumps with substantial subsidies, which results in a large amount of gas boilers and air source heat pumps installed in rural areas. But due to China's shortage of natural gas, and the subsequent soaring price of natural gas, in 2019 the clean heating policy deemphasised natural gas and instead promoted biomass boilers and heat pumps as a primary heating source in the rural area.

Heat pumps are driven by electricity, and extract heat from the external ambient air (ACs are essentially heat pumps working in reverse). Within temperature ranges of -3°C to 10°C, the COP (coefficient of performance) of an air source heat pump is about at 3-3.5 (i.e an input of 1

kWh of electricity results in an internal heat increase of 3-3.5 kWh, with the additional 2-2.5 kWh of heat extracted from the external air). This COP increases as the external temperature rises. Water source heat pumps and ground source heat pumps can have higher COPs as a result of the higher thermal storage capacity of water or soil. Air source heat pumps could be used for south China's incremental heating demand as it has wide adaptability and few restrictions: and reversible heat pumps are available which can function as AC units in summer and heating units in winter. The large use of heat pumps could improve the energy efficiency of heating significantly.

In addition to heating, cooling and lighting are also critical to building energy efficiency improvement. Although China is the largest room air conditioner market as well as production country, China's average cooling energy efficiency is only 60% of the best available technology currently. We estimate that by 2050 China's cooling efficiency could increase by 30% by increasing the minimum legal energy efficiency standard. There are also further opportunities to increase the cooling efficiency with a potential technology breakthrough in room ACs, which could improve the seasonal energy efficiency ratio¹² by 3 times from 3.5 to 10.5.

LED lighting technology has developed rapidly and increased the energy efficiency from 50 lumens per watt to 100 lumens per watt from 2010 to 2018¹³. By 2050, the energy efficiency of LED lighting could reach 200 lumens per watt, delivering a further 100% improvement of energy efficiency.

Taking all these factors into account, we estimate that by 2050, building energy efficiency improvements could result in a reduction of building energy consumption intensity by 50%-60%.

12.The seasonal energy efficiency ratio (SEER) rating of a unit is the cooling output during a typical cooling-season divided by the total electric energy input during the same period. It is similar to COP, but instead of being evaluated at a single operating condition, SEER represents the expected overall performance for a typical year's weather in a given location.

13.LED bulb efficiency is expected to continue improving as cost declines.

Exhibit 5-8. Building sector energy structure in 2050

Energy type	1000 TWh	Percentage
Coal	0.00	0%
Natural gas	0.00	0%
Electricity	3.01	75%
Industry waste heat	0.49	12%
Biomass	0.25	6%
Solar thermal	0.27	7%
Total end energy consumption	4.02	100%

Source: Rocky Mountain Institute analysis for ETC China

Achieving full building decarbonization

In addition to improving energy efficiency as described earlier, it is also essential that all energy inputs in buildings are zero carbon. That would require full decarbonization of electricity and utilization of low-carbon renewable energy, including biomass, solar thermal, and waste heat. As Exhibit 5-8 shows, we estimated that in the building sector electricity will take 75% of total energy consumption, and other renewable energy will take the remaining 25% in 2050.

Building electrification is critical to achieve zero carbon. Cooling, lighting, and appliances have already been 100% electrified. The challenges of building electrification lie in heating and cooking. With the decarbonization of the electricity sector, the climate impact advantage of heat pumps compared with fossil fuels will become huge. We estimate that by 2050 heat pumps could account for 60% of space heating and water heating. With technology improvements in electric cooking (e.g. induction hobs), both residential and commercial cooking could and should be 100% electrified by 2050. With 75% of building sector energy provided by electricity, the building electricity consumption would increase to 3,200 TWh. The decarbonization of the electricity sector is discussed in Chapter 7.

Biomass, industrial waste heat, and solar thermal can supplement the role of electricity. Biomass and solar thermal could be largely used for space heating and water heating in rural areas. Although industry sites are being moved out of cities, the technical feasibility of long-distance (200 km) heat transport means that industrial waste heat could be utilized for district heating users in urban northern China. However, in a zero-carbon economy, industrial waste heat would be less available than today, increasing the reliance on heat pumps as the primary route to decarbonization. Fossil fuels would need to be phased out of the building sector by 2050.

In summary, energy efficiency and building electrification are the two key routes to building decarbonization by 2050 in China, with biomass, industrial waste heat and solar thermal playing supplementary roles.



CHAPTER 6

MEETING THE DEMANDS:
IMPLICATIONS FOR
ENERGY SUPPLY

Given the demands by sector described from Chapter 3 to Chapter 5, the ETC's scenario suggests that China's total final energy consumption would total 64 EJ in 2050. This is about 30% less than the level of 88 EJ in 2016 and 25% less than projected for 2050 in the IEA's 2DS (see Exhibit 6-1).¹⁴

In our scenario, industry would still be the largest energy consumer, taking up 60% of the total final energy consumption. But its share would shrink slightly, as industrial energy demand falls by nearly 30% from current levels, while final energy consumption in the building and transport sectors drop by 25% and 27%, respectively. One key uncertainty highlighted in Chapter 3, was the scale of Chinese steel production in 2050. If instead of our base assumption of 475 million tonnes

for total steel production (with 190 primary production and 285 million tonnes of EAF recycling), there were 700 million tonnes in total of which 280 million tonnes of primary production, total final energy demand for steel production would increase by about 1.9 EJ (i.e about 530 TWh)¹⁵. This would still leave the reduction in total industry sector final energy demand at 25%.

These very significant reductions in final energy demand, despite rapidly growing prosperity and increased supply of "energy-based services" (e.g., kilometers traveled and air conditioning enjoyed) will be possible because of more efficient production and use of products and services, including:

- Reduction in the volume of steel and cement produced

In our analysis, China's total final energy consumption would reduce to 64 EJ in 2050, 30% less than the level of 88 EJ in 2016 and 25% less than projected for 2050 in the IEA's 2DS scenario.

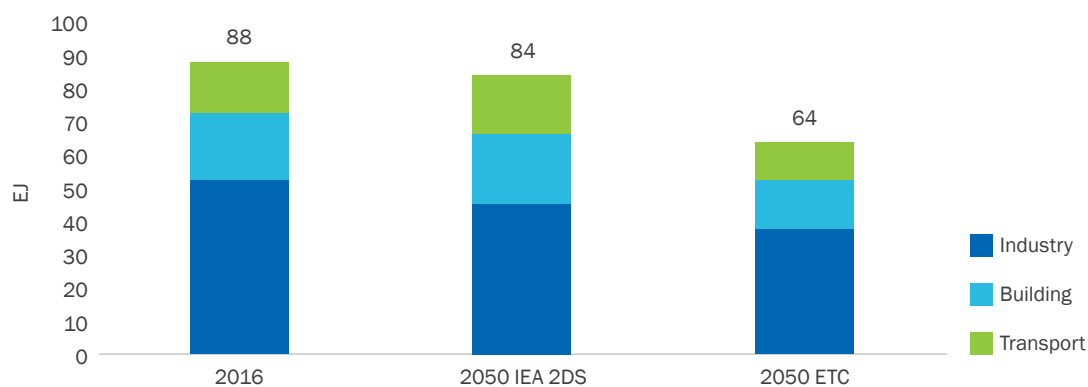


Exhibit 6-1. China's final energy demand by sector (industry, building, and transport)

Source: China Statistical Yearbook; IEA (2017), Energy Technology Perspectives; Rocky Mountain Institute analysis for ETC China

14. At a number of points in this report we compare our projection of energy demand in particular sectors with IEA projections under either (i) the IEA's Reference Technology Scenario (RTS) which is a baseline scenario in which takes into account existing energy- and climate-related commitments by countries, reflecting the world's current ambitions; (ii) the IEA's 2 Degree Scenario (2DS), which describes the combination of energy demands which might arise if public policy forced emissions reductions compatible with a maximum 2°C of warming. Our scenario produces different and in sectors significantly lower figures from the IEA 2DS because of (i) a different objective – with the 2DS scenario focused on maximum 2°C warming rather than maximum 1.5°C warming and therefore able to assume that emissions can reach net zero at a somewhat later date than the 2050 date on which we focus; (ii) different assumptions about the scale of specific sector output or about the form of energy demand, e.g. our analysis suggests significantly lower cement demand and we assume a more complete degree of road transport electrification by 2050. However the 2DS scenario provides a very useful starting point for our analysis, forcing us to identify where and why our assumptions differ from this respected external point of view: and in sectors where we do not have an explicit basis for diverging from the IEA – e.g. in relation to energy demand from general manufacturing – we use the 2DS figures.

15. The increased 225 million tonnes of steel production (60% secondary steel production, 20% primary steel production based on fossil fuel and 20% primary steel production based on hydrogen) will result in additional about 0.6 EJ coal consumption and 370 TWh electricity demand in total, including electricity to support EAF and producing incremental hydrogen demand.

as the infrastructure boom comes to an end, together with improved building design and longer building lives;

- Progress toward a more circular economy with greater recycling and reuse of materials, driving down the production volume of primary steel and plastics;
- Reduced demand for fertilizers due to more efficient use;
- Major reductions in energy use per kilometer traveled in road transport, as result of the inherently superior efficiency of EVs.

Meeting these energy demands in a zero-carbon fashion will require a major change in the mix of energy supply, with the following in particular:

- A massively expanded use of electricity, either through direct electrification or in the form of electricity-based fuels like hydrogen, ammonia, and synfuels;

• The expanded use of biomass as an energy source or as an alternative feedstock

- A very significant reduction in the role of fossil fuels;
- The application of carbon capture and either storage or use, either in industries where the inherent chemical process results in CO₂ emission (cement production) or in applications where continued fossil fuels as an energy source results in emissions

Exhibit 6-2 sets out our scenario for the possible mix of energy and feedstock sources by sector.

Massive expansion of demand for electricity and electricity-based fuels

Massive expansion of zero-carbon electricity use will be essential if China is to achieve zero emissions. Starting from 7,000 TWh in 2018, China's total electricity demand will need to increase to about 15,000 TWh (54

Meeting these energy demands in a zero-carbon fashion will require a major change in the mix of energy supply, with massive direct or indirect electrification, use of biomass and CCS, and significant reduction of fossil fuels.

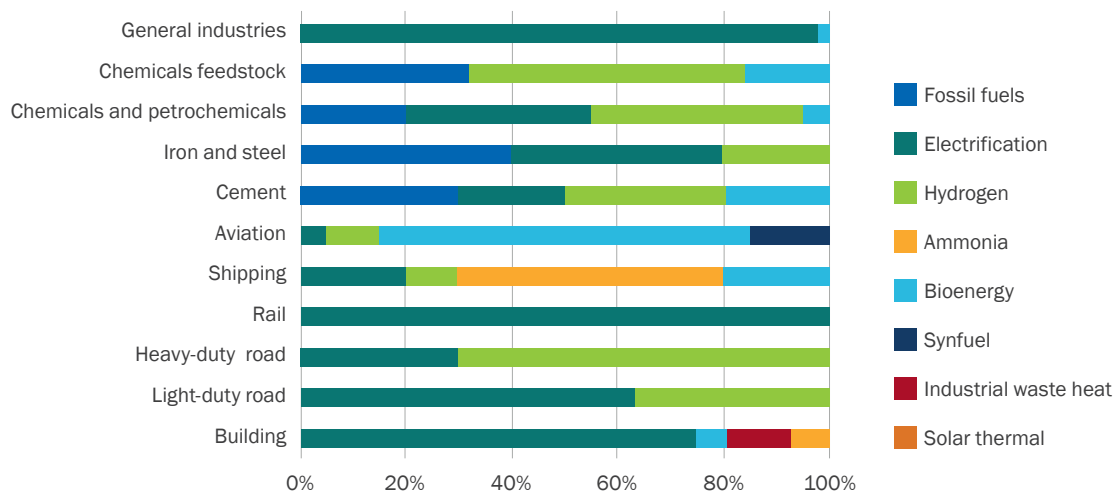


Exhibit 6-2. China's final energy consumption by energy carriers in different sectors

Source: Rocky Mountain Institute analysis for ETC China

EJ) in 2050¹⁶.

Of this total, 80% would be used for direct electrification and 20% to produce electricity-based fuels—in particular, hydrogen and ammonia. By 2050, hydrogen demand will need to have increased from 25 million tonnes annually today to 81 million tonnes per annum.

This dramatic increase in electricity demand is driven by widespread direct electrification in buildings and light-duty road and railway transportation, and by its adoption in industry wherever possible. The use of hydrogen will further enable indirect electrification of heavy-duty transport, and hydrogen will be widely used for industrial heat input and as clean material for industrial production. Specifically, for instance, China would have more steel production from EAF, and power-to-X for chemicals production would develop in scale with electricity as a main process energy source and hydrogen as a major feedstock.

Exhibit 6-3 gives the resulting electricity demands by sector, with industry accounting for 50% of all use, the building sector at 21%, and transport at 9%. Industry and transport meanwhile drive demand for hydrogen.

Growing demand for bioenergy with prioritized use due to resource limitation

Bioenergy will need to play a secondary but still vital role in China's 2050 zero-carbon economy, both as an energy source and as material feedstock for chemicals production. Our scenario suggests that total primary bioenergy input would need to rise to 13.0 EJ (3,600TWh) by 2050. Out of this primary bioenergy input, electricity generation would account for 48% (6.2 EJ or 920 TWh), direct use of bioenergy for 5.2 EJ (1,400TWh), with the remaining 1.5 EJ (420 TWh) used as industry feedstocks. Within the direct use of bioenergy, 83% of which is consumed by the industry and transport sectors (Exhibit 6-4).

Industry would account for 50% of all electricity use, the building sector 21% and transport 9%; industry and transport meanwhile drive demand for hydrogen.

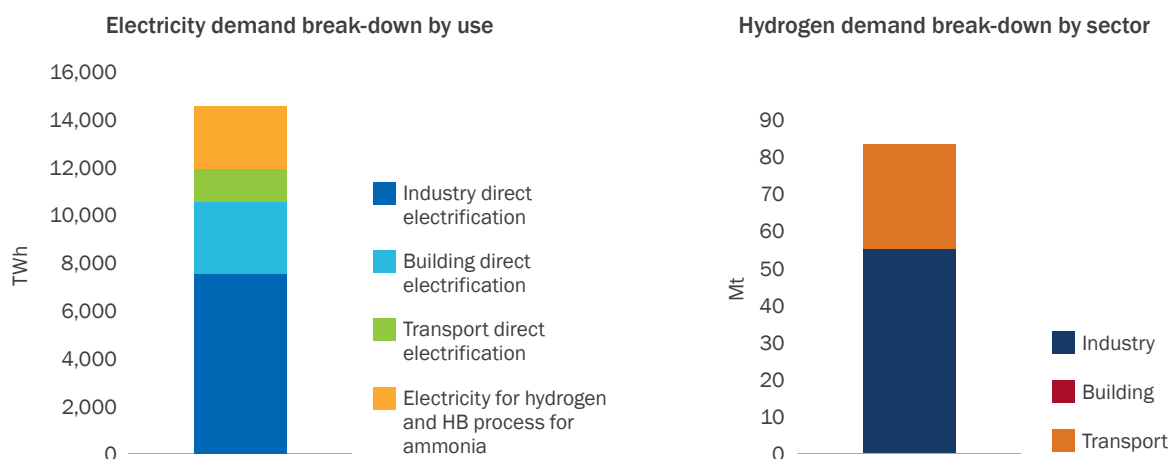


Exhibit 6-3. China's demand of electricity and hydrogen by sector in 2050

Source: Rocky Mountain Institute analysis for ETC China

16.If we assume 700 million tonnes of steel production in 2050, instead of 475 million tonnes in our base scenario, electricity demand would be increased by 370 TWh.

Unlike in the case of zero-carbon electricity—where Chapter 7 will describe China’s huge potentially available resources—the total available supply of truly sustainable bioenergy is limited. Utilization of bioenergy resources should therefore be carefully planned and prioritized in areas with better cost effectiveness or where other decarbonization solutions are not available. Our analysis suggests that aviation and chemical feedstocks would be top priorities for the use of limited bioenergy supplies, while in power generation the role of bioenergy should be focused on providing flexible backup in a system dominated by renewable and nuclear sources. Chapter 9 discusses the issue of sustainable bioenergy supply and priority use in more detail.

Remaining role for fossil fuels

In our scenario, electricity, hydrogen, and bioenergy together will supply 91% of China’s final energy demand in 2050, but there will still be a remaining need for fossil fuels in some industrial processes, as a feedstock for chemicals, and as an alternative to electrolysis in the production of hydrogen. Natural gas may also play a

role in the provision of flexible generation backup within the electricity system.

In total, coal consumption could be 4.3 EJ (150 Mtce), down from 113 EJ (3,900 Mtce) today. Natural gas could account for 5.3 EJ (180 million m³), while oil use would fall dramatically to only 1.0 EJ (24 Mtoe, or 0.5 million barrels per day) with its role in surface transport eliminated through total electrification, while oil-based marine and aviation fuels would be replaced by ammonia, biofuels, or other synthetic fuels.

Necessary role for CCUS to deal with remaining CO₂

Given the diminished but still significant role for fossil fuels, together with considerable process emissions if cement continues to be made from limestone (i.e calcium carbonate), China would still have gross CO₂ emissions of 1 gigatonne per annum in 2050. Achieving a zero-carbon economy will therefore require significant application of carbon capture and either storage or use. With a capture efficiency of 90%, the residual CO₂

Total primary bioenergy input would need to rise to 13 EJ, within which 6 EJ for electricity generation and 5 EJ for direct use; 83% of the latter is consumed by the industry and transport sectors.

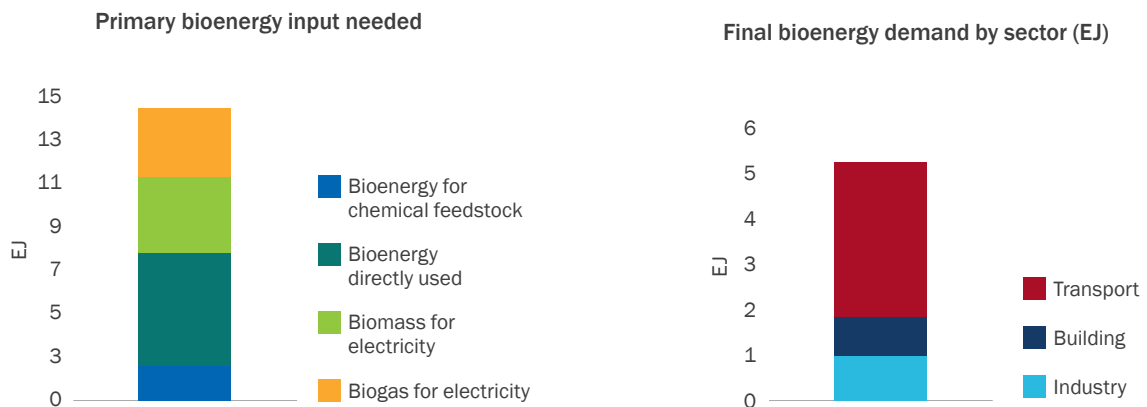


Exhibit 6-4. Final and primary bioenergy demand by use

Source: Rocky Mountain Institute analysis for ETC China

There would be a dramatic change in the primary energy mix, with fossil fuel demand falling over 90% and wind, solar and biomass playing major roles.

