CHINA'S CARBON NEUTRAL OPPORTUNITY

The growing economic advantages and co-benefits of setting aggressive decarbonization goals in the 14th Five-Year Plan and beyond

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EXECUTIVE SUMMARY

This paper examines the relationship between a strong economy and decarbonization in China.[i] Years of remarkable innovation have transformed the economics of clean energy and other clean technologies.[ii] A survey of the latest data and research on technological progress and trends in global markets concludes that more aggressive decarbonization policies present an economic opportunity for China.

Renewable power technologies like solar and wind have reached and surpassed cost-competitiveness thresholds. In much of China, it is now cheaper to decarbonize the grid than to continue relying on coal. Quickening the pace of decarbonization and embracing a more aggressive transition to renewable energy holds the promise of not just a cleaner but also a less expensive and more secure energy system.

A more aggressive domestic program will benefit export competitiveness, too. China is home to most of the world's leading manufacturers of solar photovoltaics—the technology now preferred in global markets and still gaining strength. Innovation associated with market disruption has been most remarkable in the electricity sector, but electric vehicles are also on the verge of a breakout.

Growing economic opportunities are hardly the only reason to accelerate the pace of China's decarbonization program. Of course, there is the moral imperative of maintaining a safe and hospitable climate for generations to come. And an expanding body of evidence shows the immense value of the co-benefits of decarbonization, including higher-quality development, more blue-sky days, strengthened energy security, and greater climate stability.

BUILDING A LOWER-COST ENERGY SYSTEM

The plunging costs of zero emission power from renewable sources have transformed the power sector's economics. Over the last decade, the average cost of electricity in China from new solar plants and new wind plants dropped 82 percent and 33 percent, respectively. As a result of sustained innovation, electricity from a new power plants using renewable technologies is now usually the least-cost option, cheaper than electricity from new coal power plants. Figure ES-1 below presents data on the average levelized cost of electricity from new plants, showing that the cost of new wind dropped below that of new coal in 2019, while the cost of new solar is expected to do the same in 2020.[iii]

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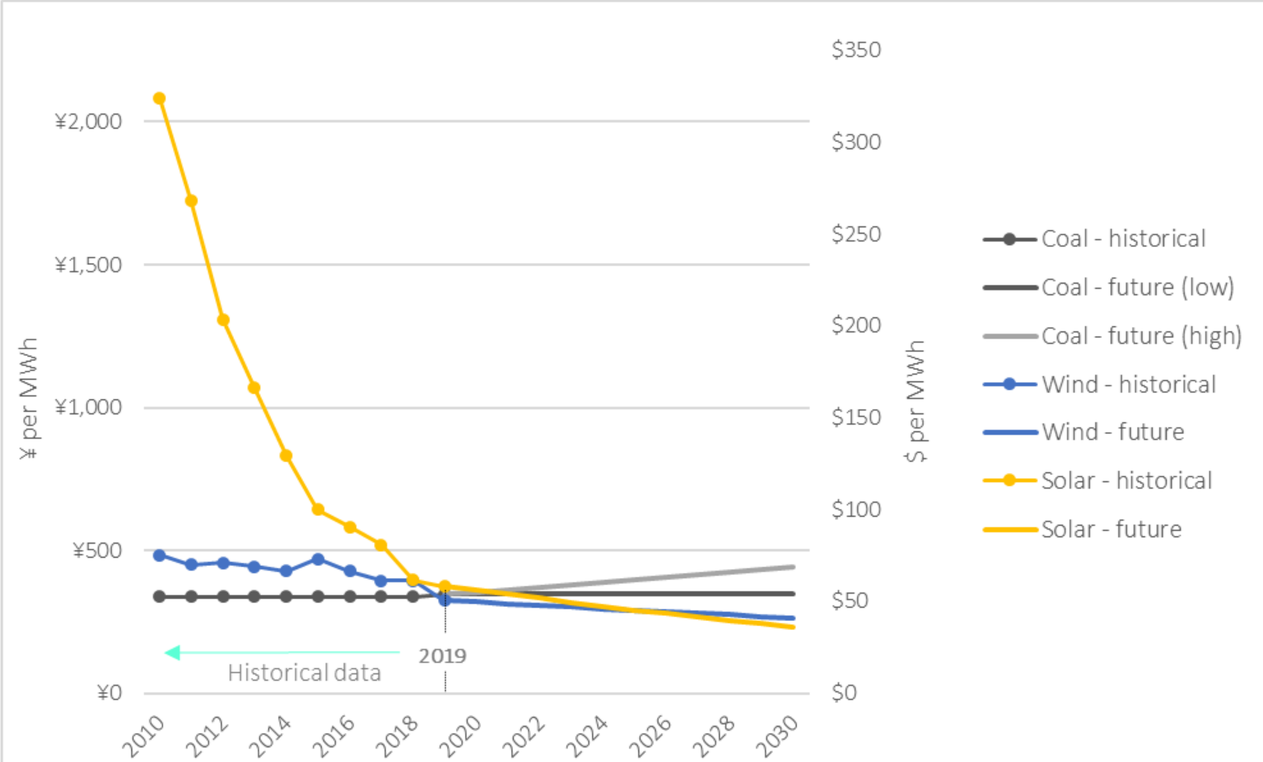
[i] Defining "decarbonization" to include actions to reduce emissions of carbon dioxide and other greenhouse gases.

[ii] Defining "clean tech" broadly to include clean energy, such as electricity generation from solar photovoltaic panels or wind turbines, as well as electric vehicles and other hardware that has efficiency benefits or that can be fueled with low-carbon energy sources.

[iii] Levelized cost of electricity is calculated as the ratio of the present value of total construction and operating costs over expected lifetime electricity generation. Solar refers to utility-scale solar photovoltaic technology. Wind refers to offshore.

Figure ES-1. Solar and wind are now competitive with coal (average cost of electricity from new plants in China)



"Solar" refers to utility-scale photovoltaic power and "wind" to the onshore type (not offshore). Data are capacity-weighted average levelized cost of electricity from new power plants in China in constant 2019 yuan and dollars per megawatt-hour. Levelized cost of electricity is calculated as the sum of construction and operating costs over expected power generation. Around each average levelized cost datapoint, there is a distribution of more and less expensive projects. In a country as large as China, costs vary significantly from region to region.

Sources: International Renewable Energy Agency [1], Carbon Tracker Initiative [2], Wood Mackenzie [3]

Figure ES-1 compares the cost of electricity from generic new renewable plants to generic new coal plants, inclusive of capital, operating, and maintenance costs. But increasingly, electricity from new renewable power plants is more affordable than electricity from existing coal plants, considering only the cost of fuel and other operational costs for existing coal. A June 2020 assessment found 43 percent of existing coal plants in China are running at a net loss and estimated that replacing these uncompetitive units with new renewable power generation capacity could have yielded net financial savings of $18 billion this year [4].

Continued investments in new coal plants and other new capital and infrastructure dependent on fossil fuel use will eventually generate "stranded costs" due to probable early retirement. The global trend has been toward retiring coal plants because of growing public health and climate change concerns as well as innovation and the increasing cost competitiveness of renewable energy—factors that are rendering coal uneconomic. The president of Energy Foundation-China warns that newly built coal plants are fated to "become nothing but scrap metal, a drag on our economic growth" [5].

Stranded costs pose a serious threat to economic development, so the time to deal with them is before further investments are made. In practice, this means shelving new coal investment in favor of a strategic focus on low-carbon sources.

Success in the transition to an energy mix dominated by renewable technologies will require a rethinking of grid management and some investments to ensure system reliability. Such system reliability adequacy costs are outside the scope of the plant-level average costs for solar and wind graphed in Figure ES-1. Even when requirements for highly reliable power supplies and resource adequacy investments are factored in, deep decarbonization shows the potential to yield overall cost savings for the electricity system [6]. One reason is that China's large existing hydroelectric capacity provides a low-cost supply of flexible zero emission power for backing up variable renewable technologies, and its value can be multiplied by investing in new transmission lines [7].

LEARNING CURVES

Improving performance and falling costs for solar and wind power are the result of learning curves for emerging technologies. Greater deployment of clean energy and other emerging technology leads to learning by doing and economies of scale, predictably boosting innovation.

Learning curves are also driving rapid technological progress in battery-electric storage and electric vehicles. The cost of battery-electric storage has plunged 87 percent since 2010, creating increasingly compelling economics for transportation electrification [8]. Electric vehicles are becoming, or in some cases are already, more affordable than conventional vehicles on a cost-per-kilometer basis [9, 10]. Upfront purchase prices, known to be a consumer priority, will reach parity by the mid-2020s if not sooner. A leading Chinese manufacturer expects electric vehicles could become less expensive to purchase than conventional gasoline cars in 2023 [11].

ENHANCED EXPORT COMPETITIVENESS

China has developed leading positions in several rising technologies, including solar power, wind power, advanced batteries, and electric vehicles. These big and rapidly growing export markets can become new pillars of the Chinese economy.

China has installed more solar power than any other country and is home to the world's largest solar power manufacturers. Just small niche players a decade ago, renewable power technologies now are emerging as the leading choice in global markets. The International Energy Agency's executive director comments: "I see solar becoming the new king of the world's electricity markets. Based on today's policy settings, it is on track to set new records for deployment every year after 2022" [12].

China has the world's largest electric vehicle market, served principally by domestic manufacturers. Electric vehicles are rapidly gaining market share and have outperformed conventional cars in the economic turbulence of 2020 [13]. Bloomberg New Energy Finance forecasts that electric vehicles will grow to 28 percent of 2030 new sales and 58 percent of 2040 new sales globally [14]. This forecast is emblematic of a growing consensus that electric vehicles will emerge as the preferred transportation technology in the coming decades.

China's progress thus far will serve it well in the global auto market. By accelerating the transition to electric vehicles, China's policymakers can spur additional movement up the learning curve, further enhancing the international competitiveness of a technology set to become the new global standard.

CO-BENEFITS OF DECARBONIZING THE ECONOMY

The case for enhanced ambition becomes still more compelling when considering the co-benefits of decarbonization, including more blue-sky days, improved environmental quality overall, and better urban mobility.

Improving air quality has been a top priority for citizens and leaders alike for years, and China has made progress on blue-sky goals [15]. There is still room for improvement on air, water, and soil quality. Ma Jun observes that "environmental degradation . . . is beginning to limit growth and may threaten social stability," [16]. An ever-strengthening body of scientific evidence demonstrates both the health benefits of breathing air free from industrial pollution and the broader value of air, water, and soil benefits from climate solutions.

Turning to the connection between sustainability and urban mobility, we see that sprawling, car-dependent cities are a recipe for gridlock, energy waste, and pollution hotspots. Roadway traffic congestion and associated environmental insults reduce Beijing's economic output by an estimated 7.5 to 15 percent [17]. Sustainable urbanization shifts travel demand to non-motorized options like walking and biking, to public transit, or to other "micro-mobility" options, reducing dependence on private car travel. Building cities for people, instead of around cars, has also been shown to improve the overall quality of urban life, retaining and attracting the most productive, talented workers. These are the ingredients of strong and high-quality growth.