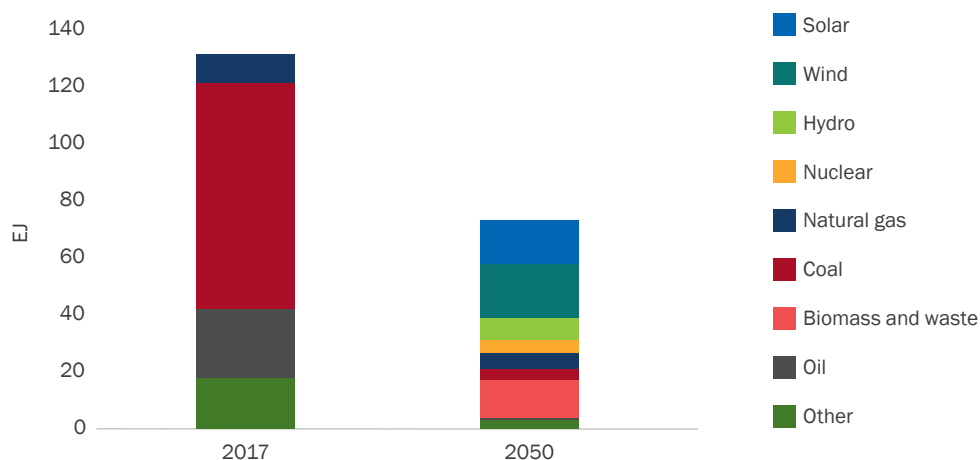


Exhibit 6-5. China's primary energy demand by energy carrier

Note: The 2017 data is from the China Statistical Yearbook. Due to different ways of organizing data, "Other" in 2017 includes hydro, wind, solar, and others.

Source: China Statistical Yearbook; Rocky Mountain Institute analysis for ETC China

emission would be about 100 million tonnes. Chapter 9 gives more detailed information.

Implications for primary energy

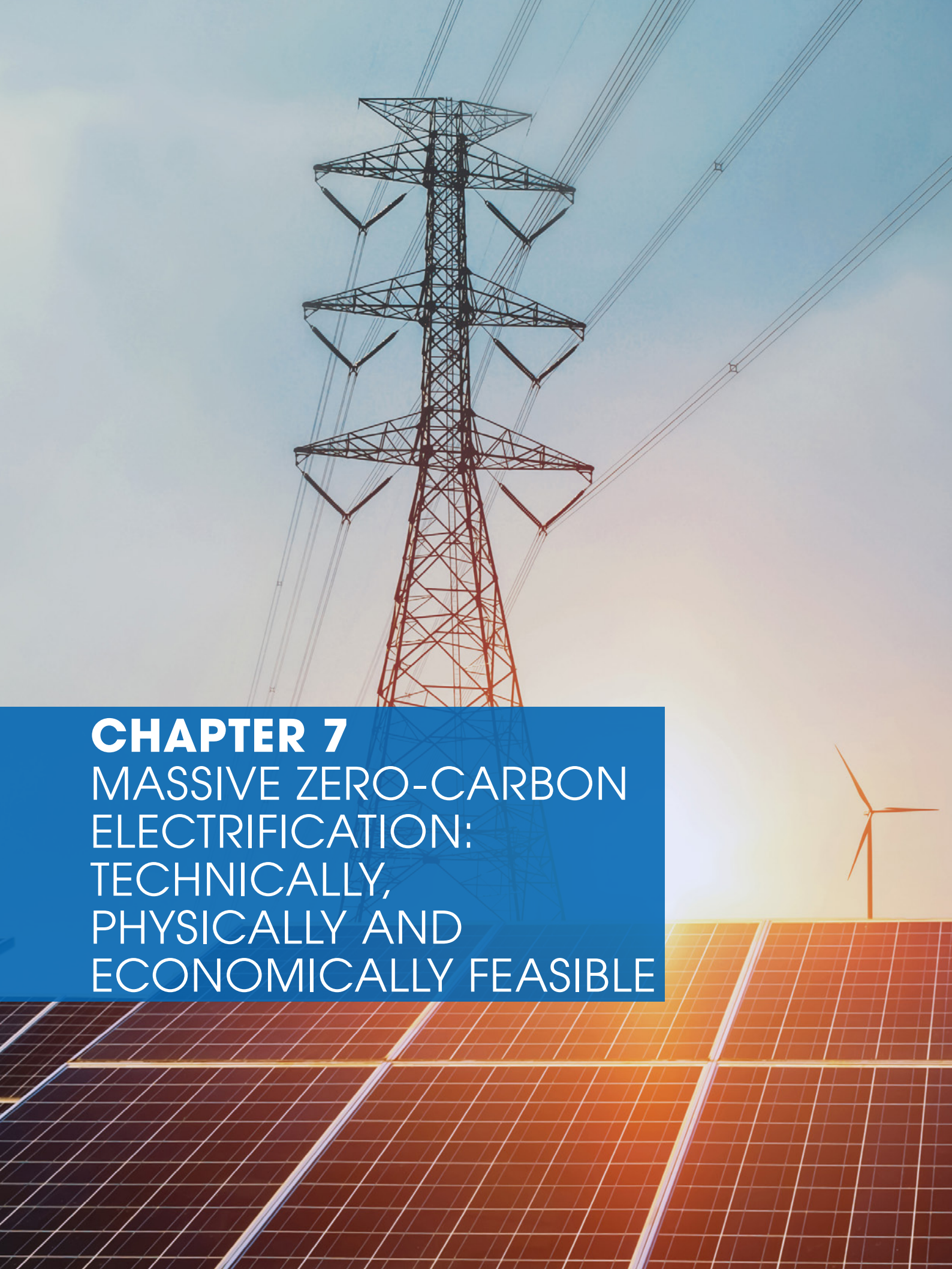
Exhibit 6-5 shows the implications of this scenario for China's overall primary energy mix in 2050. Although final energy demand would fall by 30% from 88 EJ to 64 EJ, primary energy requirements would fall by a more significant 45% from 132 EJ to 73 EJ. This larger fall in primary energy than in final energy largely reflects the elimination of the energy losses involved in today's thermal electricity production system.

Within this reduced total, there would be a dramatic change in the sources of energy, with fossil fuel demand falling over 90% while nonfossil energy would expand by 3.4 times.

In 2050, wind (19 EJ), solar (15 EJ), and biomass (13 EJ)

are expected to be the largest primary energy sources for China, together accounting for two-thirds of the total primary energy demand. Nuclear and hydro energy would also experience a major scale-up compared with the current level, responsible for 5 EJ and 8 EJ of energy demand in 2050.

Achieving zero-carbon emissions thus requires a dramatic change in China's energy mix. The crucial question is whether it is technically and economically possible to achieve the massive increase in zero-carbon electricity, the significant increase in bioenergy supply, and the scale of CCS/U application which this scenario requires. Chapters 7 to 9 consider that issue.



CHAPTER 7
MASSIVE ZERO-CARBON
ELECTRIFICATION:
TECHNICALLY,
PHYSICALLY AND
ECONOMICALLY FEASIBLE

With over 70% of electricity currently generated by thermal plants, China's power sector currently produces about 40% of China's total CO₂ emissions. If this mix were maintained as demand grew to the 15,000 TWh projected in Chapter 6, emissions would more than double. It is therefore essential to drive total decarbonization of this massively increased scale of electricity generation. China's huge available wind and solar resources, along with nuclear and hydro, make it possible to meet this need. Furthermore, a largely renewable system can meet the time profile of demand if China utilizes the full range of storage, flexibility and demand response options. And the total cost of achieving this transition will have minimal impact on China's economic growth. But achieving the goal by 2050 will require a major ramp up of the scale of investment and comprehensive planning of the transition.

Background: China's current electricity production and consumption

China is the world's largest electricity producer, surpassing the United States in 2011 after rapid growth

since the early 1990s. In 2016, electricity accounted for 17.2% of China's final energy demand. By contrast, as the ETC's global analysis indicated, in any feasible path to a zero-carbon economy, the share of electricity in final energy demand will be as high as 60%–70%, and this must be produced entirely from zero-carbon power sources.

With an overall installed power generation capacity of around 1,650 GW, China's electricity production was about 6,000 TWh in 2016, and is estimated to have reached 7,000 TWh in 2018. Of the 2016 total, 72% was generated from fossil fuels (66% from coal), 19% from hydro, 3% from nuclear, and about 5% from wind, solar, and other sources (see Exhibit 7-1).⁽⁶³⁾ Despite coal's dominance, coal-fired electricity production declined from 2013 to 2016, coinciding with a major boom in renewable energy (see Exhibit 7-1).

Thermal power also dominates total power capacity, with a share of 64%, of which nearly 90% is coal. However, solar and wind capacity has grown rapidly as cost declines have made them increasingly economically

With overall installed power generation capacity of 1,650 GW (64% thermal power), China's electricity production totalled 6,000 TWh in 2016, within which 72% was generated from fossil fuels (66% from coal), 19% from hydro, 3% from nuclear, and around 5% from wind, solar and other sources.

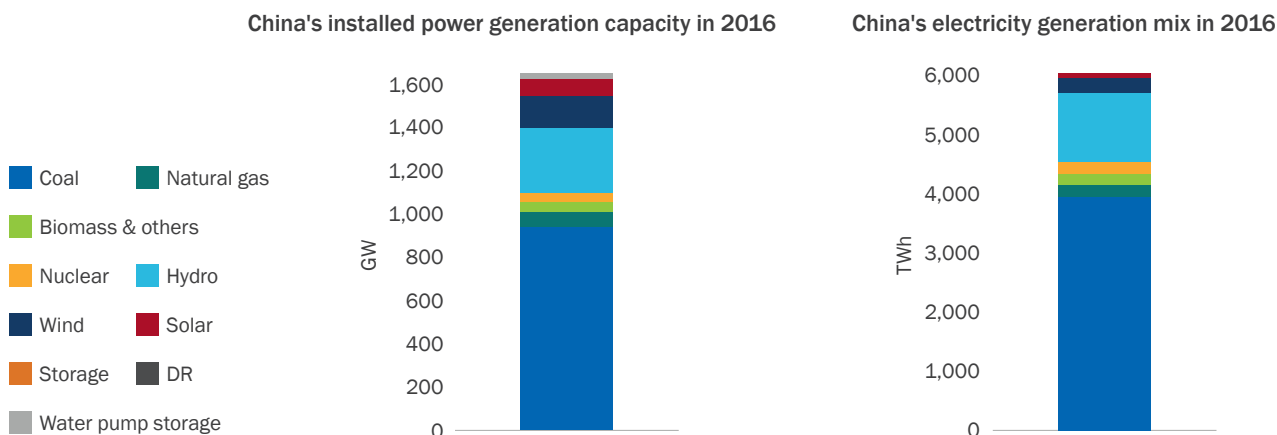


Exhibit 7-1. China's electricity generation and installed power generation capacity in 2016

Source: China Statistical Yearbook

In this zero-carbon economy, final electricity consumption could reach ~15,000 TWh, 80% of which would be used for direct electrification, 18% for production of electricity-based fuels like hydrogen and ammonia.

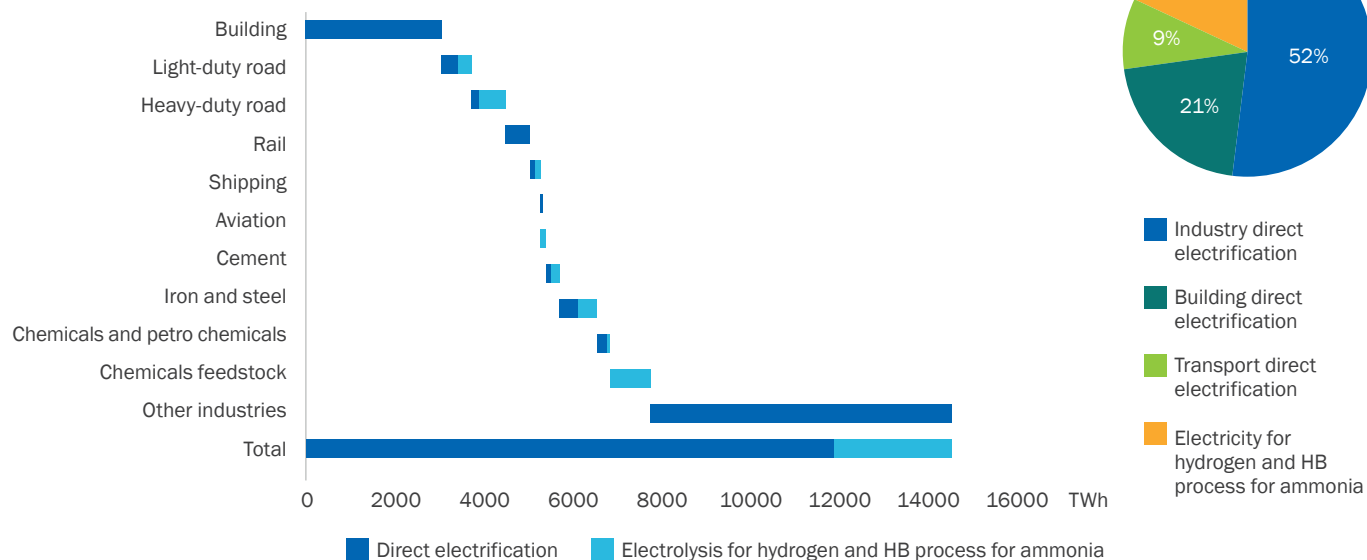


Exhibit 7-2. China's electricity generation and use by sectors in zero-carbon scenario

Source: Rocky Mountain Institute analysis for ETC China

attractive. In 2016, China had a total wind power generation capacity of 147 GW, 76 GW of solar, 305 GW of hydro and 46 GW of biomass, and accounted by then for nearly 30% of total global installed renewable power capacity. By the end of 2018, China's renewable power capacity had reached about 730 GW, 10% more than the previous year.⁽⁶⁴⁾

Massive expansion of demand for electricity and electricity-based fuels

Full decarbonization of the whole economy would require massive zero-carbon electrification. According to our model, China's total electricity demand will need to increase from about 6,000 TWh in 2016 (7,000 TWh in 2018) to 15,000 TWh in 2050. Similar to the global picture, the growth in China will be driven mainly by the wide range of direct electrification in buildings and the transport sector and its use in the industry sector wherever possible. Overall, 82% of total electricity would be used for direct electrification, with industry electrification accounting for 52% of total electricity demand. In addition, electricity will play a much

increased role in the production of hydrogen and hydrogen-based chemicals and fuels such as ammonia, with 18% of electricity used for these purposes in 2050 (see Exhibit 7-2).

Scenario for zero-carbon electricity generation mix

To deliver this greatly increased supply of electricity in a zero-carbon fashion will require a dramatic increase in zero-carbon power capacity. Total capacity in China's power system will need to increase fourfold to reach around 7,100 GW in 2050, but with a very different mix (see Exhibit 7.3). This will require:

- A dramatic increase in wind and solar capacity, with 2,400 GW of wind and 2,500 GW of solar in place by 2050, and with the two together then accounting for nearly 70% of all electricity generation;
- An expansion of the role of nuclear, growing from around 45 GW today to 230 GW of capacity, and with nuclear's share of generation growing from 4% to 10%;

Under ETC scenario, China's total electricity demand would grow from 6,000 TWh in 2016 to 15,000 TWh in 2050, over 90% of which is from zero carbon sources.

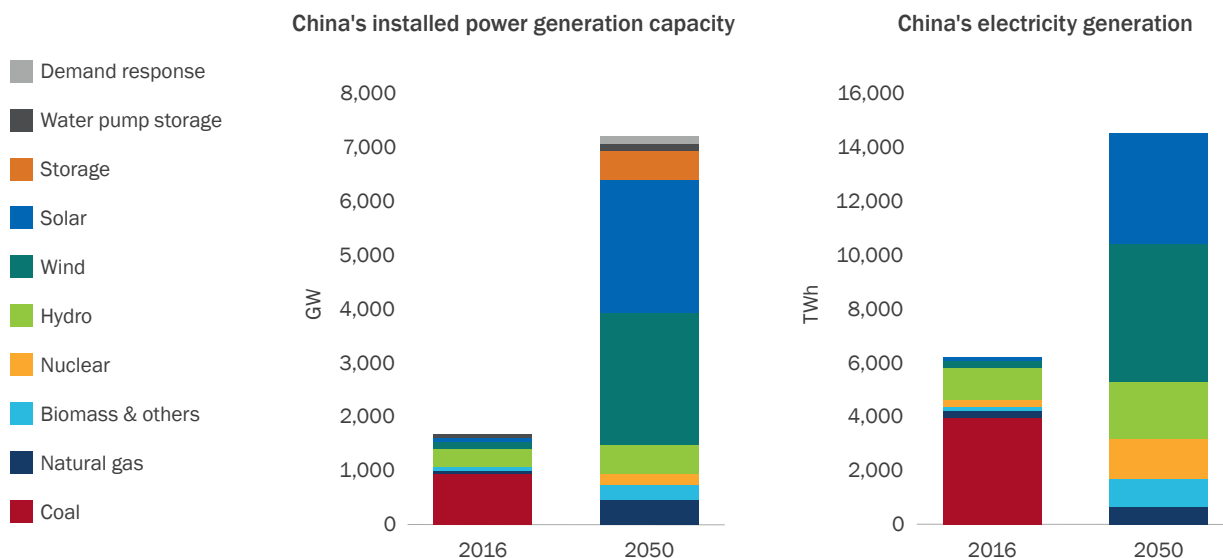


Exhibit 7-3. China's installed power generation capacity and electricity generation mix

Source: China Statistical Yearbook; Rocky Mountain Institute analysis for ETC China

- A significant further expansion of hydro capacity (from 350 GW today to 550 GW) and with hydro accounting for 14% of total generation in 2050;

- The almost complete coal elimination of coal generating plants, with thermal generation falling from 72% of the total today to just 7% in 2050, and with all of this provided via gas generation rather than coal. This phase-out of coal-fired power plants, and the related reduction in demand for coal, would have implications for employment, particularly in specific coal mining centers. Chapter 10 will further discuss this issue.

This represents a massive change from the current mix and requires huge new investments, but our analysis suggests that it is feasible given China's natural resource

Places with solar radiation of over 5016 MJ/m² and over 2,200 hours of sunshine per annum takes up 2/3 of China's land area, and installing 2,500 GW solar power only requires 0.8% of China's land mass.

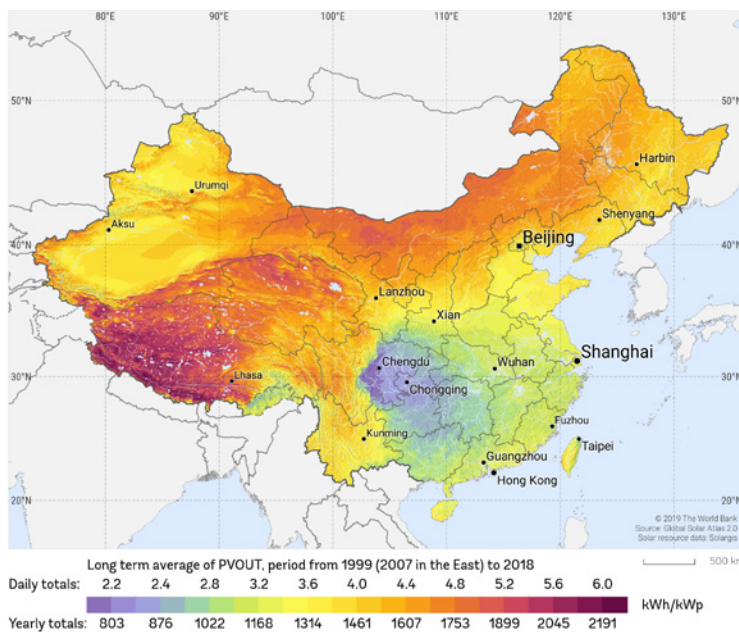


Exhibit 7-4. Solar PV power potential in China

Source: Solargis

Total onshore wind energy reserves of about 3,400 GW are available at 100 meters height;
and there are extra offshore resources of 500 GW.

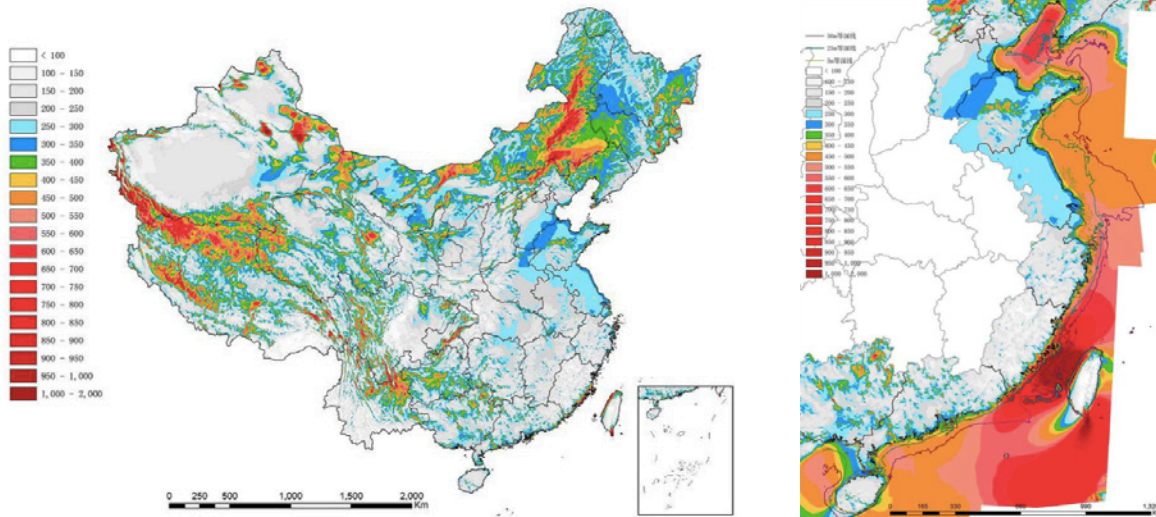


Exhibit 7-5. China's onshore (left) and offshore (right) wind energy resources at 70 meters height (unit: W/m²)

Source: Energy Research Institute, IEA (2011), Development Roadmap for China's Wind Power 2050

availability, and that it will also be feasible to balance supply and demand in a system dominated by variable renewables.

Feasibility of generation mix given natural resource availability

Solar power. The required increase in solar photovoltaic (PV) capacity, from 175 GW today to 2,500 GW by 2050, is easily feasible given China's massive potential solar resources. As Exhibit 7-4 shows, land area with annual solar radiation of more than 5,000 MJ/m² and over 2,200 hours of sunshine per annum makes up two-thirds of China's land area. By contrast, using an estimated land requirement of 32 km² per GW made by the National Renewable Energy Laboratory⁽⁶⁵⁾, installing 2,500 GW of solar power would require only a land area of 80,000 km², which is just 0.8% of China's land mass. Far greater solar PV capacity than our scenario requires would therefore be possible.

Wind power. China's wind resources are also very large (see Exhibit 7-5) and sufficient to support the capacity increase from 184 GW today to 2,400 GW in 2050 which our scenario assumes. Estimates by the Energy Research Institute⁽⁶⁶⁾ of China, National Development and Reform Commission (NDRC), suggest that in areas with higher than 300 W/m² wind resources, total onshore wind energy reserves of about 3,400 GW are available at 100 meters height; and there are offshore resources of 500 GW at 100 meters height in areas with 5-50 meters water depth.

Hydropower. Hydro has long played a strategic role in China's electricity generation system. Given its technical maturity, high energy density, and economic feasibility, further hydropower development should be a priority if possible. Estimates from the National Energy Administration (NEA) of China⁽⁶⁷⁾ suggest that China's potential hydropower capacity is up to 660 GW, out of which about 500 GW is technically exploitable and economically feasible.¹⁶ Our scenario of 550 GW of

16.China State Grid expert consultation.

capacity by 2050 would thus require exploitation of all of China's likely available resource, with this level probably reached by 2035 and little feasible expansion thereafter. It is also possible that full exploitation of the potential resource might need to limit by environmental and social considerations such as local opposition to river damming, or by international cooperation issues where the rivers flow through other countries before reaching the sea.

Nuclear power. This capacity could grow in line with the increase from 45 GW to 230 GW assumed in our scenario. The average build rate for the past five years is about 10 GW per annum, and at this pace of investment, 230 GW of capacity would be reached before 2040. National planning estimates suggest that China has the capacity to build 230 GW on coastal sites. An additional 400 GW may be possible if inland sites can also be developed, but our scenario does not assume any expansion beyond the coastal locations.

Thermal generation using biomass or natural gas with CCS are both zero-carbon technologies which can provide valuable flexibility within a power system dominated by variable renewables, providing dispatchable power when wind and solar supply is inadequate to meet demand. However, the maximum use of biomass may be constrained by limits to total sustainable biomass supply. Our model assumes that in 2050 there would be around 230 GW of biomass power capacity and 500 GW of natural gas capacity combined with carbon capture. Use of this capacity to provide 1,700 TWh (about 12% of the total) would require 6.25 EJ of biomass resource and 204 Mt of CCS capacity. The feasibility of such resources and capacity is discussed in Chapter 9.

Flexibility and important roles of storage and demand response

By 2050 our projections suggest that China will get nearly 70% of its electricity supply from intermittent

sources – wind and solar – whose availability varies between day and night and in line with unpredictable weather patterns. To balance supply and demand in such a system, China will need to use a combination of adequate energy storage, flexible generation capacity to cover peak demand or short supply periods, or demand management mechanisms which encourage people to use electricity when it is most available and cheapest.

To fully assess the scale of this “flexibility” challenge and the optimal solutions, requires detailed analysis of electricity demand and supply patterns by hour of the day, and across the seasons, taking into account different patterns of both supply and demand in China's highly varied regions. In the next step of the ETC China project, we plan to conduct such analysis. But the initial high-level analysis which we have done so far illustrates the broad shape of the supply/demand challenge which China will face, and confirms that this challenge can be met if a portfolio of energy storage, flexible capacity, and demand management options is deployed.

Drawing on available data for a typical northern city and Guangdong province in the south we have identified the broad shape of China's daily electricity demand pattern on typical summer and winter days (see Exhibit 7-6). This shows a summer demand peak which is significantly higher than in winter, and shows that in both summer and winter, electricity demand peaks in the late morning/mid-day and again during the evening. These patterns reflect the impact of residential electricity use (which in many countries tends to create an evening peak) together with the typical rotation and shift patterns of Chinese factories.

By 2050 we anticipate that total electricity demand will have increased by over twice, and the demand curves by hour are therefore bound to be on average well above the current level. But it is also possible that changes in the sources of demand will change the relative

Summer demand peak is significantly higher than in winter, and in both summer and winter, electricity demand peaks in the late morning/mid-day and again during the evening.

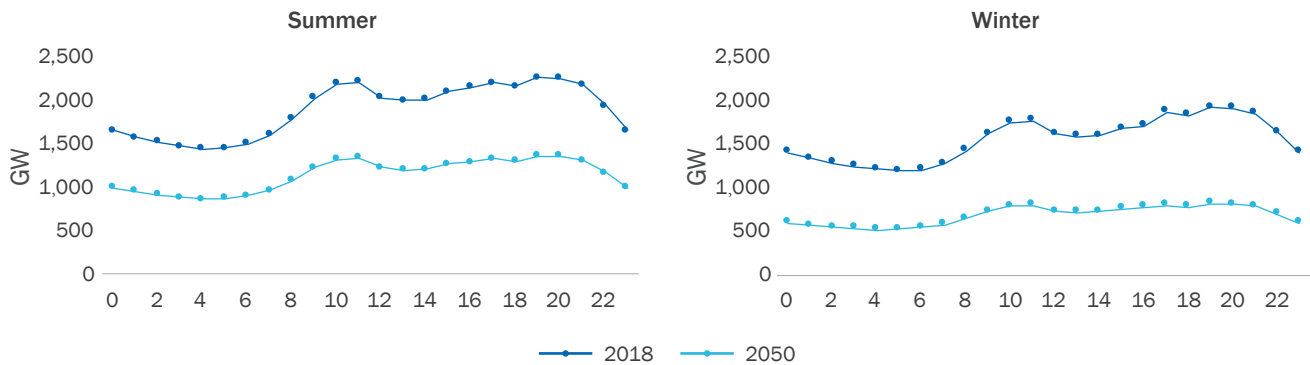


Exhibit 7-6. Demand load curve of 2018 and 2050

Source: Rocky Mountain Institute analysis for ETC China

Note: 2018 load curve is simulated by RMI, based on data of typical days in a northern city and Guangdong Province

importance of winter versus summer peaks, and that daily patterns could change as a result of greater demands for air-conditioning, a significant electricity use in vehicle charging, or other developments.

We have not yet analyzed such potential changes in detail, and we therefore assume that the hourly pattern of demand will be similar in 2050 to today. But on key change which we can clearly anticipate is that the greater use of heat pumps in winter will increase winter demand relative to summer, and we have generated possible daily curves for summer and winter in 2050 which reflect that development (see the higher line in Exhibit 7-6). These show a peak level of demand of 2,240 GW in summer and 1,900 GW in winter.

Exhibit 7-7 then illustrates how the power system of 2050 might produce electricity, hour by hour, and the resulting periods of excess supply (around the middle of the day as high solar output delivers electricity in excess of demand needs) and of short supply (in the

evening peak, when solar supply declines, but demand is boosted by residential use as people return home from work)¹⁷.

The gaps between demand and supply shown on Exhibit 7-7 defines the intra-day system management challenge which will have to be met by some mix of flexibility, energy storage and demand management responses. In addition (and not illustrated on Exhibit 7-7) the system will need to have flexibility to deal with very short-term frequency balancing, short term ramping and seasonal balance issues. There are a wide variety of flexibility resources which can meet these different needs.

Pumped hydro. This accounts for 95% of current global energy storage capacity. With its technology maturity, pumped hydro provides longer duration and bulk energy peak supply. PHS can be realized in either natural or man-made reservoirs. While pure pumped-storage plants store water in an upper reservoir with no

17.The supply curves shown assume that the nuclear capacity runs at full capacity on a continual base, while hydro power supply runs at full capacity in summer but much less in winter due to water supply constraints. For wind and solar we have assumed a pattern of seasonal and hourly supply relative to capacity in line with Californian experience: further work is needed to generate detailed patterns for China which reflect the likely location of wind and solar capacity and local weather variations. The supply profiles for biomass plants and for natural gas plus CCS plants emerge from the model (subject to maximum available capacity constraints) in order to balance total supply and demand .

Given this high-portion solar and wind electricity mix in our scenario, a portfolio of grid flexibility solutions proves it feasible to balance power supply and demand.

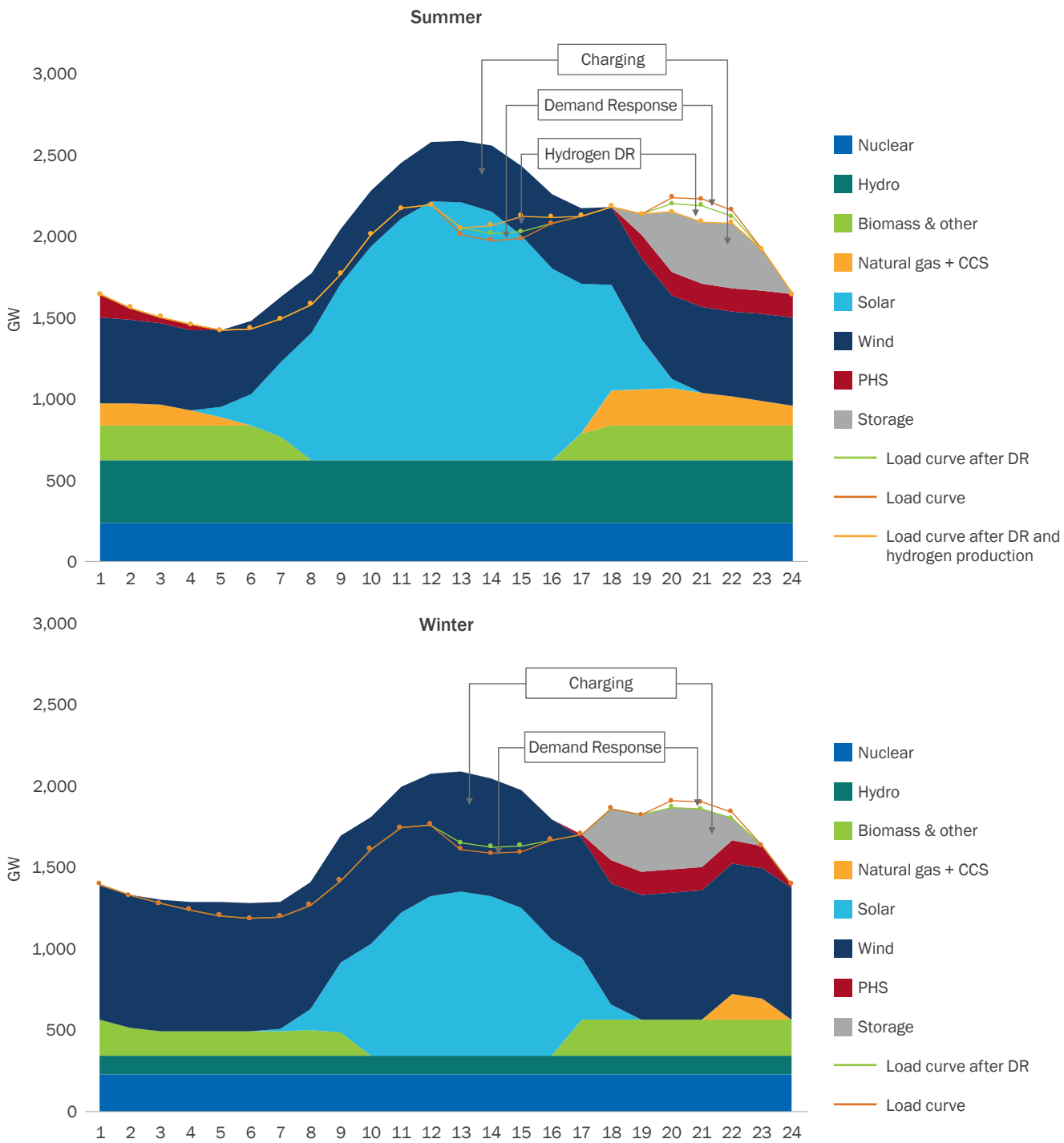


Exhibit 7-7. Daily balance in summer and winter

Source: Rocky Mountain Institute analysis for ETC China

China's current pumped hydro capacity is 30 GW, leading rest of the world, and this capacity is expected to climb to 142 GW in 2050.

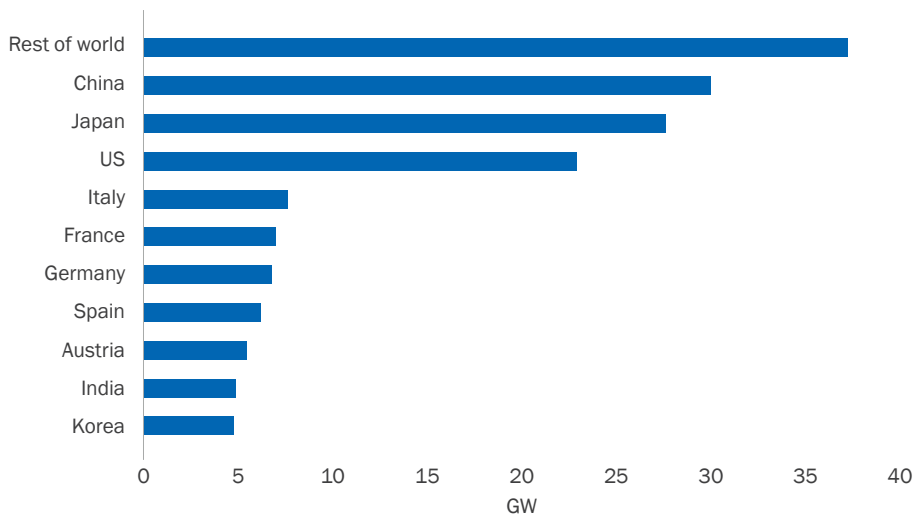


Exhibit 7-8. PHS worldwide

Source: International Hydropower Association (2019), 2019 Hydropower Status Report

natural inflows, pump-back plants utilize conventional hydroelectric plants with an upper reservoir. China's current pumped hydro capacity is 30 GW,⁽⁶⁸⁾ leading the rest of the world (see Exhibit 7-8), and this capacity is expected to climb to around 140 GW by 2050,⁽⁶⁹⁾ with rapid growth already occurring.

Battery storage. Battery storage is becoming an increasingly economic solution to intraday balance needs, providing capacity to meet short-term peaks, with many renewable supply contracts in the US now combining energy supply with four-hour battery storage. Rapid future cost reductions (driven as a by-product of massive EV battery demand) are likely to make battery solutions increasingly important from the mid-2020s on, potentially surpassing PHS to be the most commonly used form of storage around 2040.⁽⁷⁰⁾ In our model, China would have in total 510 GW of battery storage capacity in 2050, roughly half of Bloomberg New Energy Finance projected global total⁽⁷¹⁾. Lithium-ion batteries, whether newly manufactured for grid storage, or in the form of "second use" EV batteries, will play a dominant role initially, but multiple other battery chemistries are

being developed, some of which could allow batteries to meet longer term storage needs. Large increases in battery capacity will create significant demands for key minerals (in particular nickel, manganese, cobalt and lithium) but the ETC's global analysis shows that the requirements can be met given available resources and potential production capacity. We will analyze China's specific position in respect to mineral supply in the next steps of our work.

The production of hydrogen from excess electricity.

Hydrogen can be made from electricity electrolysis when electricity is surplus to requirement or cheap, and then converted back into electricity either by being burnt in gas turbines or the fuel cells. Our model projects at least 100 GW of hydrogen production capacity to provide this system flexibility of this sort. Large scale hydrogen storage would also be required.

Demand response.

In conventional power systems, dominated by dispatchable thermal capacity, customers typically demand electricity whenever it suits them, and supply responds flexibly. However, there are many

categories of demand which, if incentivized by price signals, could shift to another time period with minimal loss of consumer value. These include EV battery storage, ice storage, water heating, space heating and cooling if houses are well insulated, and many industrial processes. Many industrial processes can also run slower for periods of time when electricity is in short supply or more expensive, for instance using variable speed pumps or other equipment. The total potential for such “demand response” (DR) is in theory extensive. Flexible charging of ~420 million EVs in 2050 alone could provide around a quarter of all battery storage within the system.⁽⁷²⁾ In our model, DR provides a capacity of roughly 120 GW. But it is important to note that the potential for demand response will not be achieved without the development of appropriate market mechanisms (to face consumers with price incentives to shift demand) and smart consumption management systems.