Improved energy security is another valuable co-benefit. China's domestic renewable energy potential far exceeds current or future demand, offering a path to less reliance on imports. China is the largest petroleum importer and the fastest-growing importer of natural gas among major economies. The fraction of China's energy demand met with fossil fuel imports doubled from 2014 to 2018. The reduction in oil use from switching to electric vehicles is well understood, but a less-recognized opportunity exists in using advanced heat pump technologies for space heating and hot water in buildings instead of natural gas.

Finally, policymakers must keep in mind the imperative of preserving a hospitable climate—the main reason for more aggressive decarbonization. China is highly susceptible to climate change, facing the threat of desertification in the north, flooding from sea-level rise along the coast, and temperature and precipitation extremes nationwide. The cost of uncontrolled global warming would be catastrophic for China.

POLICY IMPLICATIONS

Despite the increasingly clear economic potential of renewable energy and other clean technologies, existing policy and market momentum are very likely insufficient on their own to drive the energy transition quickly enough. For example, even though electric vehicles are close to cost neutrality or better on an all-in cost-per-kilometer-traveled basis, consumers are known to irrationally undervalue fuel savings [18]. The exaggerated importance of purchase price in consumer decision-making makes continued incentive support vital.

China's national emissions trading system is a promising policy option, but carbon pricing is not a silver bullet. Some cost-effective emission reductions, particularly in buildings and transportation, are immune to price signals. Additional policies are thus needed, such as new building energy codes, vehicle efficiency standards, and zero emission vehicle or equipment requirements.

CONCLUSION

China has achieved rapid economic growth for decades, leading to the fastest and largest poverty reduction in human history. In recent years, the country has embarked on a new mission, creating an economy based more on quality than quantity, and building that economy on the firmaments of sustainable technologies, starting with the energy sector. China's recent pledge to reach carbon neutrality by 2060 represents another milestone on this path and has sent a powerful message to other countries about the direction of the global economy and the urgency of stronger emission reductions.

Such carbon neutrality pledges are essential but insufficient on their own. Success in limiting climate change to reasonable levels will depend on rapid reductions in global emissions over the next decade [19]. Because China's current emissions are greatest in the aggregate of any nation, the likelihood of success will be immeasurably bettered with contributions from China. Near-term reductions in total carbon emissions necessitate ambition beyond the current stated goal of peaking carbon emissions by 2030.

This paper makes the case for peaking China's carbon emissions by 2025 as a core economic strategy. Clean tech innovation has created a new era of economic opportunity in the battle against climate change. By ramping up deployment of cost-effective renewable energy and other low-carbon technologies, China can at once boost its economy and produce significant environmental benefits for its people while significantly increasing the chance of success in humanity's global efforts to halt climate change.

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INTRODUCTION

China's recent pledge to achieve carbon neutrality by 2060 has energized international climate efforts. Carbon neutrality commitments, such as China's pledge and the European Union's commitment to reach net zero carbon emissions by 2050, now extend to places responsible for more than half of current global carbon emissions.[iv] These long-term targets build political momentum, provide an objective for long-term planning, and inform research and development.

Without diminishing the importance of China's 2060 announcement, the imperative of near-term action must be emphasized. The science indicates that the battle against climate change will effectively be won or lost over the next decade. China has an opportunity to set the tone, develop the technologies, and build the momentum for ever-stronger emission reductions in the coming decade, while simultaneously reaping significant benefits.

Of course, policies to reduce greenhouse gas (GHG) emissions must be evaluated according to their domestic costs and benefits. While there is no more urgent task than battling climate change, government leaders the world over face tradeoffs and must continuously balance different priorities, including economic health, social cohesion, employment, and environmental protection.

This balancing job is clouded, in our opinion, by a long-held myth that environmental protection must come at the cost of economic growth. While *bad* environmental policy certainly can be costly, *well-designed* environmental policy can meaningfully boost the economy. This is a profound point—and urgently true for China's leaders at this moment in history.

A confluence of market and technology trends make stronger environmental protection consonant with—even a driver of—economic health, for China more than any other country. A decision by China to ramp up decarbonization could produce net economic benefits from day one, and certainly over a five-year horizon. The costs of solar and wind power have fallen so low that accelerating the clean energy transition—for example, via a coal sunset policy—holds the potential to reduce overall electricity system costs, freeing up funds to assist workers affected by the transition.

Accelerating the decarbonization of China's economy will generate other significant economic and environmental benefits. Starting with the economics: China has a head start in building the technologies of a clean energy future, especially in solar, wind, batteries, LEDs, and electric vehicles (EVs). These are great export businesses, and they will grow rapidly if China commits to

[iv] Throughout this paper, the term "carbon emissions" refers not only to carbon dioxide but also to other greenhouse gases including nitrous oxide and methane, often known as carbon dioxide equivalent (CO_2e).

further progress in clean technology.[v] Many more options are waiting: Super-efficient air conditioners with low-GHG refrigerants; concrete that sequesters carbon in its manufacturing stage; electrolysis that turns surplus electricity into hydrogen, which can itself provide a source of zero emission electricity or serve as an input for synthetic hydrogen or other low-carbon fuels; advanced design that displaces raw materials; system optimization for transportation, freight, and electricity; and much, much more. The economic frontier for clean technologies is vast.

Then there are the indirect benefits of climate solutions, such as the energy security benefits associated with reduced dependence on imported oil and natural gas. Since 2015, China has been the world's largest importer of oil, creating national security risks that can be abated by accelerating EV growth. Similarly, China is now the second-largest importer of liquefied natural gas globally, but electrifying demand for heat in buildings would reverse China's increasing dependence on natural gas imports.

The evidence keeps accumulating, meanwhile, of the immensely valuable clean air, clean water, and soil quality co-benefits associated with stepped-up action on climate change. Finally, China, like much of the world, is deeply susceptible to climate change—be it droughts in the north, sea-level rise and flooding in the eastern coastal areas, or temperature and precipitation extremes in the rest of the country. The science points to catastrophic damages from uncontained climate change. Conversely, success in avoiding these damages would represent a benefit enjoyed for generations to come. Consistent with the imperative of preserving a safe and stable climate, innovation and changing global markets are bringing about new economic opportunities in China.

THE ECONOMIC OPPORTUNITY IN DECARBONIZING ELECTRICITY

Innovation has caused the cost of generating electricity from solar photovoltaic and wind turbine technologies to plunge in China and globally. In much of China, it is now cheaper to decarbonize the grid than to continue relying on coal. The relative affordability of solar, wind, and coal technologies for electricity generation is compared using average levelized cost of electricity, a measure inclusive of installation, operation, and maintenance over a plant's lifetime.[vi] Solar and wind power are variable sources, involving some system reliability costs. Even considering these broader system costs, a 50 percent reduction in power-sector GHG emissions in 2030 presents a cost-savings opportunity [20].

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[v] Defining "clean technology" broadly to include clean energy, such as electricity generation from solar photovoltaic panels or wind turbines, as well as electric vehicles and other hardware that has efficiency benefits or that can be fueled with low-carbon energy sources.

[vi] More specifically, the levelized cost of electricity for a technology is the ratio of lifetime costs to lifetime electricity generation, both of which are discounted back to a common year using a discount rate that reflects the average cost of capital. For China, the International Renewable Energy Agency's calculations reflect a real cost of capital of 7.5 percent and exclude the impact of any financial support.

HISTORICAL DATA ON PLUNGING COST OF RENEWABLE POWER TECHNOLOGIES

Today in China, it is less expensive to build new solar and wind power plants than new coal-fired power plants. Figure 1 illustrates the plummeting costs for renewables using historical, empirical data from China. "Solar" refers to utility-scale projects,[vii] while "wind" refers to the onshore variant.

Figure 1. Plunging cost of solar and wind in China (average levelized cost of electricity, 2010-2019)

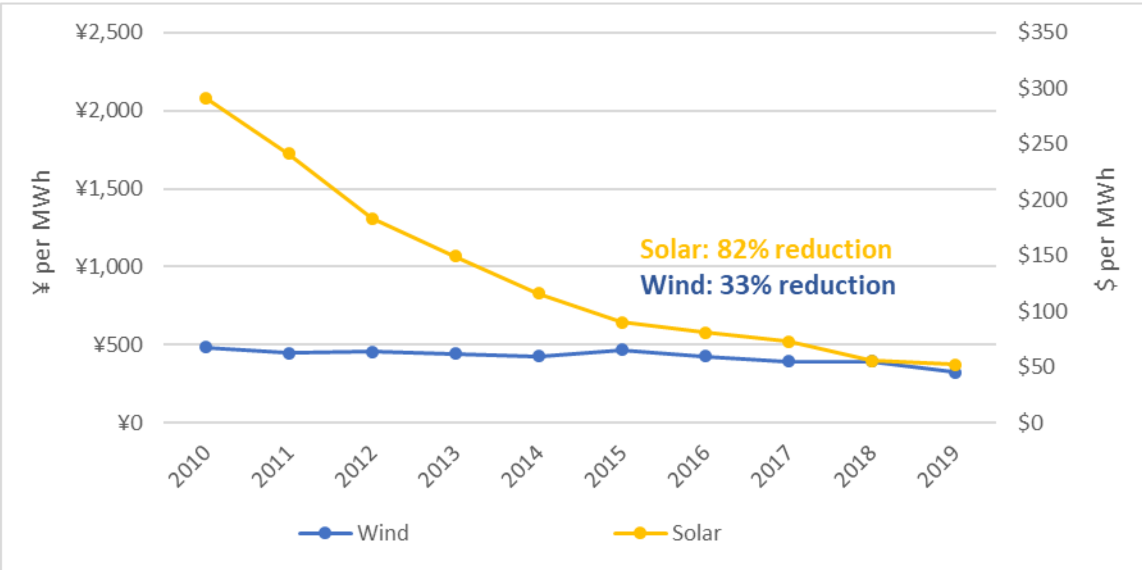


Figure 1 graphs levelized cost per megawatt-hour (MWh) in constant 2019 yuan and dollars.

Source: International Renewable Energy Agency [21]

The average levelized cost of electricity from new solar plants plunged 82 percent in China over the last decade. The average cost of electricity from new solar is expected to be lower than the average cost of electricity from coal beginning this year or next. Onshore wind is a more mature technology, further along its learning curve. Still, over the last decade, the levelized cost of electricity from new wind plants in China declined 33 percent, to ¥325 per megawatt-hour in 2019. The levelized cost of electricity for new coal was ¥340 - ¥345 per megawatt-hour in 2019, meaning that new wind power was less expensive in that year [22], [23].

The steadily declining costs for renewable power technologies observed in China are typical of global trends. Solar power has progressed to the point where the International Energy Agency concludes: "For projects with low cost financing that tap high quality resources, solar PV is now the cheapest source of electricity in history" [24].

[vii] Utility-scale projects are large installations feeding into the electricity grid. Residential and commercial projects typically exhibit higher costs than utility-scale projects. Cost of electricity figures are calculated as capacity-weighted averages. In a country as large as China, costs vary significantly from region to region. Around each average levelized cost datapoint, there is a distribution of more and less expensive projects.

GROWING FUTURE COST ADVANTAGE FOR SOLAR AND WIND

Looking forward, the consensus of global forecasts is that solar and wind costs will continue falling in future years and decades [25]. We develop a future price trend for China using a mid-point of the range of innovation scenarios developed in the International Renewable Energy Agency's latest solar outlook [26]. The methodology is discussed further in the Appendix.