Dispatchable thermal generation. Within a renewable within a primarily renewable power system, there can be an important role for dispatchable thermal plant which only runs rather small percentage of all hours, providing supply when renewables, nuclear, hydro sources are insufficient to meet demand. This implies low utilization of capital assets; such generation can be profitable since the electricity will be supplied when prices are high. In our model of the 2050 system, we assume 230 GW of biomass and 500 GW of natural gas plus CCS, running on average about 2,330 hours per annum (i.e. about 27% utilisation).

Exhibit 7-7 illustrates how these different forms of flexible response or storage could be combined to balance daily supply and demand in the 2050 system. This would entail:

- Biomass and natural gas + CCS plants not running during the midday period when solar energy is plentiful, but switching on to help meet demand in the evening

and overnight;

- Both PHS and battery storage absorbing surplus electricity during the midday supply peak, and then discharging to meet the evening peak when solar supply is unavailable;

- Demand response playing a role in shifting some demand from the evening peak to the midday hours;

- Hydrogen also playing a balancing role in the summer months in particular.

The technologies thus exist balance to balance intraday supply and demand in the renewable dominated system which we envisage for 2050. Moreover, ETC analysis in other geographies of the costs of providing all the required forms of flexibility has shown that, even in systems as much as 85% dependent on variable renewables, total system costs will not exceed more than about 130% to 175% of the levelized cost of renewable generation, which by 2050 will likely be less than half that of coal generation.

We are therefore confident that more granular analysis of the costs of providing all the different forms of required flexibility will confirm that by 2050 China could deliver 15,000 TWh of zero carbon electricity at a total cost equal to or below that of a fossil fuel-based system.

Relative cost and China’s specific considerations

The likely future costs of wind and solar power production mean that the massive expansion of renewable electricity described in this chapter can be achieved at a minimal and indeed potentially negative cost. Large potential falls in the cost of energy storage also promise to significantly reduce the cost of balancing supply and demand.

By 2050, with continuous cost reduction in equipment and improvement in efficiency, China's LCOE for onshore wind and solar power could further drop by 60% and 70%; capital cost would also see further reduction.

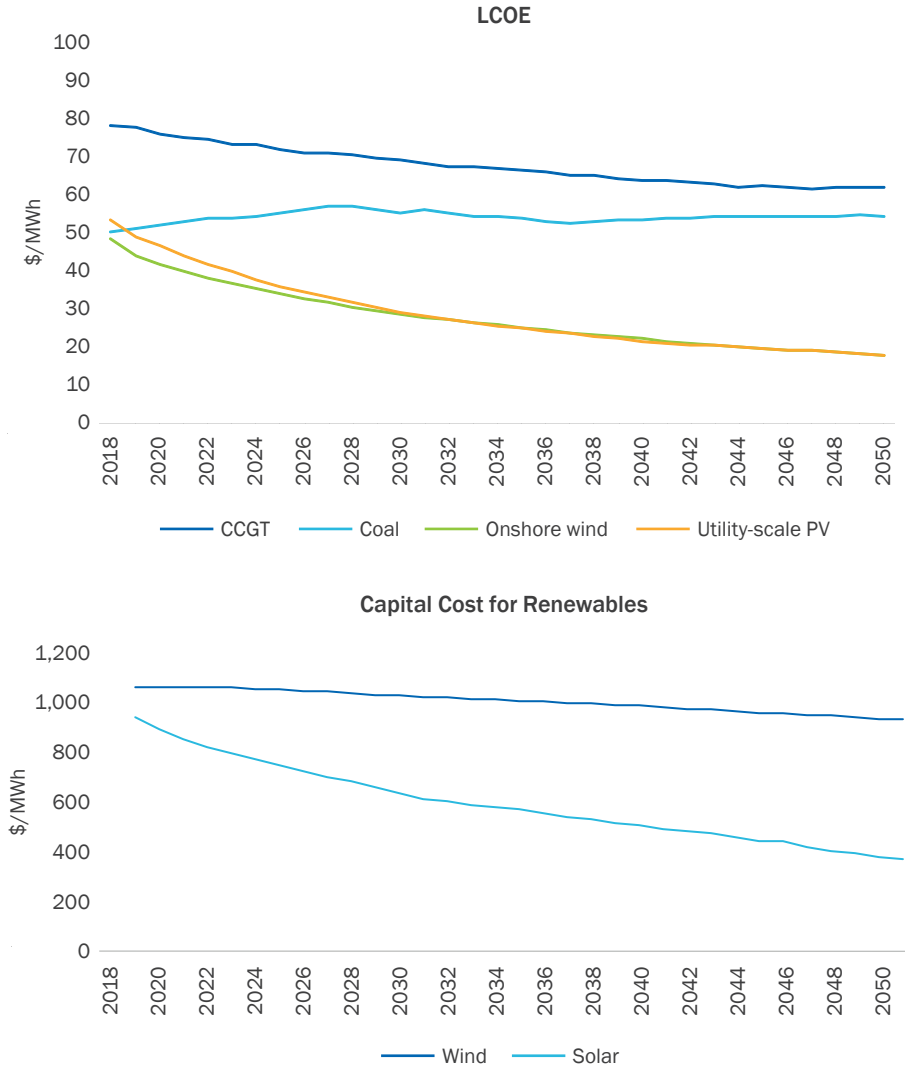


Exhibit 7-9. LCOE and capital costs for solar and wind

Source: Bloomberg New Energy Finance (2018), New Energy Outlook 2018

Since 2010, the benchmark price for solar has plummeted by 84%, offshore wind by over one-half, and onshore wind by 49%. Looking forward, Bloomberg New Energy Finance estimate that further learning curve and economy of scale effects, will reduce the “levelized cost” producing onshore wind by around 60%, from \$56/MWh in 2018 to \$21/MWh in 2050, while the cost of solar

will fall by around 70% from \$70/MWh today to \$21/MWh in 2050 (see Exhibit 7-9).⁽⁷³⁾ These estimates very rapid reductions in the price of solar PV panels, while wind costs are driven down by improvements in turbine efficiency and reduced cost of capital as the market matures and risks decline .

As a result of these cost reductions, solar and wind power will become significantly cheaper than coal or gas generation and would therefore increasingly replace coal and gas in the power system even if there were no climate driven imperative to develop low carbon energy.

To calculate total system costs we have to add also the costs of providing the flexibility and energy storage backup solutions discussed earlier. But the costs of key storage technologies are also falling rapidly and are likely to do so in future.

Lithium ion battery costs have fallen by about 85% since 2010. This reduction has so far been driven primarily by the rapid growth in the scale of EV battery development, but as a by-product of that development the price of batteries for use in grid storage is also falling rapidly, with a further 50% to 60% reduction possible by 2030,⁽⁷⁴⁾ 75% by 2040,⁽⁷⁵⁾ and yet more reductions by 2050.⁽⁷⁶⁾

The cost of making hydrogen from electrolysis is also likely to fall dramatically as the scale of total hydrogen production and consumption increases. The global ETC's report "*Mission Possible*" suggests that total global hydrogen production could increase as much as 10 times by mid-century (from 60 million tonnes to 600 million tonnes), and if this occurs, learning curve and economy of scale effects will produce very large falls in the capital cost of electrolyser equipment, with China likely to lead the way. A recent BNEF report suggests that the costs of manufacturing alkaline electrolysers in China (at around \$200 per kilowatt) are already far below those in Europe (\$1,200) and that this could fall to \$125 by 2030 and around \$90 by 2050.⁽⁷⁷⁾ Costs for megawatt scale PEM systems are likely to fall more slowly, but could still reduce from around \$1,400 per kW today to about \$100 to \$200 by 2050.

Once electrolyser costs are this cheap it would become economic to run electrolysers only a small proportion

of the year (e.g. for 10% of all hours) and during those hours the cost of renewable electricity is likely to be even lower than the LCOE estimates in Exhibit 7-9 suggest.

Combining these factors, BNEF suggests that the cost to produce hydrogen from renewable electricity could fall from a range of \$2.5 to \$6.9 per kilogram in 2019, to as low as \$0.9 per kilogram by 2050.⁽⁷⁸⁾ At these costs, hydrogen will be able to play a major cost-effective role as an energy storage provider within a renewable dominated power supply system.

In its *Better Energy Greater Prosperity* report in 2017, the global ETC estimated that once all the necessary costs of flexibility and storage were allowed for, the total average cost of producing electricity within a primarily renewable system, could be as low as \$70 per MWh in the early 2030s, undercutting the costs of a thermal system. Subsequent developments suggest that the pace of cost reduction is likely to be still faster than that report assumed. And China specific factors – in particular China's proven ability to deliver dramatic reductions in the price of mass manufactured goods such as solar PV panels, batteries, and in the future electrolysers – suggest that the costs in China are likely to be below the global average.

China can therefore commit to building a fully decarbonized electricity system confident that the cost to its economy will be either trivial or negative.

Within such a system our base case scenario assumes that there will still be a role for some thermal plant, providing flexible back up to intermittent renewable power sources. The figures presented earlier assumed that these would be either biomass or gas plus CCS, but it is also possible that already existing coal-fired power plants might provide this flexibility service, with the carbon emissions captured and either stored or used. However, in the long term, if the trends in energy

storage cost are as dramatic as BNEF suggests, storage-based solutions to the balancing challenge may dominate.

Ramping up annual investments and total investment costs

China could build a zero-carbon electricity system delivering 15,000 TWh per annum by 2050, and once it had that system in place, electricity costs would be no higher than today and potentially lower. But a very major scale-up in the annual pace of investment is required to deliver 2050's solar and wind capacity requirement. Around 70 GW of wind and 80 GW of solar would need to be installed annually between now and 2050, compared with the installation rate of 20 GW for wind and 44 GW for solar in 2018.

However, on average over the next 30 years, the capital investment required to build this solar and wind capacity would be less than 0.4% of China's annual GDP. Building the new power system would also require significant additional long distance ultra-high voltage (UHV) transmission capacity to link China's large wind and solar resources to its major centres of population and energy demand. Distribution grid investments would also be required, for instance to support greater penetration of heat pumps. And while the costs of energy storage will fall over time, significant initial investment would be needed.

We have not yet analyzed in detail the scale of these other required investments, and intend to do so as part of ETC China's 2020 work programme. Some of them may be significantly lower in China than in some other countries: in Europe, for instance, long-distance transmission costs are swollen by the high cost of land acquisition and legal and planning disputes, which are likely to be less relevant in China. And it is possible that increasingly decentralized power generation,

storage and demand management systems may emerge, reducing some of the need for centralized grid investment.

But even if the other costs increased the total required investment as much as 75%, the total required investment of 0.7% of GDP per annum would be easily economically feasible in an economy that currently invests 40% of GDP and which should ideally plan to reduce potentially wasted investment in excess property. Chapter 10 discusses these cost and investment implications further.



H₂
Hydrogen

CHAPTER 8
A CRITICAL ROLE
FOR HYDROGEN

Hydrogen is highly likely to play a major cost-effective role in the decarbonization of many harder-to-abate sectors. It will also play an important role as a source of energy storage and supply flexibility in the power system. Our analysis suggests that a net-zero CO₂ emissions China could require an increase in hydrogen production from 25 million tonnes annually today to about 81 million tonnes (2,520 TWh) by 2050. Green zero-carbon hydrogen on this scale could be produced in a number of ways, but it is likely that over time electrolysis will become the dominant cost-effective route.

Expanding demand of hydrogen in China by 2050

Hydrogen will contribute to the decarbonization of heavy industries, heavy transportation, and power system flexibility in China. Our modeling suggests that if China is to become a zero-emissions economy by 2050, hydrogen demand will need to increase from 25 million tonnes annually today to about 81 million tonnes by 2050¹⁸.

Heavy industry. Hydrogen will play an important role in achieving zero-carbon heavy industry. It will serve as a direct heat source for cement and many other industries. It will also be used as reduction agent in the DRI process to produce green steel. Power-to-X would give the chemical industry a new decarbonization option with mixtures of hydrogen, CO, and CO₂ that build up all major chemicals in the value chain. Zero-carbon hydrogen will also be needed to meet both existing ammonia demands and the additional potential ammonia demand considered below (43 million tonnes ammonia per annum in total). For methanol, catalysts are already commercially available globally for hydrogenation of CO₂, and a number of pilot plants are in operation.

Road transportation. In light-duty transport, it is likely

that BEVs will dominate, but hydrogen FCEVs may be preferred by a minority of users who frequently need to make long-distance trips. In heavy-duty long-distance freight, meanwhile, hydrogen FCEVs could play a significant role given the advantage of longer range and more rapid refueling. China is already developing plans for a significant hydrogen refueling network.

Shipping. BEV and FCEV solutions would almost certainly play a significant role in riverine, coastal, and short-distance cruising markets, and the range over which they are economic will tend to expand over time. However, for long distance journeys, BEVs will not be feasible or economic due to the excessive weight of batteries, and hydrogen FCEVs may be uneconomic due to the very large volume of fuel storage required. But in the long-distance international segment, ammonia is likely to play a major role, and ammonia will in turn be made from hydrogen using the Haber-Bosch process (7.6 million tonnes hydrogen needed per annum).

Aviation. In the aviation sector, hydrogen-based planes may be an alternative decarbonized option in short- to medium-distance flights.⁽⁷⁹⁾ Multiple plane designs are now being developed, and some experts believe that hydrogen-powered or battery-powered flights might become feasible for planes up to 100-seaters flying 300–500 km.⁽⁸⁰⁾ But the use of pure hydrogen with fuel cell for aviation still requires significant further R&D.⁽⁸¹⁾

Power system flexibility. Producing hydrogen from excess electricity has the potential to serve as an effective storage mechanism and enhance overall energy system flexibility. Our model of the zero-carbon power system described in Chapter 7 projects at least 100 GW capacity for hydrogen production with curtailed electricity, which would provide system flexibility services (generating electricity either through combustion in gas

18.If we assume 700 million tonnes of steel production in 2050, instead of 475 million tonnes in our base scenario, additional 3.5 million tonnes of hydrogen demand would be induced.

In a zero-carbon China, hydrogen consumption could reach 81.1 million tonnes annually.

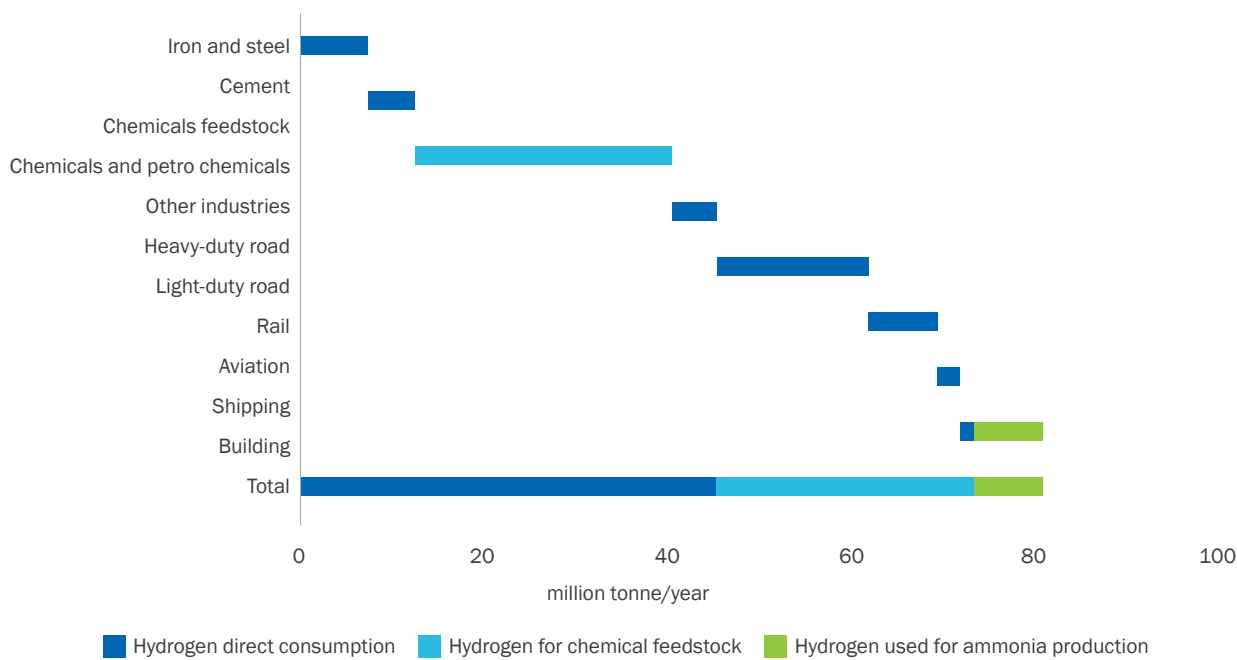


Exhibit 8-1. Hydrogen demand by sector and by use

Source: Rocky Mountain Institute analysis for ETC China

turbines or via fuel cells), through mixed gas or fuel cells, with a need for a maximum of 1 million tonnes (30.3 TWh) of excess hydrogen storage capacity.

In total, as Exhibit 8-1 shows, these demands could imply the need for 81 million tonnes of hydrogen production per annum to meet transport and industrial needs in 2050, with the biggest demands arising from the iron and steel, chemical feedstock, and heavy-duty transport sectors. In addition, hydrogen would be continually produced and used in the power sector.

Producing this hydrogen in a zero-carbon fashion will be essential if China is to achieve a zero-carbon economy.

Multiple routes for zero-CO₂ emission hydrogen production

There are several technical feasible routes for China’s

hydrogen production to meet the zero-carbon emission requirement: (1) electrolysis using zero-carbon electricity; (2) applying CCS to coal gasification and steam methane reforming; and (3) collecting and using by-product hydrogen without additional fossil fuel consumption.

Among the annual 25 million tonnes of current hydrogen production, 40% is made via coal gasification and 12% through steam methane reforming. An additional 40% is produced as by-product either from coking in steel production, the production of chlor-alkali, or the dehydrogenation and cracking of light hydrocarbons. By-product hydrogen could be counted as zero-carbon if no additional fossil fuel would be consumed to collect and purify the hydrogen, which would be otherwise wasted. Some by-product hydrogen is now used as feedstock and a heat resource onsite now, whereas the rest could be purified with the Pressure Swing Adsorption (PSA) method and collected as high-quality hydrogen.

Under ETC decarbonization analysis, water electrolysis with renewable electricity will take the majority of hydrogen production.

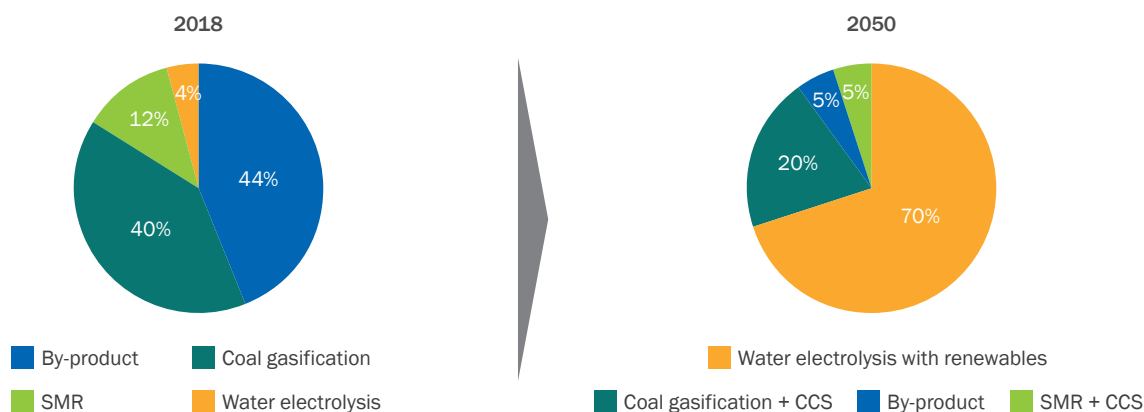


Exhibit 8-2. China's hydrogen production routes in 2018 and in 2050

Source: China Hydrogen Alliance (2018 data), Rocky Mountain Institute analysis for ETC China (2050 data)

Electrolysis, mostly using the alkaline method, is currently higher cost and accounts for only 4% of total production. At present, moreover, electrolysis is not a zero-carbon route to hydrogen production given the dominant role of coal in Chinese power generation and the resulting high carbon intensity of electricity supply. Indeed, given the current carbon intensity of China's electricity (about 590 CO₂/kWh), electrolysis could be as much as 3–4 times more carbon intense as coal gasification.

Transitioning this production mix to zero-carbon by 2050 will require some mix of :

- A massive increase in the role of electrolysis combined with decarbonization of China's electricity generation. If 70% of the estimated 81 million tonnes of future hydrogen demand were met by electrolysis, the incremental demand for zero-carbon electricity would reach to about 2,600 TWh.

- Coal gasification (or Steam Methane Reforming, SMR) combined with CCS/U may be one of the more cost-effective forms of CCS given the high purity of CO₂ stream produced from either a natural gas-based SMR or coal

gasification process. Although the current capturing technology can effectively reduce emissions 90% to 2 kg of CO₂ per kg of hydrogen, future advancement in technology may make possible a 98% reduction, to only 0.4 kg CO₂ emission per kg of hydrogen.

- Other zero-carbon hydrogen production technologies, such as thermochemical processes with High Temperature Gas Cooled (HTGC) nuclear reactor or other heat sources, methane pyrolysis and photoelectrochemical processes may provide alternative routes in the long term but are still far from commercial application.

- The production of biomethane for use instead of natural gas in an SMR process is also technically possible but is unlikely to play a major role in China, given other higher priority demands on limited sustainable biomass resources.

Relative costs: electrolysis is increasingly competitive over time

At present, the most cost-effective way to produce

hydrogen in China is via coal gasification. But the costs of electrolysis are likely to fall dramatically over time, whereas the costs of fossil fuel-based production routes will likely remain stable and indeed will need to increase as CCS is applied. As a result, it is likely that at some stage, electrolysis will become the cheapest way to produce zero-carbon hydrogen. Costs to produce zero-carbon hydrogen via electrolysis are likely to fall dramatically for two reasons—the falling cost of electrolyzer capital equipment and the falling cost of zero-carbon electricity.

Electrolyzers are likely to fall rapidly across the world due to the economy of scale and learning curve effects, and could fall particularly rapidly in China as labor costs are eliminated via automation. As already mentioned in Chapter 7, China is believed to be already producing alkaline electrolyzers at costs far below European levels (\$200 per kW versus \$1,200), with potential for costs to fall further to around \$90 by 2050.¹⁹ And a megawatt-scale Polymer Electrolyte Membrane (PEM) system capex could also fall to \$100-200/kW by 2050.^{(82), (83)}

In addition, the cost of zero-carbon electricity is likely to fall steadily as both renewable and nuclear technologies are deployed on a far larger scale. With the optimized power system design in Chapter 7, LCOE of renewable electricity could fall to \$20–\$30/MWh by 2050.

But in an electricity system dominated by variable renewables, the relevant price of electricity paid by hydrogen producers could be lower still, because the price of electricity will vary according to the balance of supply and demand, and hydrogen producers will be able to use electricity when it is cheapest. Once electrolyzer costs fall to low levels, it becomes economic to use them for only a small portion—for example, 20% or less—of all available hours. Indeed, if

renewable power would otherwise be curtailed, making the marginal price of electricity zero, Bloomberg NEF suggests that by 2030, falling electrolyzer costs could make hydrogen production competitive even if the electrolyzers were utilized only 6%–7% of all available hours.⁽⁸⁴⁾ Flexible hydrogen production could thus become a useful source of demand response within a variable renewable-dominated electricity system.

By contrast, the costs of hydrogen generation with fossil fuels are unlikely to fall significantly given the technology's maturity and the cost of input fossil fuels. Applying CCS, moreover, would result in a \$0.6/kg hydrogen incremental cost, bringing the total cost of coal gasification and SMR to about \$2.15 and \$3.12 per kilogram of hydrogen, respectively.

Exhibit 8-3 and 8-4 show how the cost of the different production routes would compare for different combinations of electrolyzer capital cost and the cost of electricity. At a \$30/MWh renewable electricity price and with electrolyzer cost of \$400/kW, electrolysis would cost less than SMR (even without CCS) and less than coal gasification with CCS, but coal gasification without CCS would still be slightly cheaper (Exhibit 8-3). For electrolysis costs to be on par with coal gasification without CCS, the system capital cost needs to be lower than about \$370/kW and the electricity price to be below \$20/MWh (Exhibit 8-4).

Given likely cost trends, it is therefore probable that, at some time, electrolysis will become the cheaper route to deliver zero-carbon hydrogen. But with coal gasification cheaper today, and a large production capacity already in place and growing, coal gasification will continue to play a major role for several decades, making it essential to also develop the CCS option.

19. The Future of Hydrogen (IEA, 2019) projects \$200–\$700/kW in 2050. Hydrogen: The Economics of Production from Renewables (BloombergNEF, 2019) projects \$80–\$98/kW for a 400 MW-scale alkaline project in 2050. Hydrogen: A Renewable Energy Perspective (IRENA, 2019) projects \$200/kW in 2050.

At a \$30/MWh renewable electricity price, electrolysis would be lower cost than coal gasification with CCS but still more costly than coal gasification without CCS.

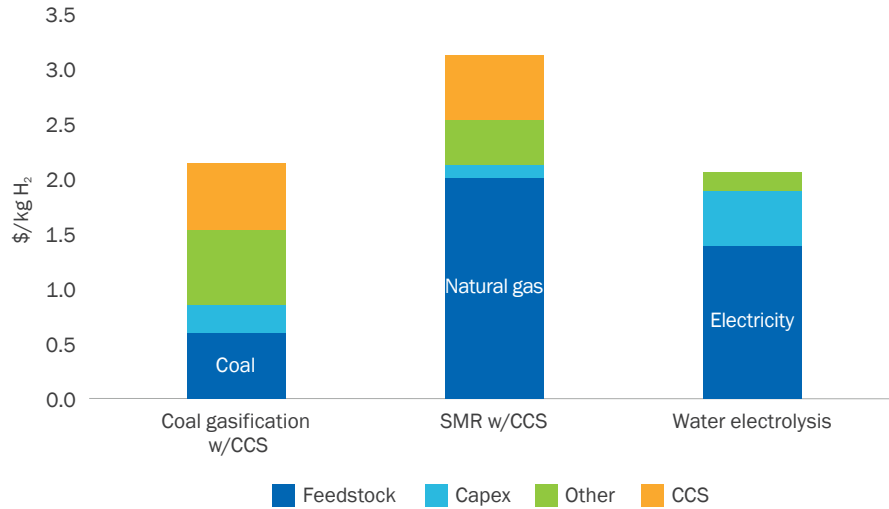


Exhibit 8-3. Zero-carbon hydrogen production cost projection

Assumptions: electricity price = \$30/MWh; electrolyzer system capital cost = \$400/kW

Source: Rocky Mountain Institute analysis for ETC China

For electrolysis costs to be on par with coal gasification without CCS, the system capital cost needs to be lower than \$350/kW and the electricity price to be \$20/MWh.

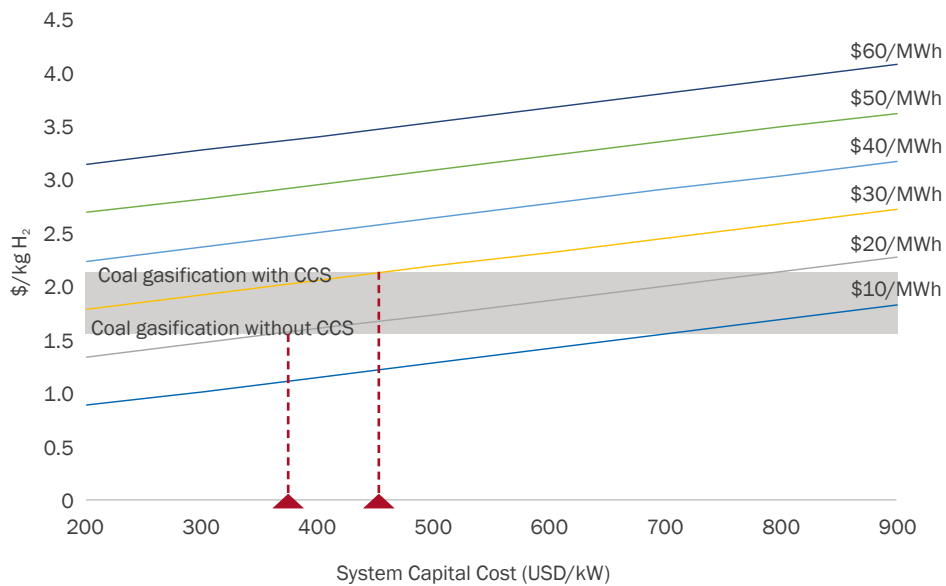



Figure 8-4 Water electrolysis hydrogen production cost under different electricity prices (\$/kg H₂)

Source: Rocky Mountain Institute analysis for ETC China

Our 2050 scenario assumes that, if China is to become a zero-emissions economy, electrolysis with renewable electricity would produce 70% hydrogen in 2050 as the cost decreases, whereas coal gasification may still make up 20% with carbon emissions captured.

Policy support on supporting various hydrogen applications, integrating electrolysis with renewable electricity, and applying CCS to coal gasification would help accelerate the decarbonization of many sectors with zero-carbon hydrogen. Great effort is also needed from industrial stakeholders and researchers on production scale-up and cost reduction.

A large pile of wood chips is being processed by a conveyor belt system in an industrial setting. The wood chips are piled high, and a conveyor belt is visible in the background, transporting the chips. The scene is set against a clear blue sky.

CHAPTER 9
BIOENERGY AND
CCS

Bioenergy: Prioritized and Tight Used

The role of bioenergy and biofeedstock in a zero-carbon economy is a complex issue, given (1) the resource supply limitation of biomass and induced land use, (2) multiple transformation mechanisms for different applications, (3) the relative to the costs of alternative low-carbon options in different sectors. Reflecting these factors, the usage of biomass in China is currently very limited right now due to all of these reasons. For China to achieve a net-zero carbon economy by 2050, our analysis suggests the following conclusions on bioenergy use: (1) there could be up to 17 EJ of potential sustainable biomass resource supply annually in China, but it needs a supporting land use policy and collection system development; (2) biomass consumption should be prioritized to aviation, shipping, chemical feedstock, and electricity generation, given the supply limitation; and (3) biomass routes could hardly be cost competitive compared to other decarbonization routes, and thus additional policy support will therefore be greatly needed to make bioenergy applications economic.

Sustainable supply potential of biomass in China

Estimates of the supply potential of biomass in China vary widely, with a range of studies suggesting figures from less than 12 EJ to about 25 EJ per annum. Our analysis suggests that up to 17 EJ (4,700 TWh) resource could potentially be supplied to support a decarbonized energy mix, including about 7 EJ of crop straws and other agricultural residues, 4–5 EJ of woody harvesting residues, and 3–4 EJ of dedicated energy crops and 1–2 EJ of municipal waste. Municipal waste is likely to increase to levels of developed countries with urbanization but may also be reduced through better waste recycling and management. As for crop straws, 50% would be needed to be reused as fertilizer or

Crop straws, woody biomass and energy crops have the largest potential to support the biomass demand for a zero-carbon China by 2050. (100% = 17 EJ)

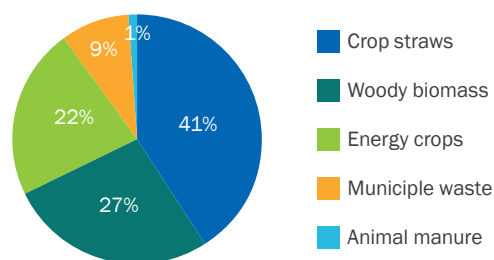


Exhibit 9-1. China's annual biomass resource potential by 2050

Source: Rocky Mountain Institute analysis for ETC China

forage, the same share as today.

But currently, only about 1 EJ of biomass resources is utilized in China annually, suggesting big obstacles in different forms of biomass use.

- **Crop straws.** Crop straw is the largest source of biomass in China given the large scale of agriculture farming. With the world's largest population, the utilization rate of arable land in China is high, and it may not change much by 2050 as the population is likely to remain stable. Thus, the national crop straw production is likely to stay at the current level of 12 EJ per annum in the future. However, the major barrier of crop straw utilization lies in ineffective collection. Lacking large-scale systematic collection mechanisms increases the price of crop straw for end use significantly while the revenues received by the farms are relatively low. Without well-functioned systems for collection and logistics, China's crop straw bioenergy utilization rate is currently very low.

- **Energy crops,** such as corn, sugarcane, sorghum, and oil plants. Energy crops produce the highest energy yields per hectare and are the easiest to convert into biofuels, but they face land use limitation. The Biomass Industry Development Plan (Ministry of

Agriculture, 2007–2015) has identified 100 million hectares of saline-alkali land that is unsuitable for normal crops in western China, but where sorghum can be grown instead, and another 300 million hectares of uncultivated land for growing cassava, sugarcane, and other energy crops. But there remains uncertainty about the precise scale of the opportunity given that in other locations energy crops could compete with food production and urbanization, with the price at which land would be available unclear.

- **Woody biomass.** This includes material harvested from forest crops and residues from logging and wood products. The former requires large-scale reforestation and careful management. Luckily, China is undergoing massive programs to afforest sandy areas, especially in western China, and is very serious about protecting its forests. Thus, the harvestable forest crops would possibly increase in the future. But all woody biomass resources also face the lack of a well-functioned collection system, as is the case with crop straws.

- **Algae.** Although algae may constitute an additional source of biomass for bioenergy and biofeedstock, developments are at an early stages, and the true potential of this biomass source is still unclear.

Effective systems of biomass resource collection are vital to expand China's biomass market and reduce the biomass prices to a reasonable level. It needs policy guidance and business model development support. Detailed land use planning is also essential to ensure the energy crop production for biofuel. After allowing for conversion losses, this 17EJ of primary energy supply potential could support 13 EJ of final demand. We would prioritize biomass demands based on these estimates.

Priority uses of biomass

Multiple sectors in China are currently using or have

the potential to use bioenergy or biofeedstock to drive decarbonization. A sustainable supply of biomass up to 17 EJ annually in China would be vastly insufficient to meet all the potential claim on biomass use in the industry, transportation, building, and power sectors. Biomass use must therefore be focused on sectors where alternative decarbonization routes are least available and cost ineffective.

In the harder-to-abate sectors, aviation and chemical sectors should be considered priority claimants on limited biomass supply, given less availability of alternative cost-effective decarbonization options.

- **Aviation.** Biofuel and synfuel are both zero-carbon solutions for long-distance flight. The relative cost trend is not clear yet, but it is likely that biofuel would play a big role in China's aviation decarbonization. Companies such as UOP and Eni are leading the technology development of aviation biofuel, and Chinese oil companies such as Sinopec and China National Petroleum Corporation (CNPC) have begun cooperation with these international companies on this front. And a partnership between Chinese oil company Sinopec, China-based Hainan Airlines, and Boeing has carried out a trial flight with biofuel.

- **Shipping.** Biodiesel and other biofuels may be cost-effective alternatives to hydrogen or ammonia for powering ship engines in the short term. But potential future cost reduction in hydrogen and ammonia production would reduce the need for bioenergy use in this sector.

- **Road transport.** Given the higher efficiency of electric engines and the vast promotion of BEVs and FCEVs in China, biofuels and biogas probably would not have a big and cost-effective role in road transport. Our analysis suggests major applications of BEVs in passenger vehicles and FCEVs in heavy trucks for a

decarbonized China by 2050.

• **Heavy industry.** Bioenergy may be particularly important in the chemical industry because it could be used as feedstock in monomer production, with the production emission being offset by CO₂ absorbed in biomass growth. Government, companies, and academia in China are making efforts in biomass-based plastics production. Commercialized corn-made plastics production lines have already been developed. Biomass could also be used directly for heat production in heavy industries. But, as explained in Chapter 3, there are alternative routes to supply-side industry decarbonization—such as the use of hydrogen, direct electrification, and carbon capture—and bioenergy may not be a cost competitive one among them.

Other than harder-to-abate sectors, biomass could also support decarbonization of building and power sectors:

• **Building heating.** Although electrification would be the main route to decarbonize building energy use, biomass could play a cost-effective and complementary role in

rural residential areas. Close availability to agricultural and forest resources would reduce the cost and favor the biomass route in rural areas. By 2015, about 100,000 biogas projects have already been built in rural areas in China with a production capacity of 19 billion cubic-meters of biogas (0.4 EJ).

• **Electricity generation:** as argued in Chapter 7, a decarbonized China would build a power system that is highly dependent on renewable energy. But biomass would still play a small role in helping with flexibility. CHP generation with biomass or biogas, which is technically mature, could also help serve the needs in rural areas or industry zones. By 2015, China’s biomass power generation capacity had already reached 10.3 GW, with half of it based on waste.

Given the limited supply of biomass in China, our analysis suggests that:

• Aviation and chemical feedstock would have the highest priorities to use biomass for decarbonization. Aviation would require about 2.92 EJ of biomass by

Biomass consumption for a zero-carbon Chinese economy in 2050 after prioritization.

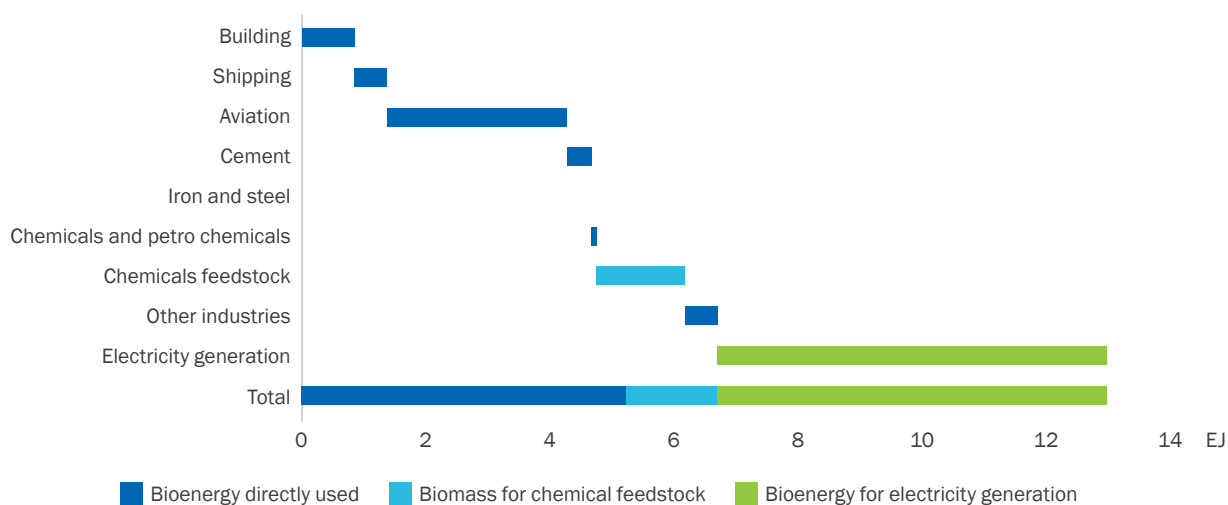


Exhibit 9-2. China’s bioenergy input demand in 2050’s zero-carbon scenario

Source: Rocky Mountain Institute analysis for ETC China

2050, and the number could be lower if cost-effective synfuel is developed. The chemicals industry would consume about 1.45 EJ of biomass feedstock annually, second to hydrogen feedstock (for the power-to-X route), but there would still be some fossil fuel feedstock needed.