Figure 2. New renewable plants in China generate electricity at lower average cost than new coal plants

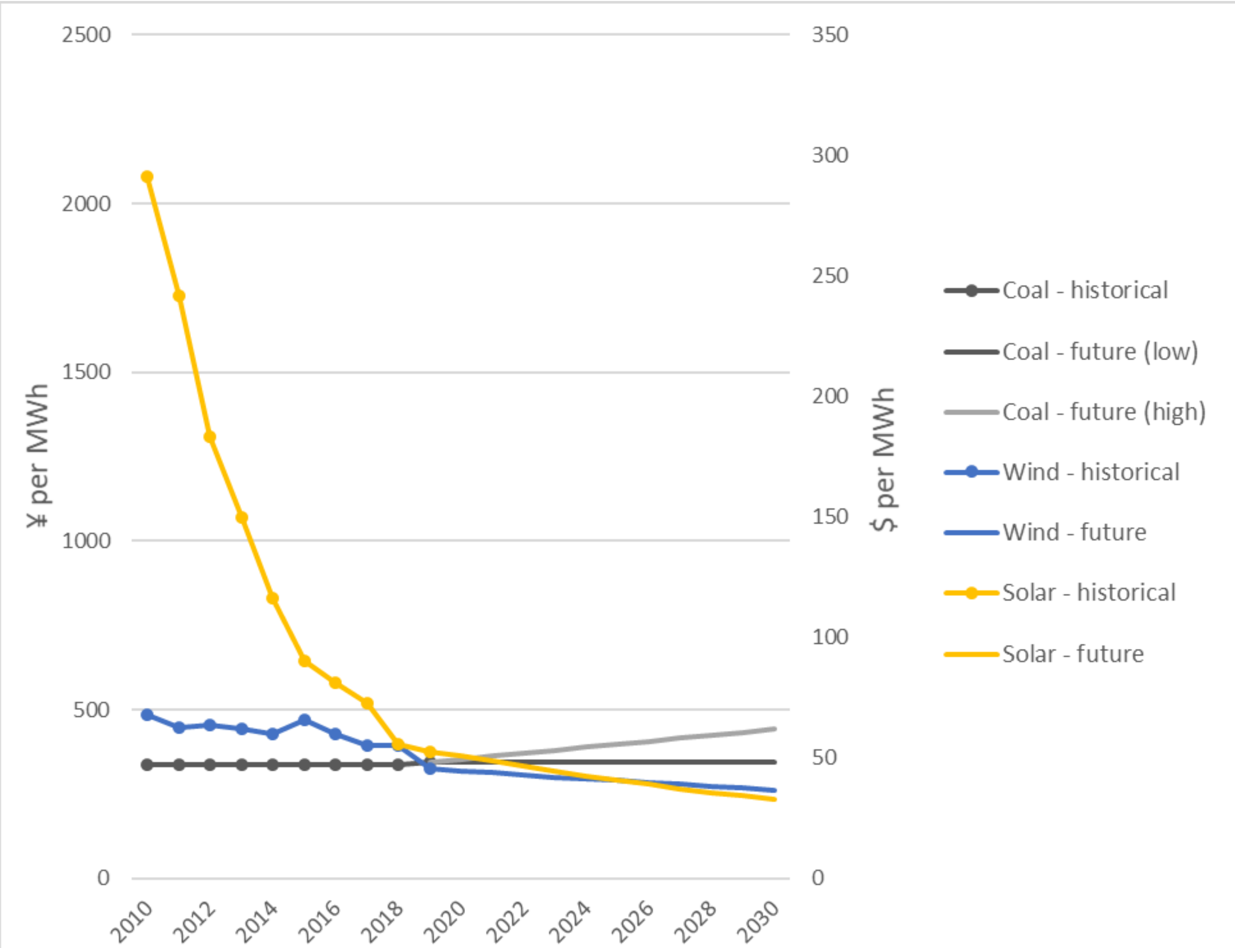
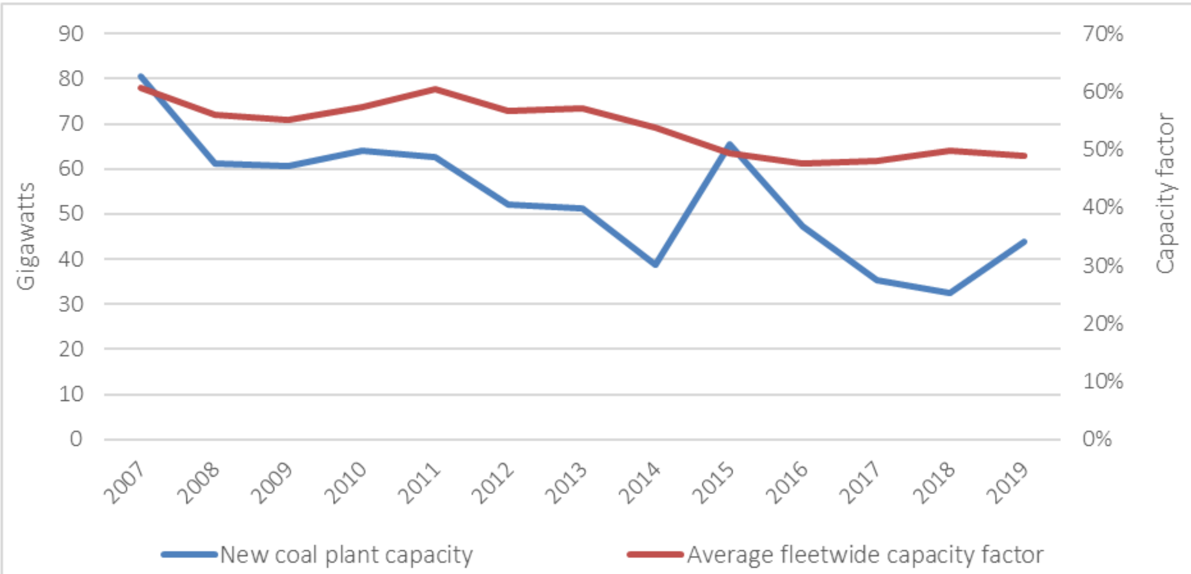


Figure 2 graphs the average levelized cost of electricity from new power plants in China. Units are levelized cost of energy per megawatt-hour (MWh), calculated as the weighted average of costs for new capacity in constant 2019 value yuan and dollars. The Appendix explains the method used to estimate future costs.

Sources: International Renewable Energy Agency [27], Wood Mackenzie [28], Carbon Tracker Initiative [29]

Figure 2 shows historical costs for solar, wind, and coal, along with future cost expectations. Low and high price bounds for coal reflect different assumptions about future capacity factors, i.e., the level of actual generation over full technical potential. The "Coal – future (low)" scenario assumes capacity factors remain at current levels. The increasing cost trend in the "Coal – future (high)" scenario reflects an assumption that future capacity factors for coal will fall, reflecting a continuation of past trends [30]. Data on average capacity factor for coal show declining utilization, as illustrated in Figure 3. New coal capacity additions, also depicted in Figure 3, have undercut public policies aiming to reduce coal power overcapacity and improve profitability in the sector.

Figure 3. Adding new coal power plants lowers capacity factors, reducing overall profitability of coal power



Source: Carbon Brief [31]

Evaluating the competitiveness of renewable technologies has, thus far, been limited to comparing the cost of a generic new renewable plant and a generic new coal power plant. But renewable technology is increasingly outcompeting even existing coal plants considering only their operating expenses, i.e., fuel and maintenance costs. Because operating costs exclude initial construction cost, the comparison to cost of electricity from existing coal plants presents a more challenging affordability threshold for renewable technologies.

In 2020, about 43 percent of existing Chinese coal plants are uncompetitive with electricity from new renewables, even including backup storage necessary to ensure reliability, according to a recent study [32]. The study also finds that investing in new renewables and backup storage to replace these uncompetitive existing coal plants could have saved an estimated $18 billion in system costs in 2020 [33]. A separate analysis, citing Chinese media sources rather than financial data, reached a similar conclusion, stating that “more than half of coal-powered firms are already loss-making, with typical plants running at less than 50 percent capacity” [34].

Looking forward, it is estimated that by 2025, 94 percent of coal plants will be more expensive to run than to replace with new renewable power plants and the storage investments to provide reliability, and failing to retire and replace these uneconomic plants, would impose a net additional cost of $98 billion [35].

A SYSTEMS PERSPECTIVE ON THE ECONOMIC OPPORTUNITY IN ELECTRICITY

To provide reliable power, an electricity system must have an adequate supply of energy to meet demand. In the transition to large shares of solar and wind power, which are variable with weather and time of day, additional investments must be made to guarantee power reliability, sometimes called resource adequacy requirements. The foregoing comparisons of levelized cost of electricity offered a plant-level perspective. Electricity grid managers must consider broader system reliability.

Even when requirements for highly reliable power supplies and resource adequacy investments are factored in, deep decarbonization shows the potential to yield system cost savings, according to an article published in the prestigious journal *Nature Communications* [36]. We review these results below, but we first give some background on the topic of reliability.

An energy mix centered on renewable technologies requires a rethinking of grid management. It would be a mistake to assume each unit of variable power requires one unit of fossil fuel combustion as backup to ensure power reliability. A more efficient approach involves optimizing a mix of flexible supply- and demand-side resources to ensure system reliability. A more flexible system can signal consumers to reduce demand at times of peak use, among other strategies to ensure demand never exceeds supply.

A full treatment of grid reliability is beyond the scope of this paper, but China enjoys several advantages meriting enumeration. The infrastructure development necessary to move power over long distances is likely to be more feasible in China than it has been in the United States or Europe [37]. The ability to access power from distant sources improves reliability by expanding the system's geographic reach. Wind speed and solar insolation variability is less pronounced when viewed over broader geographic areas. Therefore, the importance of weather conditions for electricity system stability, be they clouds shading solar panels or a lack of air currents to drive wind turbines, is reduced with broader geographic coverage.

When renewable electricity capacity is distributed over a larger area and is made accessible through long-distance transmission lines, extreme conditions that might otherwise threaten reliability become easier to manage. Therefore, increasing an electricity system's reach by extending its geographic coverage boosts predictability of renewable technologies, contributing to reliability.