- The biggest demand for biomass would come from power generation with 6.29 EJ to provide 7% of China's electricity supply. The need for this application could however decrease if there were very rapid declines in the cost of renewable generation and of other flexibility options such as smart demand management and energy storage technologies, etc..

- Biomass would also help with shipping, building heating, and heavy industry heating, but it would require a sustainable and cost-effective supply of biomass. Alternative decarbonization routes, especially in heavy industries, should be prioritized.

Cost-competitiveness of bioenergy

Bioenergy costs are complicated to assess due to (1) regional variations, (2) multiple biomass resources with different costs, (3) collection and transportation loss of different biomass forms, and (4) various transformation processes some of whose future costs in commercial scale operation are still unclear. As discussed earlier, the lack of well-functioned collection systems could significantly increase the cost of biomass for end uses. The cost of crop straw would also vary from \$40/tonne in the northeast to \$170/tonne in the southeast due to the different farming patterns and resource availability.

Municipal waste is almost certain to be the cheapest biomass source and biofuels or biogas made from municipal waste may therefore become available at costs fully competitive with fossil fuels or natural gas. But the total quantity of municipal waste available is greatly limited (1.6 EJ).

When taking the cost of transformation in different applications into account, the costs of final bioenergy forms remain uncertain. Estimates of liquid biofuel costs differ greatly and would change a lot as new technologies become available. Current estimated costs of bio jet fuel production suggest a large cost premium over conventional jet fuel (e.g., 100%). Some suggest that, even in the long term, biofuels would be competitive with gasoline and diesel only if crude oil prices rise above US\$60–\$80 per barrel. Given that oil prices are likely to decline over time, if demand decreases and prices are set by lower marginal cost producers, a carbon price will likely continue to be required to make biofuels cost-competitive.

As for biogas, costs may be competitive for rural areas' electricity and heating generation projects in China. But for large-scale utilization, biogas is significantly higher than natural gas costs, and almost certain to remain so, according to Ecofys' research.⁽⁸⁵⁾

The costs of solid biomass for use in electricity generation in China right now is also significantly more expensive than unabated coal or gas and could survive only with restricted quotas or subsidies. Also, according to McKinsey & Company, the cost of biomass routes would be at least 3 times higher than hydrogen and carbon capture routes for chemical production, regardless of electricity price.

It is therefore likely that most forms of bioenergy will continue to cost significantly more than fossil fuel equivalents, implying that significant carbon prices, or other forms of policy support, will be required to make them economic. Biomass-based solutions may also be more expensive than alternative decarbonization routes like electrification, hydrogen, or carbon capture in some applications; if this is the case, the role of bioenergy may be less than our scenario suggests.

CCS: A Strategic Option but Limited Role

Given China's very large renewable electricity resource, and the potential to develop hydrogen and bioenergy decarbonization options, CCS needs only to play the limited but still vital role in achieving a zero-carbon Chinese economy, with its application primarily focused on industry and hydrogen production, rather than in the power sector. Our estimated carbon capture requirement of about one gigatonne per annum is easily within China's total storage capacity.

Background: The approach to CCS in China

As a coal-dominated economy, China has for a long time considered CCS as the only currently available technology that can almost fully decarbonize its coal-fired power plants and coal-consuming industries. In addition, it has seen CCS as an interim solution to buy time for transforming toward a low-carbon energy system while still relying largely on coal. The Chinese government has therefore invested millions of RMB

in CCS research and development as early as the beginning of the 11th Five-Year-Plan period (2005–2010).

Pilot projects and large-scale demonstration projects at various stages of development have been put in place.⁽⁸⁶⁾ For example, CNPC's Jilin oil field launched its CCS-EOR (enhanced oil recovery) demonstration project in 2007, with an annual carbon-avoided capacity of 100,000 tonnes; Huaneng Beijing's CHP (combined heat and power) post-combustion capture pilot project began operation in 2008, with annual capture capacity of 3,000 tonnes, and Huaneng also started pilot testing of precombustion capture technology in its integrated gasification combined cycle plant in Tianjin since 2011; Huazhong University of Science and Technology set up a pilot test project on oxy-fuel capture in 2011, with an annual capture capacity of 50,000–100,000 tonnes.

Despite these numerous initiatives, there are not clear and committed plans for the wide deployment of CCS. Most current projects indeed are driven by the application of EOR, which helps create a business case for CCS, but which inevitably increases fossil fuel

Our analysis suggests that carbon capture technology will need to be applied to 1 Gt of carbon emissions, with a 90% capture rate reducing residual emissions to just 100 Mt per annum.

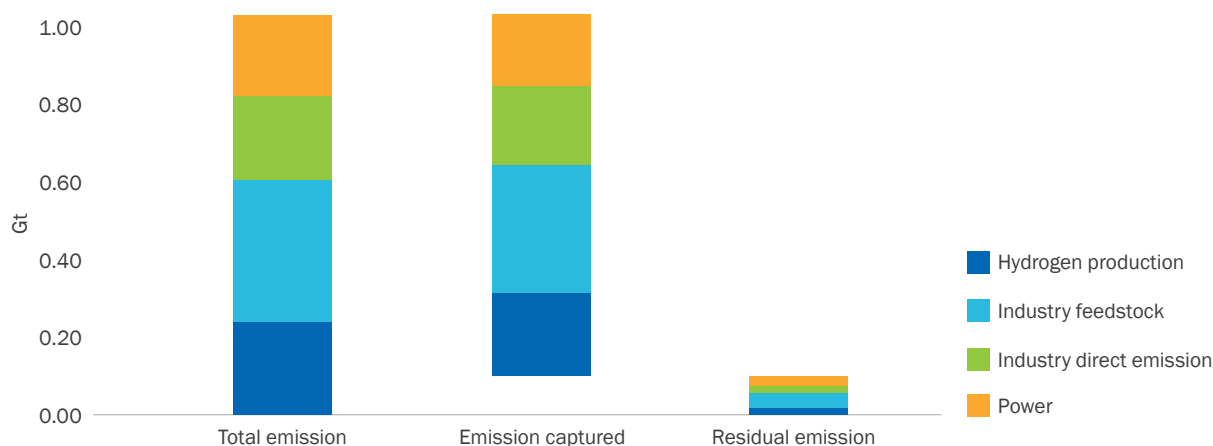


Exhibit 9-3. China's total, captured, and residual emissions

Source: Rocky Mountain Institute analysis for ETC China

production and subsequent emissions.

At the strategic level, this limited progress also reflects the Chinese government’s hesitation to bet a major part of its energy transition on coal plus CCS. The ETC’s global Mission Possible report confirms that this hesitation is well placed, given the potential for electrification and hydrogen to provide a more direct route toward energy transition, their greater potential for future cost reductions, and the massive scale of China’s wind and solar resources.

ETC China scenario: CCS’s limited but still vital role

Our ETC scenario suggests that carbon capture technology will need to be applied to 1 gigatonne of carbon emissions, with a 90% capture rate reducing residual emissions to just 100 million tonnes per annum (see Exhibit 9-3). Key applications of carbon capture will be in (1) hydrogen production, where coal gasification plus CCS, and SMR plus CCS, will continue to play a role alongside electrolysis; (2) fossil fuel used as fuel in the industry sector; (3) chemical feedstock and various industrial processes, such as in steel and cement

(combined, referred to as “industry feedstock” in Exhibit 9-3); and (4) the power sector, where thermal plants are used for short-term and seasonal peak generation.

These estimates include an allowance for CCS/U applied to end of life plastics incineration, since limits to land availability are likely to constrain the role of land fill. But still more complete recycling than we have assumed, together with a potential role for highly secure and tightly managed end of life plastics storage, may and ideally should remove any role for plastic waste incineration. Incineration plus CCS is also likely to be an expensive decarbonization route, given the low density of the CO₂ stream produced and thus high capture costs.

Also, there might be additional 95 million tonnes of carbon emissions to be captured if we assume 140 million tonnes of primary steel production with fossil fuel, instead of 95 million tonnes assumed in the base scenario.

The total of 1 gigatonne is lower than the 2.6 gigatonnes assumed within the IEA’s Beyond 2 °C Scenario, and while China National Petroleum Corporation (CNPC) Beautiful China scenario figure is only slightly higher—

The total 1.0 Gt is lower than the 2.6 Gt assumed within several other scenarios, reflecting our confidence that other routes to decarbonization will be more feasible and lower cost than other scenarios assume.

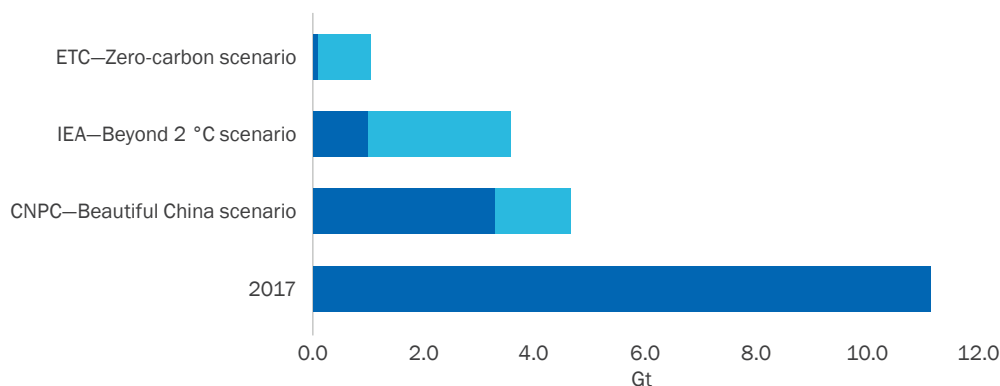


Exhibit 9-4. Emitted and captured CO₂ in different scenarios in China in 2050

Source: IEA (2017), Energy Technology Perspectives 2017; CNPC Economic and Technology Research Institute (2019), World and China’s Energy Outlook 2050; Rocky Mountain Institute analysis for ETC China

at 1.3 gigatonnes per annum—that scenario would still leave China with 3.3 gigatonnes of total net emissions per annum in 2050 (see Exhibit 9-4).

Our lower ETC estimates for required carbon capture, despite the objective of net zero emissions by 2050, reflects our confidence that other routes to decarbonization—in particular, electricity and hydrogen—will be more feasible and lower cost than some other scenarios assume.

Technical feasibility of carbon utilization or storage

Captured carbon emissions could either be utilized or stored underground. There are multiple ways in which CO₂ could be utilized, but it is important to distinguish between:

- Options such as carbon mineralization, or the use of CO₂ in curing concrete²⁰, which produce permanent sequestration, and which are thus compatible with a truly zero-carbon economy.
- The use of captured CO₂ to create chemicals which are then incorporated in plastics, which can create a zero-carbon total cycle as long as the plastics are in turn recycled rather than incinerated.²¹
- Uses such as biofuel from microalgae, methanol, and chemical synthesis, where the CO₂, although initially utilized in a manufactured fuel, will be subsequently emitted when the fuel is burned. Although these forms of utilization reduce emissions by effectively “using the carbon molecule twice,” they cannot deliver a zero-carbon economy.^{22,23,24}

China has approximately 2,500 Gt of theoretic carbon storage capacity, within which is 1,500 Gt of effective and practical capacity, theoretically making it possible to absorb 1 Gt per annum for 1,500 years.

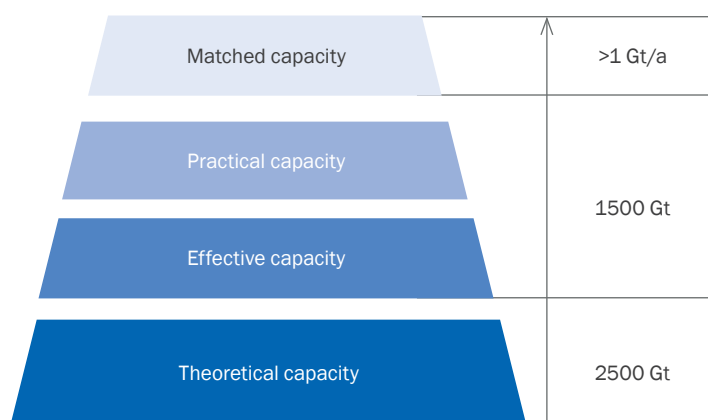


Exhibit 9-5. China's carbon storage capacity

Source: Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

20.This technology has for instance been developed by the US company Solidia.

21.Sichuan University's research team has developed the technology that uses captured carbon to produce high-value chemical products.

22.In our vision, although EOR and ECBM help reduce the costs of CCS and may therefore be critical technologies to drive CCS deployment, because they help produce more fossil fuel, we don't consider them to be zero-carbon solutions.

23.In 2019, China University of Science and Technology's team developed a new catalyst to convert CO₂ into methanol.

24.China ENN Energy Group pilot-tested a microalgae carbon absorbing system to use CO₂ captured from a coal-fired power plant.

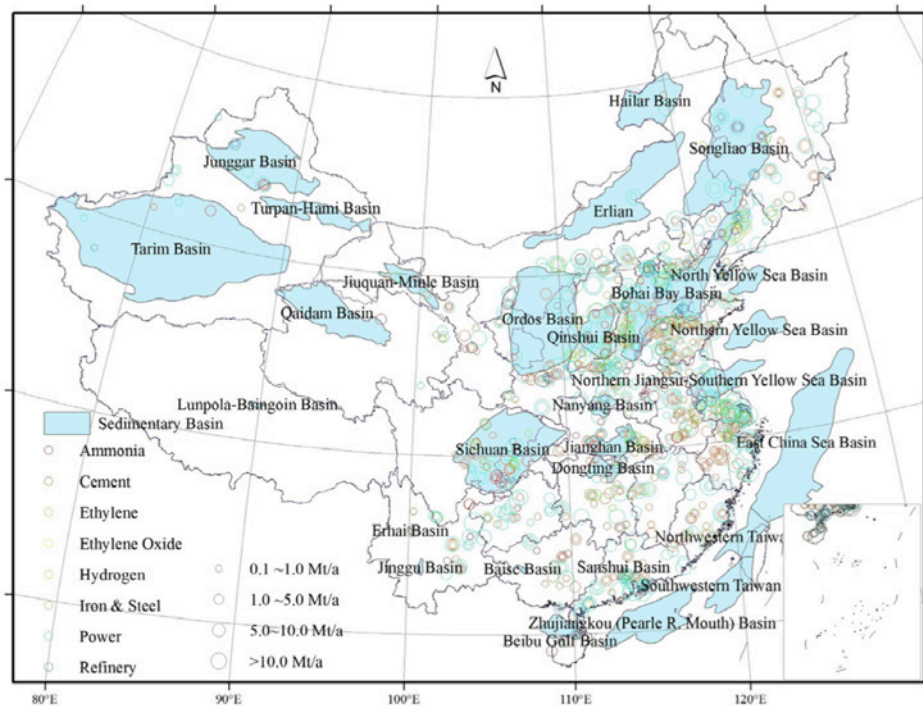


Figure 9-6. China's carbon emission sources and storage sites

Source: Institute of Rock and Soil Mechanics, Chinese Academy of Sciences

- The use of CO₂ storage to achieve EOR or enhanced coal-bed methane (ECBM) recovery, which will result in carbon emissions when the oil is burned, and which could lock in the economy to a high carbon future.

Although mineralization and concrete curing options that a company called Solidia demonstrates have considerable potential and should be developed as strongly as possible, it is still likely that the majority of captured CO₂ emissions will need to be stored. Estimates of China's total storage capacity suggest that this is easily feasible in a way which would minimize transportation costs.

According to a study by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, China has approximately 2,500 Gt of theoretic carbon storage

capacity, mostly aquifer storage sites (see Exhibit 9-5). Applying filters relating to technical efficiency, environmental and geographical risk management, and social and economic impacts suggests a total effective capacity of 1,500 gigatonnes, theoretically making it possible to absorb 1 gigatonnes per annum for 1,500 years.

Furthermore, a study by the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, shows that if one assumes a 250 km limit to the distance between the emission source and the storage location, China has a "matched capacity" to store 1 gigatonnes of CO₂ per annum. China could thus meet the required ETC scenario while avoiding the higher transportation costs needed to take CO₂ from the East Coast of China to, for instance, the very large Ordos Basin aquifer sites in the

northwest (see Exhibit 9-6).


Costs of carbon capture, transportation, and storage

The costs of applying CCUS in China are likely to be similar to or below global estimates of current and future cost.

- The *Mission Possible* report, drawing on estimates from the Global CCS Initiative, showed that capture costs are likely to vary significantly by application, from as low as \$12 per tonne CO₂ for SMR to about \$60 for steel production and \$90 for cement. When carbon capture is applied to the power sector, the significant efficiency losses are an important part of the total cost.

- Transportation costs depend on the distance over which the CO₂ must be moved, whereas storage costs vary as between onshore and offshore locations. Global estimates suggest total onshore transportation and storage costs of between \$7 to \$12 per tonne, and offshore equivalents of \$16–\$37 per tonne.

Given China's favorable storage capacity—which results in storage cost estimates ranging between \$2 per tonne for Bohai Bay and \$10 per tonne within the Ordos Basin—plus the limited need for long-distance transportation suggested by the study of the Institute of Rock and Soil Mechanics, total storage plus transportation costs are likely to be lower in China than in some other locations. And given the large scale of China's economy and its industrial sector, capture costs in China are likely to be reduced via economies of scale and learning curve effects. Estimates from the Institute of Rock and Soil Mechanics suggest that the total cost of capture, transportation, and storage, averaged across all applications, might be about \$55 per tonne.



CHAPTER 10
DECARBONIZATION
ROUTES: SMALL
COSTS AND MAJOR
OPPORTUNITIES

Chapters 3 to 5 argued that it is technically possible to eventually decarbonize China’s industry, building, and transport sectors with multiple options (summarized in Exhibit 10-1). Chapters 7 to 9 proved that it is feasible to provide sufficient zero-carbon electricity, hydrogen, and sustainable biomass, or to use matched carbon capture capacity, to achieve a fully decarbonized economy by 2050. This chapter shows that this decarbonization can be achieved at a minimal economic cost to growth and consumer living standards. It covers in turn:

- The different abatement costs per tonne of CO₂ saved in the different sectors;
- The economic cost of achieving “zero by 2050”, including impacts on growth and investment;
- Costs to consumers and producers; the “competitiveness” challenge;
- Other economic, social, and environmental benefits

of decarbonizing China, together with the challenge of managing employment effects in specific regions.

Overall it is clear that the costs of achieving a zero carbon economy will be very small relative to the costs which unabated climate change would impose on China and the whole world.