Transmission investments and broader grid coverage have additional value, more generally increasing system flexibility and reliability by allowing grid managers to access a broader array of generation resources at any given time. With broader grid coverage, China's existing hydroelectric resources could serve as an important source of flexible electricity supply, ramping up or down to allow supply to match demand.[viii]

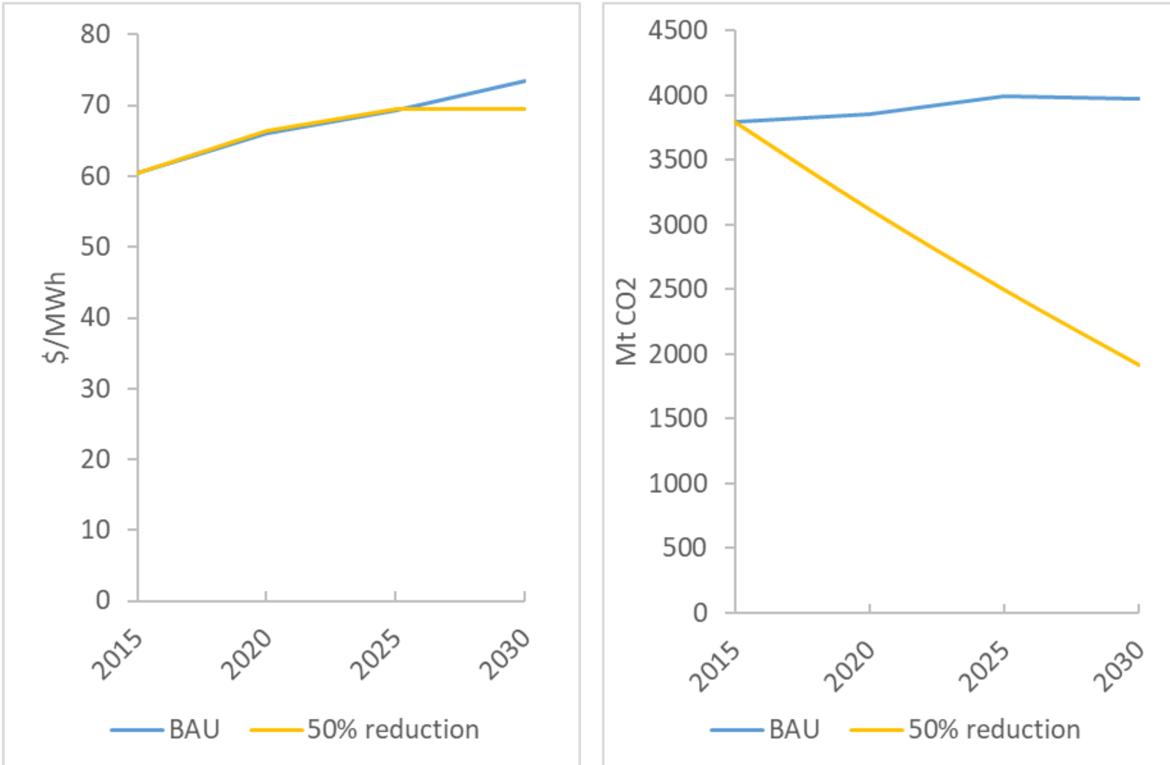
Another strength for China is its well-developed advanced battery industry. Battery-electric storage is another type of investment used to guarantee power reliability as the share of renewables grows. In addition to grid-dedicated batteries, research suggests batteries in EVs could provide a valuable energy supply in some circumstances, reducing the need for other types of flexibility resources [38].

Recent work by Gang et al. published in *Nature Communications* offers new quantitative insight into the cost implications of stronger climate policy for China's power sector. The work finds that a reduction in power-sector GHG emissions of 50 percent by 2030 is roughly cost neutral, delivering cost savings in later years [39]. Specifically, the study indicates that the cost of delivered power rises to $73.5 per megawatt-hour in 2030 under a business-as-usual scenario compared to $69.5 per megawatt-hour in the scenario reflecting a 50 percent reduction in emissions.

The analysis by Gang et al. looks forward through 2030, as illustrated in Figure 4. Consideration of a longer timeframe would have shown increasing cost effectiveness in 2031 and later years for the 50 percent decarbonization scenario because it represents a more capital-intensive and less fuel-intensive set of supply-side resources. Solar and wind plants have no fuel cost; their lifetime costs are largely frontloaded. The solar and wind plants added in the 2020s in the 50 percent reduction scenario are investments that will continue to pay dividends in 2031 and later years in the form of electricity with exceedingly low operational costs.

[viii] A growing body of evidence finds significant negative environmental and social impacts from conventional hydroelectric power technology. For this reason, building new conventional hydroelectric capacity is not recommended. Still, investment in new transmission lines to make better use of existing hydroelectric capacity may be part of an optimal mix. Existing hydroelectric capacity may also be transformed into a type of electricity storage by moving water from lower elevation to higher elevation for later use ("pumped hydroelectric power").

Figure 4. Power-sector costs and emissions: business as usual vs. 50 percent reduction by 2030[ix]



"BAU" refers to the business-as-usual scenario. "50% reduction" refers to a scenario in which emissions are halved in 2030. The left-hand panel shows system cost to deliver power in dollars per megawatt-hour ($/MWh). The right-hand panel graphs annual power-sector emissions in $MtCO_2$ (million metric tons of carbon dioxide).

Source: *Nature Communications* [40]

LEARNING CURVES IN EMERGING TECHNOLOGIES

The trends in solar and wind power technologies described above demonstrate learning curves in action. The "learning curve" for a technology refers to the pattern of regularly improving performance and declining costs commonly observed for new technologies. These improvements accrue because of learning in research settings; learning by doing in production and application; and economies of scale when market viability is reached and production ramps up.

Interdisciplinary studies have solidified understanding of how learning curves work. Laboratory research and development are just the first step on a new technology's journey to market

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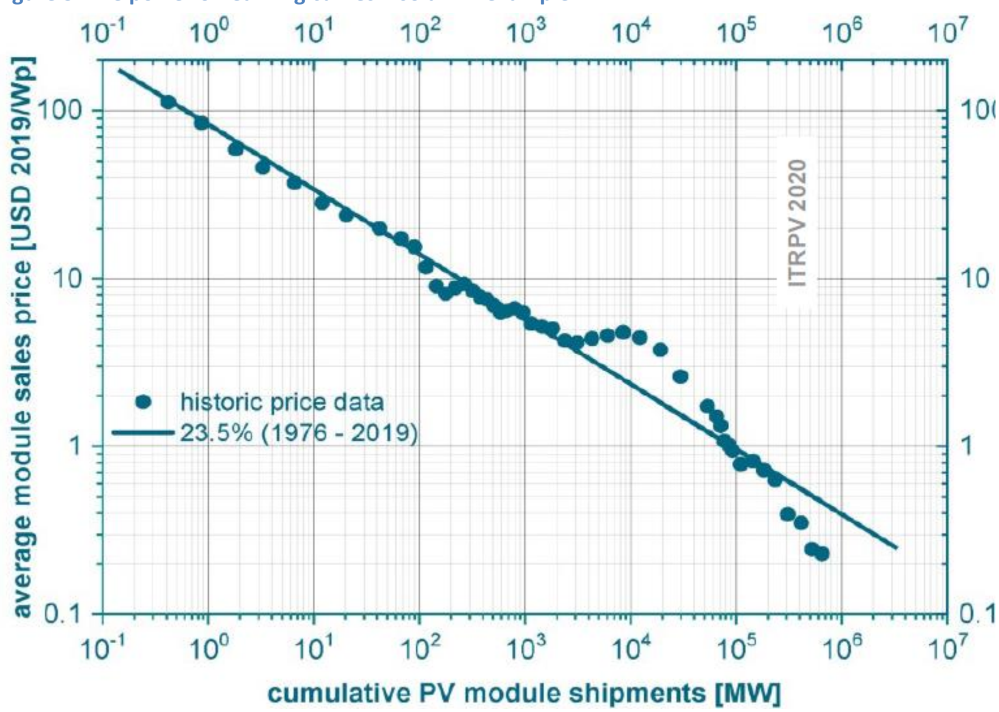
[ix] In addition to the scenarios graphed in Figure 4, the study by Gang et al. finds a cost-minimizing scenario (i.e., "least-cost" scenario, in this case meaning the modeling imposed no carbon constraint). The least-cost scenario achieves 2030 emissions 34 percent lower than business as usual. The least-cost scenario results in an estimated 2030 average cost 11 percent less expensive than business as usual ($65.1 vs. $73.5 per megawatt-hour). By comparison, average costs in the "50% reduction" scenario shown in Figure 3 are 6 percent higher than the least-cost scenario ($69.5 vs. $65.1 per megawatt-hour). Note that renewable energy costs are assumed to be the same in both decarbonization scenarios. If the stronger policy induced additional innovation, the cost differential would decrease. See Gang He et al., "Rapid Cost Decrease of Renewables and Storage Accelerates the Decarbonization of China's Power System," *Nature Communications* 11, no. 1 (May 19, 2020).

readiness. Successful technologies must next navigate the jump from the lab to the market. Once commercial viability is reached, often with initial government support, mass production and deployment begin in earnest. As more units of a technology are manufactured and installed, economies of scale lower the cost. Mass production vastly increases learning across production, installation, and adaptation to real-world conditions, further improving performance. Price declines are not automatic: A technology must be actively researched (in early stages) and deployed (in middle and later stages) to realize cost reductions. Solar photovoltaic (PV) electricity generation is a good example. This technology dates to the 1950s, but for many years it was too expensive to be used commercially except in very limited circumstances, such as to power satellites.

Figure 5 charts solar panel prices and cumulative global shipments using a log-log scale. Over time, laboratory research (including learning from the commercial semiconductor industry) drove down prices, and as prices declined, more commercial applications for solar became feasible and deployment accelerated—a positive feedback loop further driving prices down. The price per watt of a solar cell reached $0.23 in 2019, a reduction of more than 99.5 percent compared to the 1976 cost of $100 per watt [41].

Figure 5. The power of learning curves – solar PV example[x]



Source: International Technology Roadmap for Photovoltaics [42]

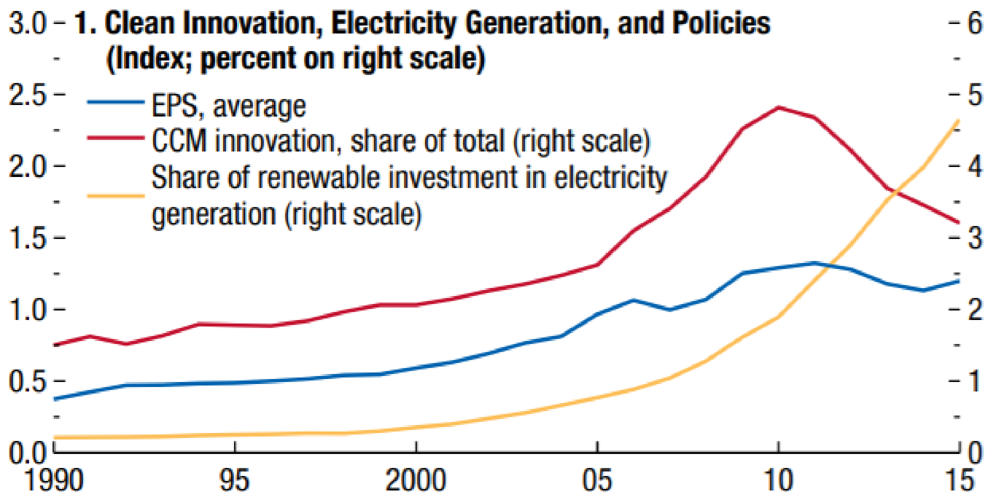
In the last 20 years, an array of studies using different methods—statistical analysis [43], economic history [44], and case studies [45]—have solidified the science of learning curves. A

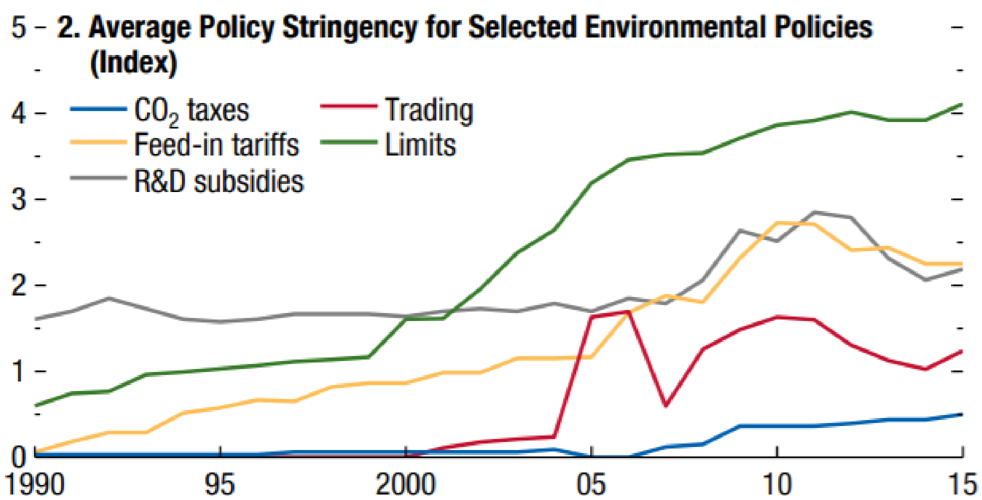
[x] Polysilicon input shortages, no longer a factor, explain the deviation from the trend that occurs starting in 2003.

study in the economics literature finds "strong evidence that environmental regulations induce innovation activity in cleaner technologies" [46]. Several studies have shown how deployment itself and associated learning by doing have been core drivers of clean tech advancements in China [47, 48].

The International Monetary Fund's latest World Economic Outlook has pioneered a unique empirical study of learning curves, illustrated in Figure 6 with a two-part graphic. The bottom panel presents an index of environmental policy stringency (EPS) as a function of key policies. The top panel shows how renewable energy investment and clean energy innovation have grown with increasing policy stringency. Clean energy innovation (CCM innovation) is measured as the fraction of clean energy technologies in total electricity sector patents.

Figure 6. Evidence for learning curves in analysis by the International Monetary Fund





Source: International Monetary Fund [49]

As a result of learning curves, induced innovation is the predictable result of strengthened climate policy. More aggressive decarbonization will spur advances and growth in industries that China has elevated as development priorities. Technologies important to reducing carbon emissions and to promoting clean energy, EVs, and energy-efficient technologies were among the strategic industries identified in the 13th Five-Year Plan.

China's economic development strategy calls for growing the knowledge-creation and advanced manufacturing segments of the economy. Induced innovation from more aggressive decarbonization will directly contribute to this economic priority.

BROADER ECONOMIC ADVANTAGES

The preceding section establishes that accelerating clean energy adoption in the electricity sector offers an opportunity to build a lower-cost electricity system. Case studies in solar and wind introduce the concept of learning curves in emerging technology. By extension, deployment itself is a fundamental innovation strategy. Induced innovation, not just in electric power but across all energy sources and energy-consuming technology, can advance other strategic priorities for China, such as supporting higher-quality economic growth and international competitiveness in advanced technologies.

In the words of Xie Zhenhua, director of Tsinghua University's Institute for Climate Change and Sustainable Development and formerly China's longtime Special Representative on Climate Change Affairs: "It can be seen that policy actions to address climate change will not only not hinder economic development, but also help improve the quality of economic growth and foster new industries and markets" [50].

HIGHER-QUALITY GROWTH

For several years, China's economic strategy has emphasized the transition from high-speed growth to high-quality growth. Ma Jun, a leader in the recalibration of economic policy, has written that "environmental degradation . . . is beginning to limit growth and may threaten social stability" [51]. He urges placing less weight on conventional economic metrics, such as gross domestic product (GDP), because they fail to effectively capture welfare and can mask risky social and environmental conditions. Nobel Laureate Joseph Stiglitz makes a similar case: "If we measure the wrong thing, we will do the wrong thing. If our measures tell us everything is fine, when it really isn't, we will be complacent" [52].

More aggressive near-term decarbonization efforts will directly contribute to the goal of higher-quality growth, as the requisite policies will help correct existing market failures. The next section covers co-benefits and specifically discusses how climate action leads to improvements in air, water, and soil quality as well as urban mobility, making cities more livable.

Coupled with his recommendation to deemphasize and lower GDP growth targets for China, Ma Jun points to the advantage of technological progress: "Technological innovation and reforms can cushion the deceleration [of economic growth]" [53]. Indeed, the Economic Sciences Prize Committee awarded Paul Romer his Nobel Prize "for integrating technological innovations into long-run macroeconomic analysis" [54]. Technological progress has become recognized as an important driver of growth. Given the predictable effects of learning curves, strengthening climate policy in China will surely yield a more innovative economy, which in turn will accelerate high-quality economic growth.

Though integrating innovation into macroeconomic theory has been one of the field's most important modern advances, few economic analyses of climate policy have evaluated the effects of induced innovation. Even historical innovation and cost reductions are inadequately captured by economic analysis simply because of the rapid pace of change.

An exception in the literature is *Declining Renewable Costs, Emissions Trading, and Economic Growth: China's Energy System at the Crossroads*, a new study that applies a state-of-the-art computable general equilibrium model for China. The work examines the impact of a 50 percent reduction in 2030 electricity sector emissions compared to business as usual.[xi] When the costs of renewables are updated to fully account for technological progress to date, the work finds electricity sector decarbonation boosts economic growth, increasing China's GDP in 2030 by an estimated 6.9 percent. When the potential for greater innovation induced by policy is factored in, the study shows China's 2030 GDP will grow by more than 15 percent, concluding:

> First, the economic benefits of renewable energy now substantially exceed their direct costs, and adoption of renewable technologies can proceed without the still-controversial interventions needed to recognize the social cost of carbon. Second, modernizing the electric power system can support a new generation of more diverse domestic job creation, facilitating an essential transition for millions of workers in the carbon fuel supply chain, one of the last great artifacts of the Industrial Age. Overall, our results suggest that China should accelerate its clean energy transition, not only for the air-quality and climate benefits, but also for the broad and positive impact on innovation, employment, and economic growth. As China considers its post-COVID recovery measures, building green energy infrastructure should simultaneously support sustained economic growth and climate mitigation [55].

[xi] The study's business-as-usual scenario forecasts constant emissions in future years. So, the emissions reduction level considered in the study also represents a 50 percent reduction in 2030 below business-as-usual emissions.

The study quoted above joins a growing body of work finding net positive economic effects of more aggressive climate policy. For example, two recent studies find national carbon pricing will increase Chinese GDP by 1-2 percent in 2030 and by 2-3 percent in 2050 while also boosting employment [56], [57]. Economic benefits estimated in these studies come about due to structural rebalancing away from heavy industry to other, more labor-intensive sectors. Even before considering the innovation advantage, much less co-benefits, Huang et al. conclude: "It should be feasible for China to reconcile its aggregate growth and environmental goals, sustaining higher GDP per capita and lowering emissions, while shifting the structure of its economy" [58].

CLEAN TECH EXPORT COMPETITIVENESS

More aggressive domestic decarbonization policies will induce additional innovation, expanding and upgrading the clean technology offerings of Chinese firms. The effect will be enhanced competitiveness in global markets for clean technology, an example of what economists call the home market effect, referring to the causal relationship between establishment of a domestic market and international export success [59], [60], [61].

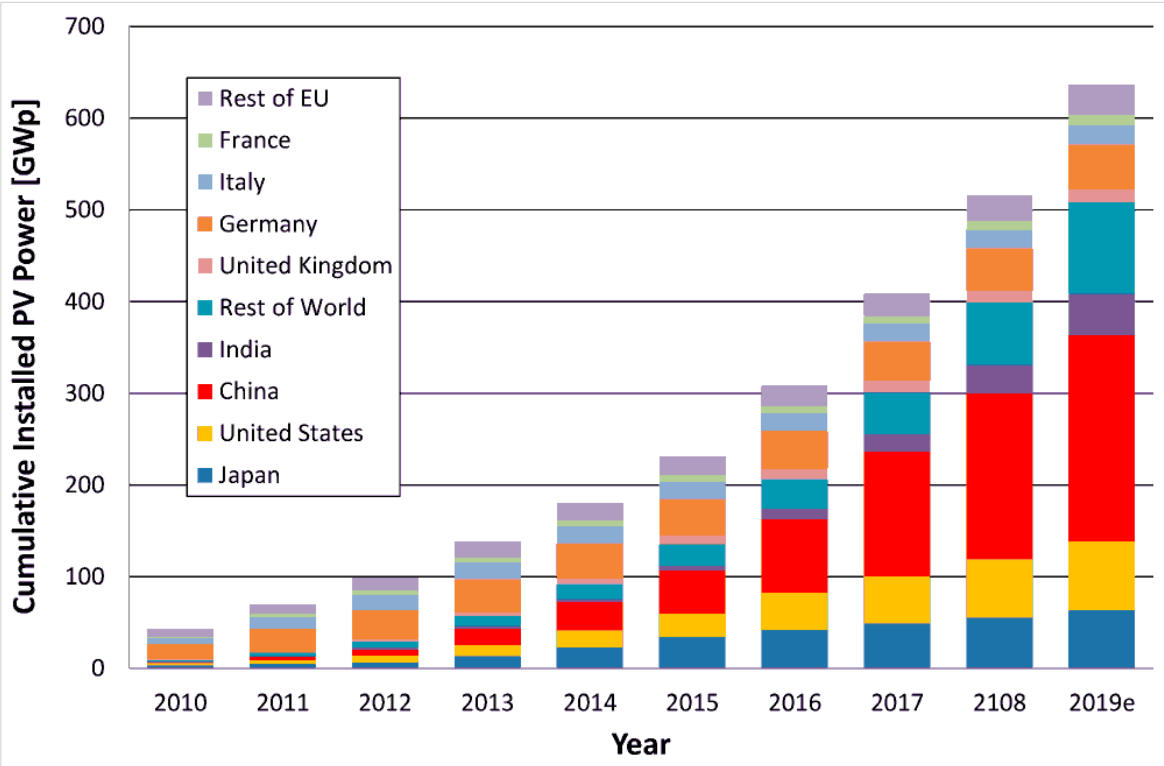
Case study: solar PV

China's solar power industry provides a case study in home market effects and benefits. By 2020, 2.2 million Chinese people had jobs in the solar industry, two-thirds of the global total [62].

The country's installed capacity of solar panels in 2018 accounted for one-third of the global total and half the world's new solar capacity added that year [63]. Figure 7 graphs global cumulative solar power capacity over time, showing how China built up its edge with several years of record investment and deployment in solar power.