Abatement costs per tonne of CO₂ saved

The ETC’s *Mission Possible* analysis—together with the analysis in our earlier report, *Better Energy, Greater Prosperity* (2017)—has illustrated the wide variety of marginal abatement costs by sector of the economy. In the electricity sector, systems that are as much as 85% dependent on variable renewables will become fully cost competitive with fossil fuel-based systems by the mid-2030s, even after allowing for the costs of flexible backup and energy storage required to deliver electricity throughout the day and year. The long-term marginal abatement cost in electricity will therefore be either nil

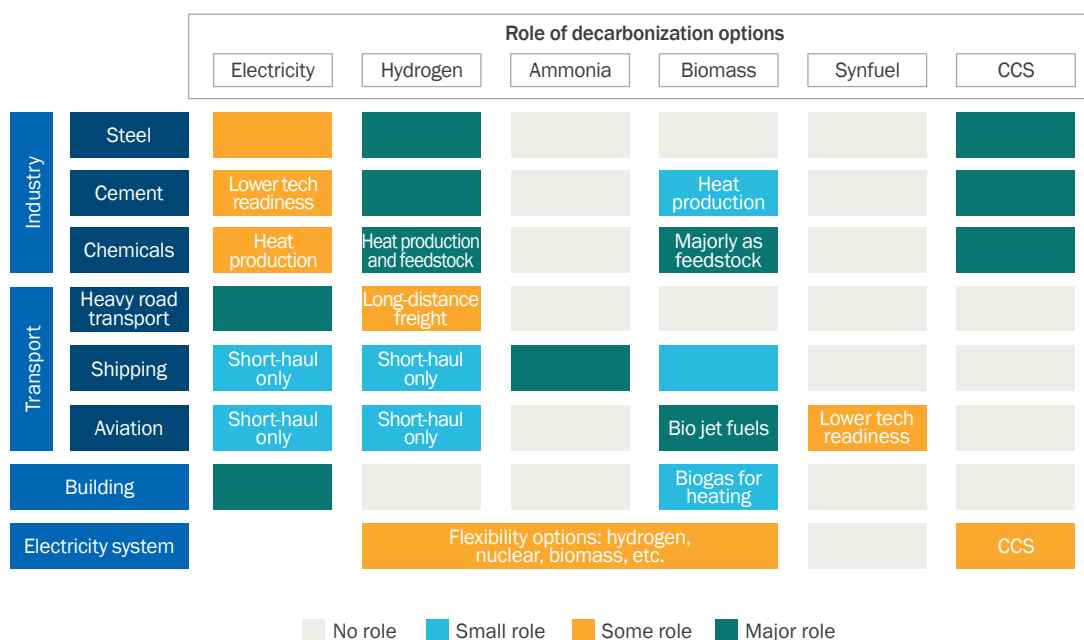


Exhibit 10-1. Multiple decarbonization options by sector

Source: Rocky Mountain Institute analysis for ETC China

or negative.

Similarly, the electrification of surface transport, both for light-duty vehicles in the short term and eventually heavy-duty vehicles as well, will result in significant cost savings. In the harder-to-abate sectors, however, we estimate significant marginal abatement costs, at least in the medium term, ranging from \$25–\$60 per tonne for the steel sector to \$150–\$350 for the shipping sector (see Exhibit 10-2).

We have not yet conducted analysis of marginal abatement costs specifically in China, but inherent Chinese actors make it likely that in several sectors the costs will be below global average levels. In particular:

- Although the cost of decarbonizing electricity relative to the current fossil fuel alternative may be significant in the short term, because coal resources are very cheap, in the long run China’s exceptional endowment of wind and solar resources makes it well placed to decarbonize

electricity at low or negative costs. Cheap renewable electricity will in turn make it possible to decarbonize industries such as steel (via hydrogen direct reduction) or shipping (through the use of ammonia derived from zero-carbon hydrogen) at a lower cost than the global average.

- China’s huge economic scale and high savings rate will make it possible to achieve economies of scale and learning curve effects in key technologies (such as electrolysis), and to mobilize the massive investments needed (in particular in renewable electricity) at a lower cost of capital than in other countries.

- In addition, as Chapter 9 described, China is well placed to deploy CCS at a relatively low cost.

- Conversely, however, supplies of sustainable biomass seemed likely to be more constrained than in some other countries (e.g., in South and North America), making it likely that bioenergy costs may be somewhat higher than the global average.

Costs of harder-to-abate sectors decarbonization vary greatly.

Harder-to-abate sectors abatement costs in a low-cost and high-cost scenarios
US\$/tonne CO₂

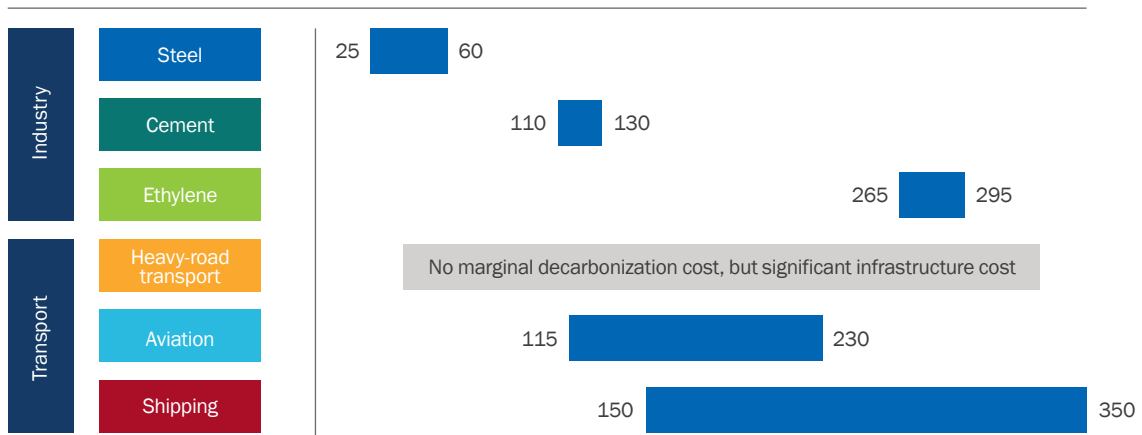


Exhibit 10-2. Harder-to-abate sectors abatement costs per tonne of CO₂ abatement costs by sector

Source: Industry data comes from McKinsey & Company, 2018, Decarbonization of Industrial Sectors: The Next Frontier; Shipping data comes from UMAS analysis for the Energy Transitions Commission, 2018; Data for other transport sectors comes from SYSTEMIQ analysis for the ETC, 2018

In ETC China’s future work, we will conduct more detailed analysis of China’s specific abatement costs, but overall it is reasonable to use our global costs per tonne saved to establish a maximum cost to decarbonize the Chinese economy.

Actual costs could be significantly lower both because of favorable Chinese specific factors and because our analysis excludes possible but currently uncertain technological breakthroughs. If, for instance, technological advances achieved major breakthroughs in cement chemistries, battery density, or new routes to produce biofuels, the total cost of decarbonization would be further reduced.

Minimal costs to the economy: growth and investment

Many global studies, starting with the Stern Commission

report in 2006,⁽⁸⁷⁾ have shown that it is possible to decarbonize the global economy at a cost of no more than 1%–2% of GDP foregone in 2050. Combining our global estimates of marginal abatement costs with China’s specific industrial structure, and thus material production volumes, suggests that the cost of the Chinese economy will be still lower.

In the long run, the costs of decarbonizing electricity and electrifying surface transport will be around zero or possibly negative. For the harder-to-abate sectors, our estimates suggest potential costs ranging from 0.3% to 0.6% of GDP (see Exhibit 10-3), with the most significant additional costs arising, in China as across the world, in shipping, aviation and cement.

In addition, the additional investments required for better building insulation and installation of heat pumps could impose a net cost burden in the building

Our estimates suggest potential costs ranging from 0.3% to 0.6% of GDP with the most significant additional costs arising, in China as across the world, in shipping, aviation and cement.

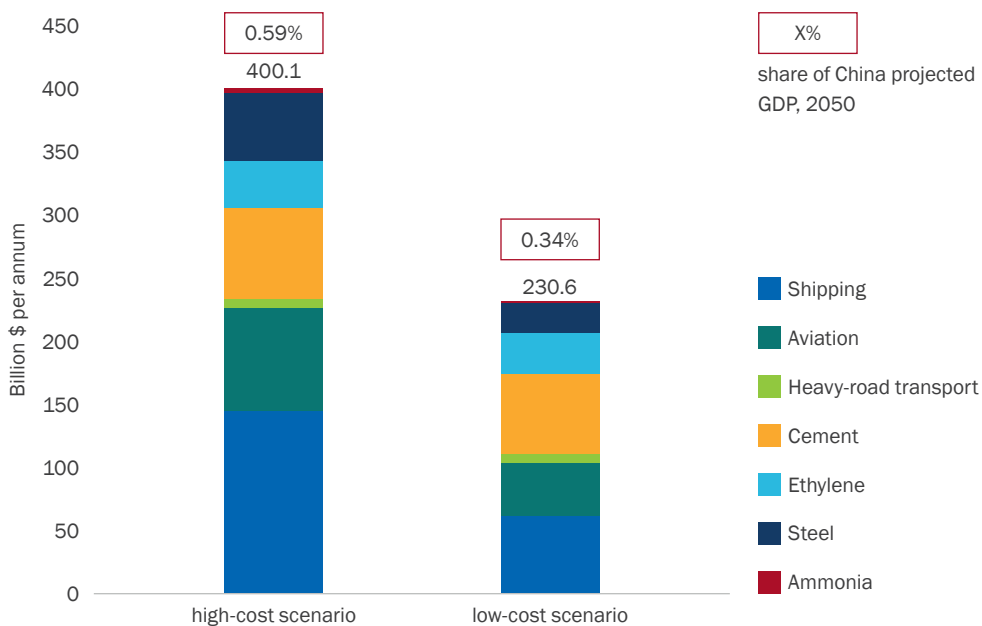


Exhibit 10-3. Total cost estimation of demand-side decarbonization

Source: Rocky Mountain Institute analysis for ETC China

sector. But overall, it is unlikely that the total cost to decarbonize the Chinese economy will be more than 1% of China’s 2050 GDP, implying only a few months’ delay in reaching the standard of living attainable by that date – a standard which by then will be that of a fully developed rich economy.

Meanwhile, estimates of the additional investment required, while very large in absolute dollars or RMB terms, are small relative to China’s savings and investment capacity.

The IPCC’s review of estimates of the additional investment required to achieve a 1.5 °C climate objective shows a median value of about \$0.9 trillion per annum over the next 30 years, which will be something like 0.6% of global GDP in that period. By far the largest element within this is the capital expenditure to build massive amounts of renewable energy capacity. Our analysis confirms these order-of-magnitude figures:

- McKinsey & Company’s analysis⁽⁸⁸⁾, which was input to the *Mission Possible* report, suggests that total additional investment required in the industry sector could amount to about 0.4%–0.8% of global GDP between 2020 and 2050. It is likely that China’s additional investment requirement in these sectors would be a similar percentage of GDP.
- In China and across the world, meanwhile, building

a zero-carbon economy will require annual rates of investment in wind and solar generating capacity of 2 to 4 times the current levels. But in China’s case, our analysis suggests that the additional capital investment required to deliver this generation capacity would still be less than 0.4% China’s likely aggregate GDP over the next 30 years (see Exhibit 10-4). Even allowing in addition for investments in the electricity transmission and distribution system, the total is unlikely to exceed 0.7% of GDP.

These additional investment requirements are quite small relative to China’s high saving and investment rate of over 40% of GDP. Moreover, as China’s population stabilizes and then slowly declines, and as urbanization approaches completion in the next 10–15 years, investments in infrastructures and real estates are bound to fall over time. The investment required to build a zero-carbon economy by 2050 is thus easily affordable and could indeed play a useful macroeconomic role in compensating for the decline of other categories of investment.

Costs to producers and consumers: the “competitiveness” challenge

Given the small impact of complete decarbonization on GDP growth, the impact on consumer living standards must also be quite trivial. But it is important to recognize that the impact on intermediate producer prices can

Annual newly installed capacity	ETC zero-carbon scenario requiremen		2018 actual
	2018-2030	2030-2050	
Wind	76 GW	65 GW	20 GW
Solar	73 GW	83 GW	44 GW

Aggregate investment required would be <0.4% of aggregate GDP




Exhibit 10-4. China’s newly installed wind and solar capacity and aggregate investment

Source: Rocky Mountain Institute analysis for ETC China

Decarbonization of the harder-to-abate sectors would have a significant impact on the price of intermediate products.

		Impact on intermediate product cost US\$ / % price increase	
Industry	Cement	+\$100 per tonne of cement (+\$30 per tonne of concrete)	+100% (+30%)
	Steel	+\$120 per tonne of steel	+20%
	Plastics	+\$500 per tonne of ethylene	+50%*
Transport	Heavy-road transport	No price impact	None
	Shipping	+\$4 million on typical bulk carrier voyage call per annum	+110%
	Aviation	+\$0.3-0.6 per liter of jet fuel equivalent	+50-100%

Exhibit 10-5. Cost implications of decarbonizing harder-to-abate sectors

Source: SYSTEMIQ analysis for the ETC, 2018

still be large in some sectors, with implications for appropriate public policy.

Exhibits 10-5 and 10-6 illustrate this distinction between producer and consumer prices on average over the world. For the industrial sectors:

- Decarbonizing steel production could add 20% to the cost per tonne of steel, but requiring that all automobiles were made from zero-carbon steel, that would add no more than 1% to the price of a typical auto;
- Similarly, decarbonizing cement might increase cement costs by as much as 100%, but the impact on total building costs will be a quite small +3%;
- For plastics, an increase in the price of ethylene of +50% would have an almost imperceptible impact on the price of a liter bottle of soft drink.

The implication is that although China can be confident

that total decarbonization of heavy industry will have only a minimal impact on consumer living standards, companies cannot decarbonize alone without facing a competitive disadvantage. Carbon prices or regulations are therefore essential to drive across-the-board decarbonization; and, as Chapter 11 will discuss, international coordination, or domestic carbon prices combined with border carbon tariff adjustments, will be required in some sectors (in particular, steel) to prevent companies from suffering international competitiveness disadvantages.

In the heavy and long-distance transport sectors, the picture is more varied:

- Decarbonizing trucking is likely to impose no cost penalty over the long term, and there are no international competitiveness considerations that need reflecting in policy;
- Decarbonizing international shipping via the use of new low-carbon fuels (such as biofuel or ammonia)

Decarbonization of the harder-to-abate sectors would have a very small impact on prices for end consumers.

		Impact on intermediate product cost US\$ / % price increase	
Industry	Plastics	+\$0.01 on a bottle of soda	<1%
	Steel	+\$180 on the price of a car	+1%
	Cement	+\$15,000 on a \$500,000 house	+3%
Transport	Heavy-road transport	No price impact	None
	Shipping	+\$0.03 per kilogram of imported sugar	<1%
	Aviation	+\$40-80 on a 6,500-km economy class flight	+10-20%

Exhibit 10-6. Cost implications for end consumers

Source: SYSTEMIQ analysis for the ETC, 2018

might require a significant increase in freight rates, but will have only a trivial impact on the price of consumer products;

- However, aviation is the one sector where a major increase in intermediate costs could have significant implications for the end-consumer price. If bio or synthetic jet fuel cost 50%–100% more than conventional jet fuel, this could add 10%–20% to international air ticket prices across the world.

As a result, and as Chapter 11 will also discuss, although countries can take unilateral action to decarbonize domestic trucking, shipping, and aviation, the optimal approach to international shipping and aviation requires international coordination.

Technology and employment opportunities and air quality improvement

Achieving net-zero emissions by 2050 will therefore have only a limited impact on China’s growth rate and

consumer living standards in that year. It will also bring major opportunities to build new technologies and competitive advantage, to create employment, and to improve air quality. But employment effects in specific regions will need careful management.

Technological advance and competitive advantage. A strong commitment to achieve net zero emissions by 2050 would stimulate technological advance in multiple sectors, reinforcing China’s leadership in technologies that will be needed across the world. In particular, for instance:

- Massive electrification will stimulate further development of wind and solar technologies, where China already has two of the top five wind turbine manufacturers and eight of the world’s largest solar panel manufacturers.

- The development of a hydrogen economy will be speeded by technical progress in the electrochemistry of electrolyzers and fuel cells, and by cost reduction

achieved through economies of scale and learning curve effects. In all these respects, China is well placed to be a global leader, mirroring its already strong position in battery technologies.

- China’s leadership role in the electrification of surface transport, if reinforced by a commitment to achieve total electrification by 2050, would make it very well placed to achieve breakthroughs in new battery density chemistries and improved energy density, as well as to be a dominant global competitor in the manufacture of electric autos, buses, trucks, and trains.

- And China’s huge market share in the production of steel and cement leaves it well-placed to develop and deploy at large scale both already applicable new technologies (such as hydrogen direct reduction of iron) and technologies still in the early stages of development (such as direct iron electrolysis and new cement chemistries).

Overall, the NDRC estimates that the gross output value of new energy industries could reach \$2 trillion by as early as 2020. By 2050, it is possible that the hydrogen industry alone could represent a \$1 trillion gross output value opportunity.⁽⁸⁹⁾

Employment creation. A zero-carbon economy will create a large number of jobs. The International Renewable Energy Agency (IRENA) estimates that the global renewable energy sector (including solar, wind, hydropower, bioenergy, solar heating and cooling, heat pumps, and geothermal energy) already employs 11 million people in 2018, with China accounting for 4 million, or 36% of the global total (see Exhibit 10-7). This figure could rise to 24 million globally by 2030 and 29 million by 2050, with something like 10 million jobs in China—considerably more than are employed in the coal industry today. In addition, large numbers of jobs will be created in the EV battery businesses, in high-quality construction to deliver better insulated and more

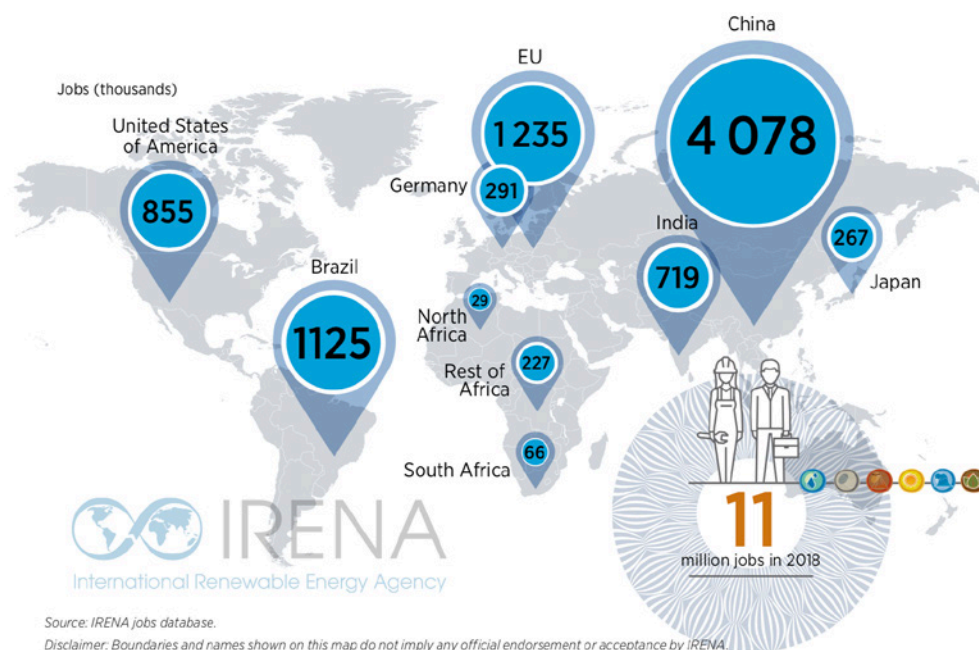


Exhibit 10-7. Renewable energy employment in selected countries

Source: IRENA jobs database

energy efficient businesses and in many other sectors.