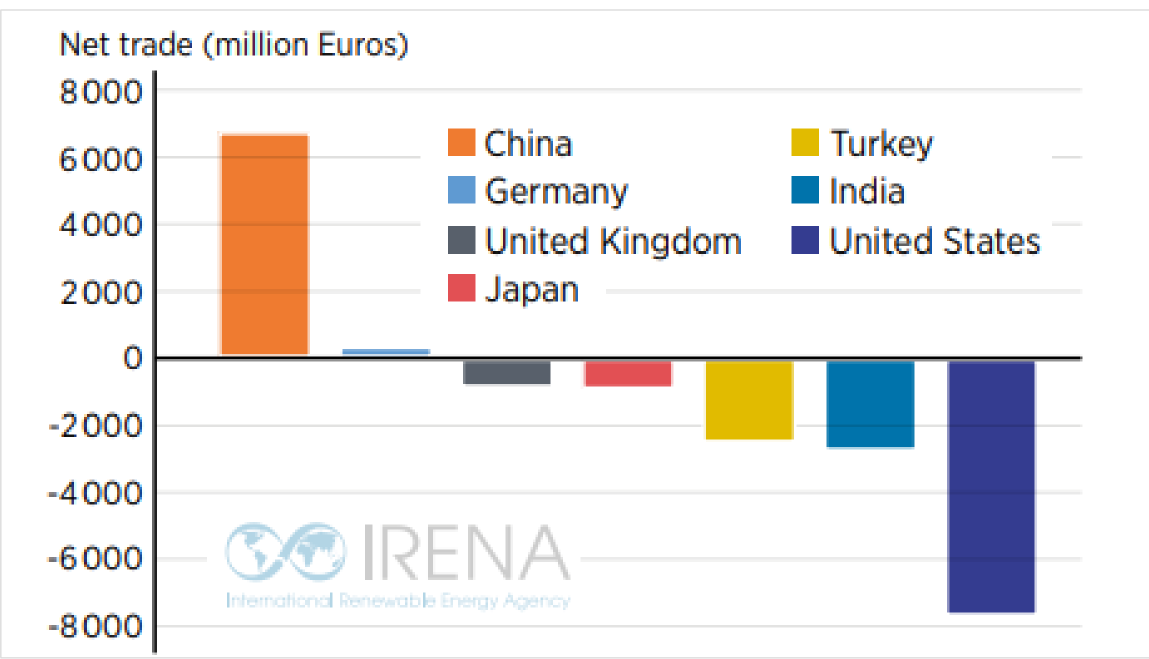
Figure 8 shows that China's solar industry has achieved unequaled success in international markets, garnering a net trade balance of more than €6 billion in 2016. Germany was the only other country with a net positive trade balance in that year.

Figure 7. Solar power capacity installed in China far exceeds capacity installed in other countries



Source: Jager-Waldau [64]

Figure 8. Net international trade flows in solar PV by country

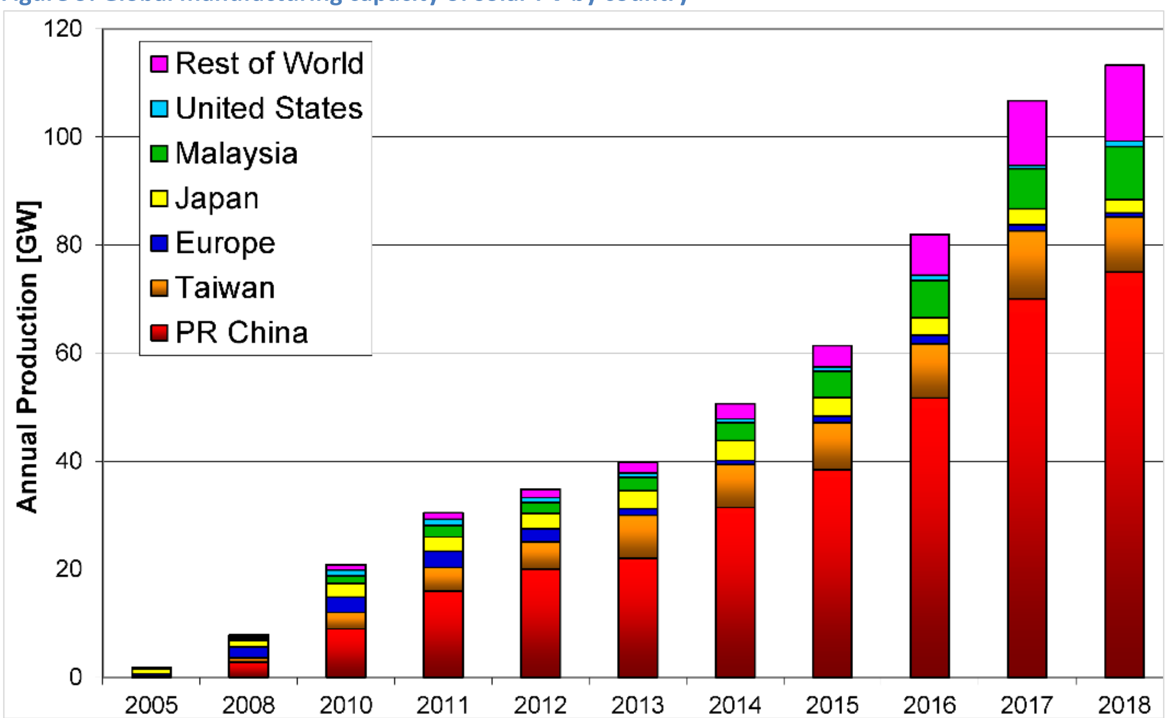


Source: International Renewable Energy Agency [65]

China's solar PV manufacturing output has grown steadily on the strength of its domestic deployment and international trade. In 2018, Chinese factories produced more than 60 percent of the global supply of solar PV panels, as illustrated in Figure 9, below.

Looking forward, a consensus view has emerged that solar PV technology will be the leading choice for electricity generation in coming decades [66]. Even without additional policy commitments, the International Energy Agency's 2020 World Energy Outlook predicts: "Solar PV will become the new king of electricity supply and looks set for massive expansion. From 2020 to 2030, solar PV grows by an average of 13 percent per year, meeting almost one-third of electricity demand growth over the period. Global solar PV deployment exceeds pre-crisis levels by 2021 and sets new records each year after 2022" [67].

Figure 9. Global manufacturing capacity of solar PV by country



Source: Jager-Waldau [68]

Though many factors determine international trade flows, China's domestic investments clearly played a role in developing its very strong position in global solar markets. Expectations about the likely payoff from China's advantage in solar power technology continue to grow.

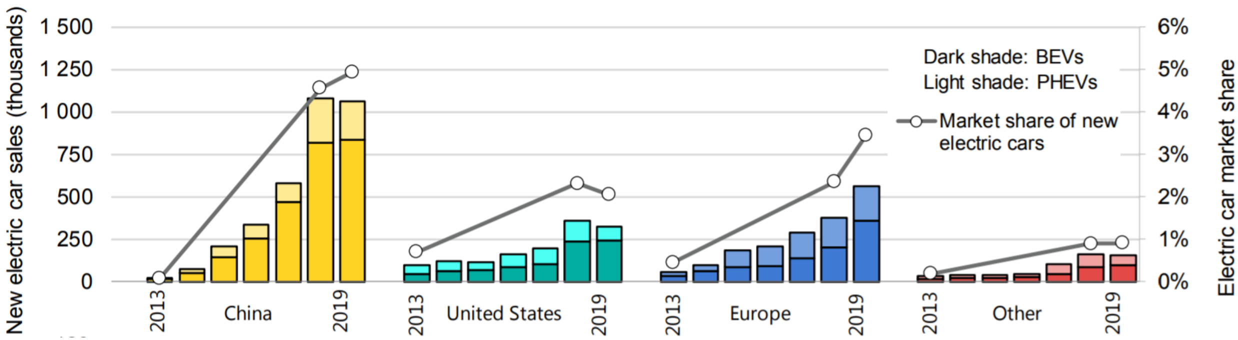
Case study: EVs and batteries

While the story of solar is remarkable, it is more harbinger than outlier. It is increasingly evident that EVs will displace vehicles with conventional internal combustion engines. California added to the sense of momentum and inevitability with its commitment in September 2020 to prohibit the sale of new cars and SUVs with internal combustion engines by 2035. In November, the United Kingdom announced plans to do the same by 2030.

Driven by innovation in battery-electric storage, EVs are becoming—or in some cases are already—more affordable than conventional vehicles on a cost-per-kilometer basis [69, 70]. Upfront purchase prices, known to be a consumer priority, will reach parity by the mid-2020s if not sooner. A leading Chinese manufacturer expects EVs could become less expensive to purchase than conventional vehicles in 2023 [71].

China is well positioned to compete. In recent years, China has established itself as both the largest producer of EVs and the largest market for EVs, with annual sales surpassing the rest of the world combined in 2018 and 2019, as documented in Figure 10.

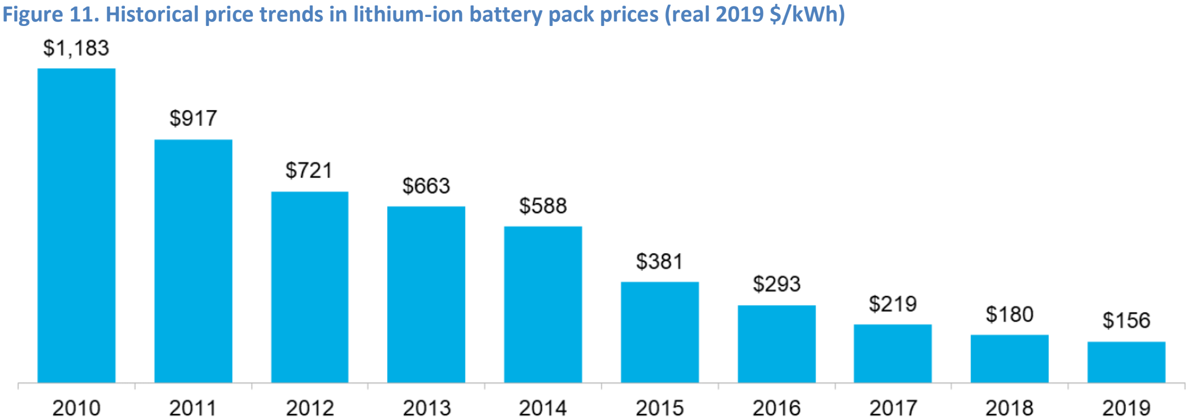
Figure 10. Global data show China has developed the largest domestic EV market (2013-2019)



Source: International Energy Agency [72]

The cost of battery-electric storage accounts for most of the cost difference between electric and conventional vehicles. So progress in battery-electric storage performance and cost is critical to the competitiveness of EVs. Battery costs dropped by 87 percent in real terms between 2010 and 2019, from $1,183 to $156 per kilowatt-hour (kWh) [73].

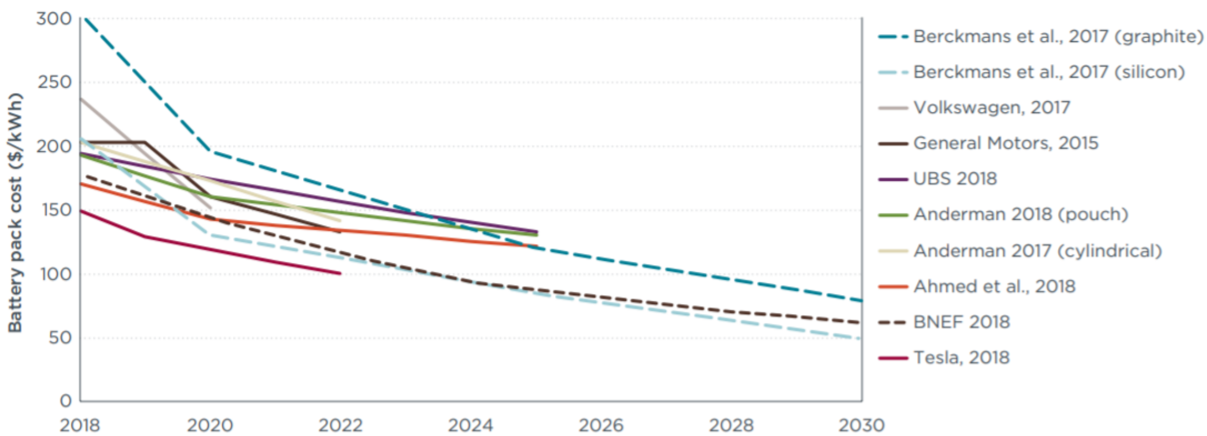
Figure 11. Historical price trends in lithium-ion battery pack prices (real 2019 $/kWh)



Source: Bloomberg New Energy Finance [74]

Most technology analysts expect that battery costs will keep falling due to continued learning by doing, economies of scale with existing technologies, and development of new chemistries. The potential for novel chemistries is evident in reports of new commercial affordability thresholds within reach, thanks to a cobalt-free lithium iron phosphate battery, suggesting that battery packs at a cost below $80 per kWh may be available as soon as 2021 [75]. Figure 12 graphs a range of scholarly and industry forecasts of battery pack prices through 2030, all projecting substantial decreases in the coming decade.

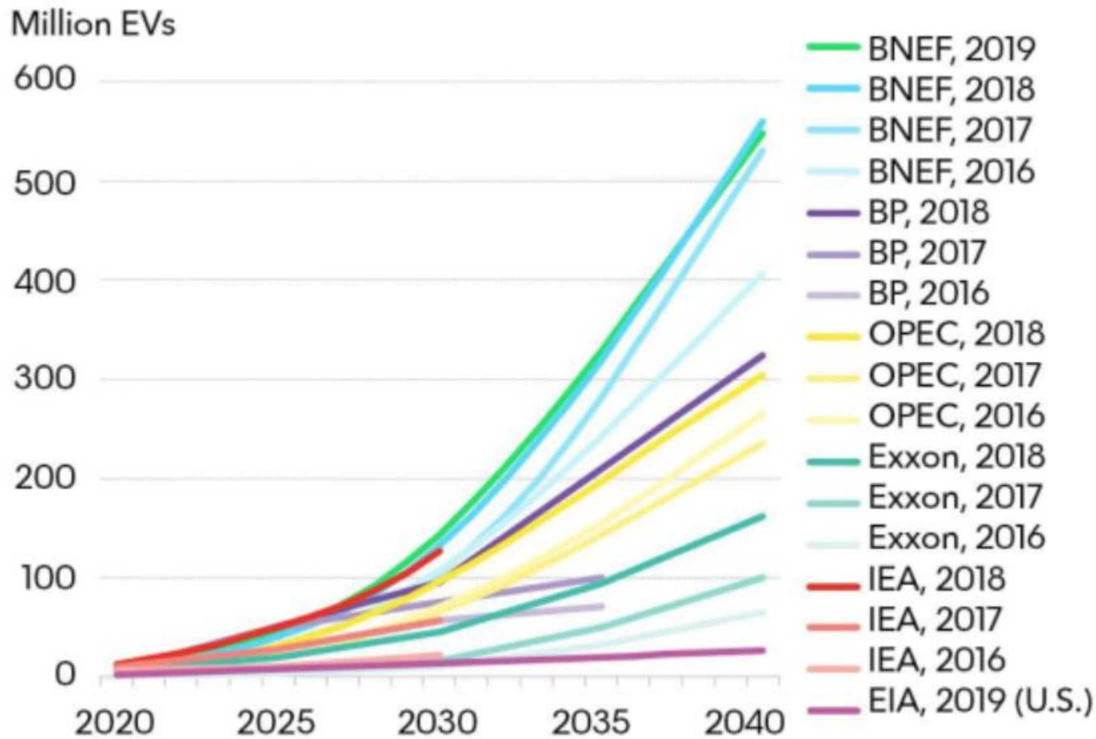
Figure 12. Expectations vis-à-vis future price trends in lithium-ion battery pack prices



Source: International Council on Clean Transportation [76]

The increasingly compelling economics, and policy support due to clean air and climate benefits, are quickly moving EVs into the mainstream of motor vehicle markets. Bloomberg New Energy Finance's latest industry outlook forecasts that EVs will represent 28 percent of new car sales in 2030 and 58 percent in 2040 [77]. That forecast will underestimate the actual increase in EV market share, if history is any guide. Figure 13 depicts how EV sales forecasts have evolved for five different global EV outlooks, in each case showing strengthening over time.

Figure 13. Comparison of five forecasts for EV sales over time



Source: Bloomberg New Energy Finance [78]

LOWER STRANDED COSTS

"Stranded costs" (or "stranded asset risk") refers to costs from early shutdowns of working capital. Political, technological, or market forces may precipitate premature retirement. Financing markets are devoting increased attention to the "carbon bubble"—the idea that trends in climate impacts, scientific understanding, and political appetite could come together to keep large amounts of fossil fuels in the ground.

Ma Jun has often raised the importance of anticipating and avoiding stranded costs, writing on October 8, 2020: "As governments take action to reduce emissions and as progress is made in green technologies, exposure to polluting assets is higher risk. Institutional investors could see their assets devalued" [79].

The risk extends not just to energy supplies, such as oil fields, but also to major energy-using investments with large carbon footprints, such as coal-fired power plants. Wind and solar power generation investments are recognized as highly secure, in contrast to coal [80]. Petroleum and related infrastructure and capital are also subject to increasing concerns about stranded costs.

An Oxford University study found the value of Chinese coal assets at risk to be 3-7 trillion yuan, equal to 4-9 percent of annual GDP, and documented steadily declining profit margins, which shrank from 23 percent to 9 percent between 1995 and 2015 [81]. Due to overcapacity, China's coal plants already operate at less than 50 percent capacity [82]. If current plans to build new coal plants come to fruition, overcapacity in the sector will worsen, causing further deterioration in profitability.

Zou Ji comments: “Many coal-fired power plants have been given the go-ahead lately in order to boost the economy. This is ‘drinking poison to ease thirst.’ Those power plants will become nothing but scrap metal, a drag on our economic growth” [83].

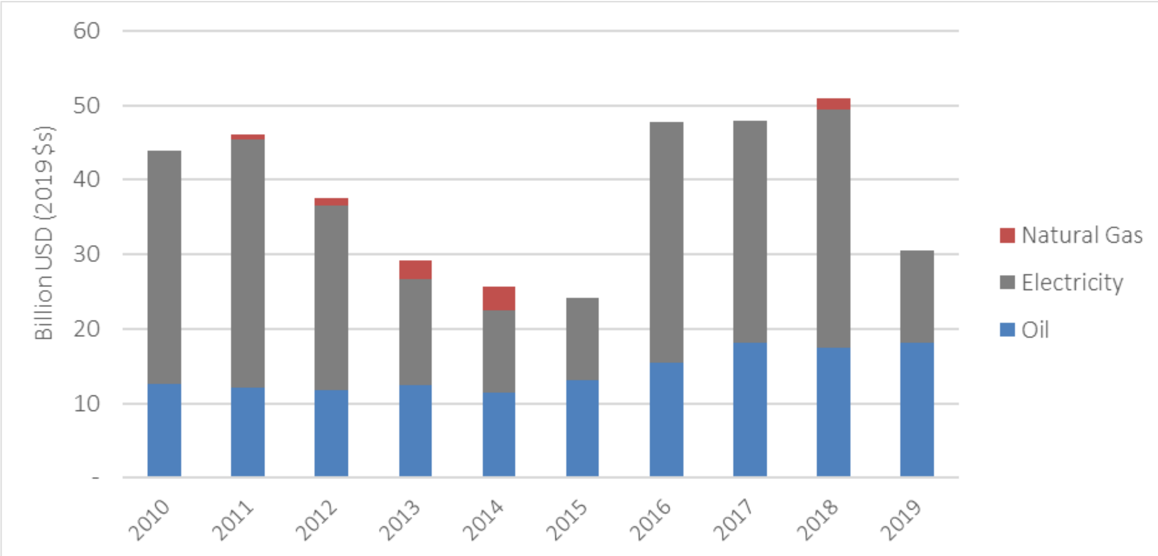
AVOIDED FOSSIL FUEL SUBSIDIES

The future of China’s power sector can be viewed as a competition between two categories of domestic resources: coal and renewable technologies. Government support for coal power undercuts renewable energy development both by improving coal’s competitive position and by siphoning away limited funding that otherwise could advance renewable technologies. Direct subsidy payments for coal might also have gone to fund social safety nets or innovation.

Direct cash transfers are an iconic subsidy type, but they do not drive China’s support for coal power. Rather, national support for coal largely takes the form of administrative dispatch rules, i.e., the rules electricity system operators use to decide which available power to draw upon. Dispatch in China is governed by the “three equals system” that allocates each plant a guaranteed share based on technology, not cost.

The difference between energy market prices and the true social cost is known as the price gap method for valuing subsidy support. The price gap method excludes upstream subsidies, e.g., for coal mining, as well as subsidized research and development. Estimates based on the price gap approach therefore understate total fossil fuel subsidies as well as their impact on economic efficiency and trade. The International Energy Agency employs the price gap method in its global subsidy database, which includes annual data for China graphed in Figure 14 (below), charting support over time for oil and natural gas as well as for coal, which is the principal beneficiary of support and is labeled, “Electricity.”

Figure 14. China's fossil fuel subsidies (2010-2019)



Source: International Energy Agency [84]

In 2009, all countries in the G20, including China, promised to end inefficient fossil fuel subsidies, agreeing they "encourage wasteful consumption, reduce our energy security, impede investment in clean energy sources and undermine efforts to deal with the threat of climate change" [85]. By 2019, however, total global subsidies for fossil fuels had declined only 29 percent, from $450 billion to $320 billion [86]. China is hardly alone in needing stronger action to reduce fossil fuel subsidies.