In some other specific sectors there will inevitably be job losses, with coal mining jobs in particular almost entirely disappearing. There are estimated to be about 3.3 million coal miners in China by the end of 2018.⁽⁹⁰⁾ In aggregate terms this prospective job loss over 30 years is clearly manageable given that China is currently creating over 10 million new urban jobs each year, and that its working age population (if defined as people aged 20-64) is projected to fall from 926 million today to 750 million in 2050. Indeed, China has over the last 6 years absorbed a loss of about 2 million mining jobs, as the government has enforced the closure of small inefficient mines and concentrated production in a smaller number of large SOEs such as Shenhua Group and China National Coal Group which have productivity rates twice the national average.⁽⁹¹⁾ Estimates suggest moreover that almost 75% of the mining workforce is over 40 years old, and thus certain in any case to leave mining employment by 2050. Nevertheless, since coal mining is concentrated in particular provinces (for instance a quarter of all Chinese coal production is from Shanxi), the loss of jobs in particular regions and cities could have serious local economic impact which will need to be carefully managed.

Improved air quality. Decarbonization of electricity generation and electrification of both surface transport and building heating will also deliver major air quality improvements.

- Road vehicles are a major contributor to both nitrogen oxide and particulate matter (PM) emissions in urban areas; this local pollution effect can be entirely eliminated by vehicle electrification, even while electricity is generated from combustion sources, with all upstream emissions also eliminated once electricity generation is decarbonized.

- Coal-based residential heating is another major contributor to PM emissions in winters in China. Researchers⁽⁹²⁾ have found that heating in northern China results in a 50% increase of PM2.5 emissions compared to nonheating seasons. Since 2017, public policies have sought to change the heating source in northern China from coal to gas or electricity. However, China's limited gas supplies constrain the potential to switch to gas, and although gas heating is better for local air quality than coal, the latest research indicates that gas also has a significant adverse impact on air quality when compared with the zero-emissions solution of electrification.⁽⁹³⁾ The Netherlands, the UK, and parts of California therefore already have plans to ban gas connections to new homes in the near future.



CHAPTER 11
POLICIES TO DRIVE
THE TRANSITION

It is technically and economically feasible for China to achieve net zero emissions by 2050. But this will not be achieved without a clear strategic commitment, set at the highest level of government and supported by multiple forceful government policies and investment plans²⁵. China's economic and political system, which combines the use of market instruments with clear quantitative plans, strong regulation, and a capacity for long-term state-driven investment, makes it well placed to drive rapid progress toward a zero-carbon objective. So too does the potentially important role of provincial and city governments, which often compete to showcase innovative policies and some of which have already committed to specific climate related objectives.

Setting a clear 2050 target

Many countries are now making commitments to zero-carbon targets and dates. As the United Nations Framework Convention on Climate Change reported in September 2019, 60 countries have now committed to reach zero-carbon emissions by 2050 or even well before 2050. The UK is now legally committed to achieve net zero emissions by 2050, with France on a path to do the same. Sweden, Norway, and Finland have all set significantly earlier dates. And the EU will likely soon set a target of zero by 2050.

China should provide global leadership by making a net zero by 2050 commitment. Given China's political and policymaking context, setting such a target would itself have a very strong impact, changing the behavior of state-owned and private firms and providing a clear framework for subsequent decisions by multiple powerful government agencies that have influence over the energy system, such as the NDRC, NEA, Ministry of Ecology and Environment, MIIT, and the State-owned Assets Supervision and Administration Commission.

Powerful policy instruments

Within the context of a clear end objective, an array of policy instruments and specific state investment actions can then be used to ensure progress. These should include:

- Specific quantitative targets for particularly important and clearly necessary investments, such as in renewable and nuclear power development.
- Specific major investments in crucial areas of infrastructure, such as the electricity transmission system, high-speed rail network, and vehicle charging infrastructure.
- Carbon pricing, which can drive change among multiple companies and decision makers, using the power of market incentives to drive a search for least-cost solutions. Policy here should reflect the increasing likelihood that other countries—including the EU and even the United States—will introduce carbon pricing combined with “border carbon tax adjustments,” which impose a carbon price on imports from countries that do not impose similar taxes. A current proposal in the United States by the Climate Leadership Council, for instance, proposes an initial carbon price of \$40 per tonne, rising at 5% per annum. Rather than seeing this as a threat, China could take a leadership position in proposing and imposing a significant carbon price, confident that, as Chapter 10 illustrated, the impact on domestic living standards will be very small.
- Regulation, which can play a particularly powerful role in driving energy efficiency improvement in industry and in commercial and residential buildings, ensuring progress toward a more circular economy, and driving total electrification of surface transport.

25. It is also vitally important for the Chinese government to carefully balance other policies priorities, including energy security, pollution control, poverty eradication and economic growth, while setting up climate targets.

- Government procurement, which could be used to stimulate demand for low-carbon products. Ministry of Finance estimates showed this as 4% of China's GDP in 2018 – but this is likely to cover only direct central government procurement – provincial and city government would also need to be taken into account, as well as the ability within the Chinese system for the government to influence the state-owned enterprises.

- Support for technology innovation and for the early deployment of technologies likely to play a role in the transition to a zero-carbon economy.

The balance between these different policy levers will and should vary by sector. And in two sectors—aviation and shipping—Chinese policy will be most effective if coordinated with global actions. Key sector priorities include:

Power

Decarbonizing power will require a 2–4 times increase in the pace of wind and solar investment, together with the implementation of the nuclear expansion program and significant hydro development. A significant carbon price could play an important role in encouraging these developments, but rapid progress will also require clear long-term commitments to the necessary investments by either the state or the private sector. Policy should therefore include:

- Clear commitments to reduce the carbon intensity (grams of CO₂ per kilowatt hour) of electricity nationally and at a provincial level to reach zero by 2050, with credible intermediate targets for 2030 and 2040;

- Quantitative targets for the growth of renewable power, with auctions used to assure that growing quantities of renewable power are delivered at the lowest potential price; these should be combined with actions to resolve

current problems renewable curtailment;

- Clear strategic plans and investment commitments to support the development of the transmission lines needed to support renewable power generation across the country;

- Reform to the electricity power market to remove barriers to the dispatch of renewable power and to create incentives for the provision of storage and other flexibility options which help balance supply and demand and ensure security of supply;

- Strong support for innovation in multiple energy storage technologies;

- Quantitative targets for the growth of renewable power, with auctions used to assure that growing quantities of renewable power are delivered at the lowest potential price; these should be combined with actions to resolve current problems renewable curtailment;

- Clear strategic plans and investment commitments to support the development of the transmission lines needed to support renewable power generation across the country;

- Reform to the electricity power market to remove barriers to the dispatch of renewable power and to create incentives for the provision of storage and other flexibility options which help balance supply and demand and ensure security of supply.

Industry

Unlike in the power sector, where it is possible to define a small number of clearly essential developments, industrial decarbonization will require multiple actions by state and private companies seeking to find the least-cost route to decarbonization. China should therefore

play a leadership role in putting in place a significant and rising carbon price, combined with border carbon tariffs against imports from countries that do not impose a similar price and rebates for exports.

But regulations also have a crucial role to play in driving energy efficiency improvement and a more circular economy. Policies should therefore also include:

- Using public procurement to favor the use of zero-carbon materials—in particular, steel and cement—in publicly financed infrastructure investment, plus regulations to require the use of zero-carbon products in privately financed investments;
- Strong regulation of plastics sorting and recycling processes to maximize the potential for mechanical recycling;
- Bans on plastic export, landfill, and incineration, which will ensure that all plastics are recycled in either a mechanical or chemical fashion.

Buildings

In the building sector, regulations rather than prices are likely to be the most powerful lever, with appropriate policies including:

- Strong regulation of the insulation standards of new and retrofitted buildings;
- Continued regulation of the appropriate heating and cooling standards of commercial and residential buildings in different parts of China;
- Clear committed targets for the phase-out of coal and gas heating and the move to fully electric solutions, with heat pump installation required wherever possible.

Surface transport

In this sector, regulation and quantitative targets are as important as prices, but public investment also has a crucial role to play. Key policies should include:

- Clear quantitative targets to drive the shift from internal combustion engines to electric engines, while leaving open the balance between BEVs and FCEVs in the trucking and long-distance bus sectors;
- Setting clear future dates for banning the new sale of ICE autos and vans (and, subsequently, light and then heavy trucks). Several countries have already set such dates (e.g., Norway 2025, France 2040, UK 2040, and Ireland 2032). In the UK's case, the date will almost certainly now be brought forward as a logical and necessary consequence of setting the 2050 net-zero emissions target. Given China's already strong leadership role in EVs, and its potential to gain competitive advantage from a rapid shift to EVs, it should set a world-leading early date;
- Public or mandated investment in electrical charging networks and potentially in hydrogen refueling networks;
- Continued rollout of the high-speed rail network and investment in subway and other public transport systems, combined with policies to completely decarbonize the rest of the rail network via either electrification or deployment of hydrogen trains.

Shipping and aviation

In these sectors, China can take unilateral domestic action to drive the decarbonization of domestic aviation and shipping by:

- Imposing a zero-carbon aviation fuel mandate that requires a rising percentage of domestic aviation fuel to

come from zero-carbon sources;

- Mandating a shift of riverine and coastal shipping to electric, hybrid, ammonia, or other zero-carbon technologies beyond specified dates.

In international aviation and shipping, however, decarbonization will occur most rapidly and smoothly if coordinated at an international level. Both the International Maritime Organization and the International Civil Aviation Organization have already set indicative targets to drive down CO₂ emissions by 50% by 2050. China should play a leadership role in arguing within these organizations for a shift to 100% reduction targets, supported by strong international regulations and fuel mandates.

Support for technology innovation and employment

This report has illustrated that it is technically and

economically possible to achieve net-zero carbon emissions by 2050 using technologies that are already known. But some of these technologies are still at a very early stage of commercial deployment and need to be deployed at scale to drive cost reductions. In addition, further technological progress along multiple dimensions could deliver entirely new capabilities that would significantly reduce the costs of the transition to a zero-carbon economy. China is well placed to drive these technological developments and to gain competitive advantage as result.

Public policy should therefore support both fundamental new technology development and early stage deployment of already known technologies.

Exhibits 11-1 and 11-2 set out a preliminary assessment of priority areas for the focus of that support.

Priorities and opportunities in technology development: fuels, materials and carbon capture

Plastics recycling	Reduced costs and increased efficiency of chemical and mechanical recycling
New cement chemistries	Substitution of alternative minerals in place of limestone Concrete curing with CO ₂ instead of water
Carbon capture	New solvents and process designs to reduce cost
3rd Generation biofuels (for aviation)	Reducing cost of production from woody biomass, wastes, algae and other potentially sustainable sources
Synthetic fuels	Reducing cost of synfuel production for H ₂ plus CO ₂ from direct air capture

Exhibit 11-1. Priorities and opportunities in technology development: fuels, materials and carbon capture

Priorities and opportunities in technology development: electricity and hydrogen

Solar PV	Driving further improvements in yield (20% → 30%) via new chemistries (e.g. perovskites)
Hydrogen electrolysis	Driving cost reduction via massive economy of scale (\$850 per kW → \$200 per kW)
Hydrogen fuel cells	Driving cost reduction and efficiency improvement
Hydrogen/ammonia storage and handling	In compressed gas or liquid form; in metal hydrides
Nuclear fusion	May become economic in 2030s
Batteries	Further cost reduction (\$150 per kWh → \$50 per kWh) of lithium ion and gradual improvement in energy density (250 Wh per kg → 500 Wh per kg) New chemistries to achieve major increase in energy density and charging rates
Other storage options	Phase change materials, liquid air, molten salts, compressed air
Heat pumps	Improving coefficients of performance, particularly in very cold weather

Exhibit 11-2. Priorities and opportunities in technology development: electricity and hydrogen

REFERENCES

- (1) United Nations Online population database, median projection.
- (2) Qianzhan Industrial Research Institute. (2018). Report of Prospects and Investment Strategy Planning of China Steel Industry.
- (3) McKinsey & Company. (2017). The Growing Importance of Steel Scrap In China.
- (4) UBS. (2018). How Will a Lower Long-term Scrap Price Impact the Industrial Value-chain?
- (5) China Statistical Yearbook.
- (6) Data from Global Cement and China Cement Research Institute.
- (7) Data from General Administration of Customs, China Cement Association and China Digital Cement.
- (8) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (9) Tsinghua University. (2019). Annual Report of Building Energy.
- (10) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (11) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (12) Changming Gao. (2019). World and China's Cement Industry Development Outlook.
- (13) Technical Approaches to Low-Carbon Transformation of China's Cement Industry (2019).
- (14) Data from Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.
- (15) China Energy Statistical Yearbook.
- (16) IEA. (2017). Energy Technology Perspectives.
- (17) IEA. (2019). The Future of Petrochemicals.
- (18) IEA. (2019). The Future of Petrochemicals.
- (19) Data from Food and Agriculture Organization of the United Nations.
- (20) Data from Innovative Green Development Program.
- (21) Allen G. Good and Perrin H. Beatty. (2011). "Fertilizing Nature: A Tragedy of Excess in the Commons," PLoS Biol 9(8): e1001124.
- (22) Xin Zhang et al. (2015). "Managing Nitrogen for Sustainable Development," Nature 528: 51–59.
- (23) Material Economics (2019), The Circular Economy – A Powerful Force for Climate Mitigation.
- (24) Material Economics. (2019). Industrial Transformation 2050: Pathways to Net-Zero Emissions from EU Heavy Industry.
- (25) The Future of Petrochemicals (2019).
- (26) Material Economics. (2018). The Circular Economy: A Powerful Force for Climate Mitigation.
- (27) Data from China Petroleum and Chemical Industry Federation.
- (28) McKinsey & Company. (2018). Decarbonization of Industrial Sectors: The Next Frontier.
- (29) OECD and IEA. (2007). Tracking Industrial Energy Efficiency and CO₂ Emissions.
- (30) Alexis Michael Bazzanella and Florian Ausfelder. (2017). Low Carbon Energy and Feedstock for the European Chemical Industry.
- (31) DEHEMA. (2017). Low carbon energy and feedstock for the European chemical industry – technology study.

- (32) The Energy Transitions Commission (2019), Mission Possible.
- (33) Natural Resources Defense Council. China Coal-Cap Project.
- (34) China Ministry of Transport. (2019). Statistical Communique of China's Transport Development in 2018.
- (35) Data from China Ministry of Public Security.
- (36) China Railway. (2019). Statistical Communique of China Railway 2018.
- (37) China Urban Rail Transport Association. (2019). Statistical Communique and Analysis of China's Urban Rail Transport in 2018.
- (38) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China
- (39) China Industry Information. (2018). China Vehicles Number and Structure Analysis 2017.
- (40) Data from US Bureau of Transportation Statistics.
- (41) Data from US Bureau of Transportation Statistics.
- (42) Data from US Bureau of Transportation Statistics.
- (43) China Industry Information. (2019). Statistics on China's New Energy Vehicle Sales in 2018.
- (44) Data from www.autohome.com.
- (45) Data from LARGE.
- (46) Data from China Ministry of Public Security.
- (47) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (48) Hong Huo et al. (2007). Projection of Chinese Motor Vehicle Growth, Oil Demand, and CO₂ Emissions through 2050, Transportation Research Record: Journal of the Transportation Research Board (2038) 69–77.
- (49) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (50) China Energy Research Institute of NDRC, Lawrence Berkeley National Laboratory and Rocky Mountain Institute. (2017). Reinventing Fire: China.
- (51) Civil Aviation Administration of China. (2019). Statistical Communique of China's Civil Aviation Development in 2018.
- (52) China Ministry of Transport. (2019). Statistical Communique of China's Transport Development in 2018.
- (53) The Energy Transitions Commission (2019), Mission Possible.
- (54) GIZ. (2013). Climate and Environmental Impact Assessment of Electro-Mobility in China.
- (55) Rocky Mountain Institute. (2019). Breakthrough Batteries: Powering the Era of Clean Electrification.
- (56) China Ministry of Industry and Information Technology. (2016). Technology Roadmap for Energy-Saving and New Energy Vehicles.
- (57) China National Technical Committee on Hydrogen Energy Standardization. (2016). Blue Book on Hydrogen Industry and Infrastructure Development.
- (58) Statista. (2017). Amount of Trucks in China from 2007 to 2017.
- (59) Tsinghua Building Energy Research Center. (2019). China Building Energy Annual Report.
- (60) China Statistical Yearbook.
- (61) Tsinghua Building Energy Research Center. (2019). China Building Energy Annual Report.
- (62) IEA. (2018). The Future of Cooling.
- (63) Data from China National Bureau of Statistics.
- (64) CNREC. (2018). China Renewable Energy Outlook 2018.



- (65) NREL (2013). Land Use Requirements for Solar Plants in the United States.
- (66) ERI, CNREC, and IEA (2014), China Wind Roadmap 2050.
- (67) NEA. (2016). 13th Five-Year Plan for Hydropower Development.
- (68) International Hydropower Association. (2019). 2019 Hydropower Status Report.
- (69) Data from Energy Research Institute, National Development and Reform Committee of China.
- (70) State Grid Energy Research Institute. (2018). China Energy & Electricity Outlook.
- (71) BNEF (2019), Energy Storage Outlook 2019.
- (72) Reinventing Fire: China.
- (73) BNEF. (2019). New Energy Outlook 2019.
- (74) China National Renewable Energy Center. (2018). China Renewable Energy Outlook 2018.
- (75) IRENA. (2017). Electricity Storage and Renewables: Costs and Markets to 2030.
- (76) EU Science Hub.
- (77) Bloomberg New Energy Finance. (2019). Hydrogen: The Economics of Production.
- (78) Bloomberg New Energy Finance. (2019). Hydrogen: The Economics of Production.
- (79) IRENA. (2018). Hydrogen from Renewable Power: Technology Outlook for the Energy Transition.
- (80) ICAO Secretariat. (2019). Chapter 4: Electric, Hybrid, and Hydrogen Aircraft – State of Play, 2019 Environmental Report.
- (81) IEA. (2019). The Future of Hydrogen.
- (82) IEA. (2019). The Future of Hydrogen.
- (83) IRENA. (2019). Hydrogen: A Renewable Energy Perspective (IRENA, 2019).
- (84) Seddon D. (2006). The Hydrogen Economy: Economics of Hydrogen Production from Natural Gas.
- (85) Ecofys. (2018). Gas for Climate.
- (86) ADB. (2015). Roadmap for Carbon Capture and Storage Demonstration and Deployment in PRC.
- (87) LSE. (2006). The Economics of Climate Change: The Stern Review.
- (88) McKinsey & Company. (2018). Decarbonization of Industrial Sectors: The Next Frontier.
- (89) China National Hydrogen Alliance of Hydrogen and Fuel Cell. (2019). China Hydrogen Energy and Fuel Cell Battery Industry White Paper.
- (90) Data from CEIC Data.
- (91) Chinese Academy of Social Sciences' Institute of Urban and Environmental Studies, the Research Institute for Global Value Chains at the University of International Business and Economics. (2019). Research On Employment Issues Associated With Coal Industry Transition.
- (92) Xuan Liang et al. (2015). "Assessing Beijing's PM2.5 Pollution: Severity, Weather Impact, APEC and Winter Heating," Proc. Royal Society A. 471: 20150257.
- (93) Rocky Mountain Institute. (2019). Getting the Facts Right: Clean, Electric Buildings Can Reduce Greenhouse Gas Emissions and Save Money in New Construction.

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