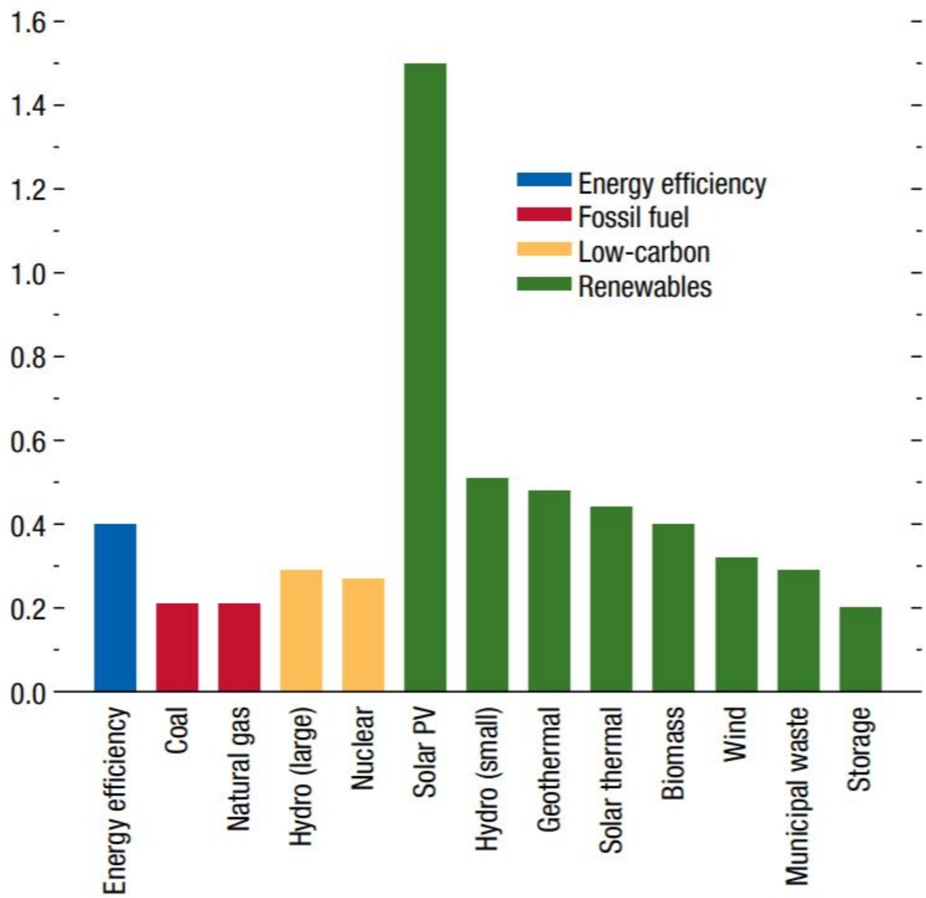
Subsidizing coal power gives a lifeline to 20th century technologies. Renewable and other low emission and zero emission technologies are better job creators, as documented next. An effective and fair strategy for transitioning away from coal will give due attention to the well-being of displaced coal workers, including social safety net guarantees and retraining for younger people, while leveling the playing field for renewables.

JOB CREATION

A large body of evidence shows that renewable electricity technologies are more labor intensive than sources based on fossil fuel combustion, such as coal or natural gas. Many studies have compared renewables to other power technologies based on employment impact per dollar invested. An influential U.S. study found three times more jobs are created by spending in renewable energy and energy efficiency, showing that per $1 million invested, renewable energy creates 7.49 jobs, energy efficiency creates 7.72 jobs, and fossil fuels create just 2.65 jobs [87]. Therefore, shifting spending from fossil fuels to renewable energy and energy efficiency generates a net increase of five jobs for each $1 million invested.

The International Monetary Fund has analyzed employment per unit of electricity generated over a project's lifetime, considering both direct employment and indirect employment (jobs created upstream by suppliers). The International Monetary Fund's findings are reproduced as Figure 15, which is notable for the extent to which solar PV stands out as the superior option for job creation, and which also broadly shows renewable energy and energy-efficiency technologies creating more jobs than coal and natural gas technologies [88].

Figure 15. Renewable electricity technologies create more jobs (job-years per gigawatt hour[xii])

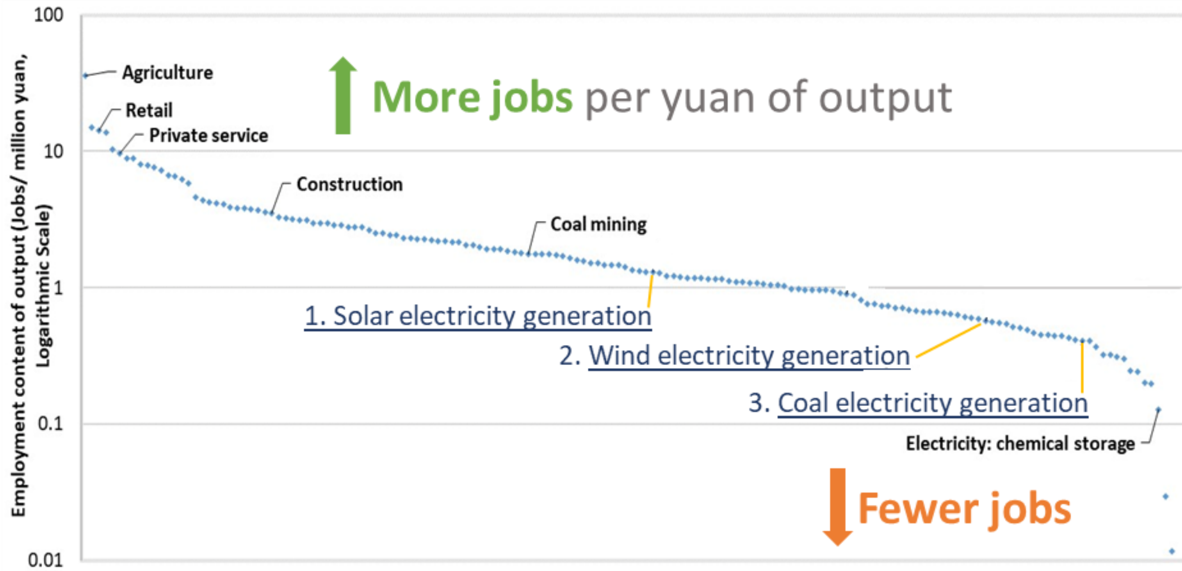


Source: International Monetary Fund [89]

Declining Renewable Costs, Emissions Trading, and Economic Growth: China's Energy System at the Crossroads provides China-specific data, graphing the number of direct jobs per unit of economic output in different sectors. Though direct jobs are a narrower metric than in the International Monetary Fund's analysis, the results are broadly similar. Figure 16 presents data on direct jobs per unit of economic output, showing by this measure that solar was the leading creator of jobs, followed by wind and trailed by coal power.

[xii] Job-years per gigawatt hour calculated as estimated job-years created over expected lifetime power generation.

Figure 16. Employment content of 2017 economic output in China



Source: Chen et al. [90] [xiii]

CO-BENEFITS

Decarbonization projects often have significant impacts in addition to reducing GHG emissions. Such ancillary effects are referred to as "co-benefits." Though they are often excluded from climate policy analyses, research has demonstrated that co-benefits may have tremendous economic value. The International Monetary Fund's 2020 World Economic Outlook concludes: "Many countries would experience substantial economic gains from co-benefits—on the order of 0.7 percent of GDP immediately and 3.5 percent of GDP by 2050 for China" [91]. The co-benefits outlined in this section, such as cleaner air and better environmental quality overall, would lead to economic gains in the form of improved public health, lower health costs, increased productivity for workers, and better student performance.

AIR QUALITY

Xie Zhenhua explains: "In most cases, air pollution results from fossil fuel combustion that also emits [GHGs]. Hence, reducing fossil fuel use cuts emissions of both carbon dioxide and other air pollutants, bringing co-benefits to both climate and the environment" [92].

Understanding of the health costs of air pollution and the benefits of cleaner air has strengthened in recent years. China's Ministry of Ecology and Environment has found that air pollution causes 500,000 premature deaths in China each year [93]. A recent article in the journal *Nature Sustainability* found that electrifying 27 percent of private vehicles in China would prevent more than 17,000 deaths annually—and health benefits were even larger than the value

[xiii] Presenting a modified Figure 2 from Chen et al. to highlight the rank order of power generation technologies.

of avoided climate damage due to lower GHG emissions [94]. In a landmark study dating to 2006, the cost of damage from air and water pollution in China was estimated to be the equivalent of 2.7 to 5.8 percent of GDP [95].

Because most air quality problems stem from the same sources as GHGs—burning fossil fuels—there are huge economic advantages to investments that reduce both GHGs and local air pollutants at the same time. For example, while putting scrubbers on coal plants will reduce air pollution but increase GHGs (due to additional energy needed to run scrubbers), replacing coal with wind reduces both local pollutants *and* GHGs. The stranded cost problem is made worse, too, if a government deals with air quality and not GHG emissions, or vice versa.

Two other recent studies indicate that the air quality co-benefits of China's national emissions trading system (ETS) are likely to dwarf economic transition costs. A team led by Stanford University's Larry Goulder found the air quality benefits of China's proposed ETS will be three times greater than adjustment costs [96]. Research published in the prestigious journal *Nature Climate Change* adds to the evidence that the health benefits of a national ETS will far outweigh the mitigation costs [97]. The research estimates the policy will yield health benefits of $465 billion, resulting in a four-to-one benefit-to-cost ratio, concluding: "Air quality improvement is a valuable co-benefit of carbon pricing that increases with policy stringency in China. Even without considering the social cost of carbon . . . health co-benefits can outweigh policy costs to households" [98].

URBAN MOBILITY AND QUALITY OF LIFE

Sustainable urbanization also delivers substantial co-benefits, particularly better mobility in cities and improved quality of life overall. One authoritative study found better urban design could reduce transportation energy needs and associated emissions by 30 percent through better efficiency and reduced waste [99].

In many Chinese cities, the legacy of prior urban planning norms is evident in wide avenues dominated by cars, and large undivided blocks. This type of urban form causes demand for personal passenger vehicles to overwhelm the transportation system. Lengthy commutes and traffic congestion lead to wasted time, wasted energy, and higher emissions. Urban congestion and environmental damage are estimated to reduce Beijing's economic output by 7.5 to 15 percent, one indicator of the high costs of snarled, car-centered transportation systems [100].

Sustainable urbanization involves increasing accessibility of public transit, walking, biking, and emerging "micro-mobility" options to reduce dependence on private car travel. To make such a transportation system viable requires mixed-use and compact development, rather than a sprawling form. Compact, mixed-use urban form allows people to live near where they work and generally creates more walkable places.

Guangzhou is celebrated globally for its bus rapid transit and larger transit system, green space restoration, and pedestrian experience improvements. A study of Guangzhou's investment in more extensive public transit service demonstrates how such investments shorten commute times and lower emissions [101]. Analysis of Guangzhou's creation of mixed-use neighborhoods in areas previously zoned exclusively for residences shows that the change led to increased property values [102]. From neighborhood and household studies to global-scale research, a growing body of evidence points to urban climate solutions delivering co-benefits: more efficient mobility, more enjoyable public space, more vibrant streets, and better-loved neighborhoods [103].

SOIL QUALITY AND WATER QUALITY

Land-based actions in forestry and agriculture that are designed to mitigate climate change often deliver soil and water co-benefits. Typically, natural area preservation and other types of sustainable land management not only reduce carbon emissions but also protect existing ecosystem functions, benefitting water and soil. Such projects improve water quality and availability through natural filtration and flow regulation, ensuring reliable supply and protecting against flooding. And projects may benefit soil quality by countering erosion and improving productivity.

Chinese Academy of Science-affiliated research urges more investigation of the optimal role for natural solutions within the context of economy-wide decarbonization [104]. The literature on the air quality co-benefits of decarbonization is much more developed than the literature on soil and water co-benefits. A recent review of the scientific literature finds 10 times more studies on air quality than on soil and water quality co-benefits [105].

Though ongoing research aims to estimate benefits more precisely, the existing evidence is adequate to show that soil and water quality co-benefits of decarbonization are quite valuable. An evaluation of forest ecosystem services in China estimated these services' monetary value to be 10 trillion RMB/year in 2008, equal to 33 percent of GDP that year [106].

Field sampling of different cropping methods on 403 farms across China found that sustainable methods increased productivity by 18 percent while lowering methane emissions from rice cultivation by 7 percent and reducing fertilizer use by 22 percent, with concomitant lessening of energy use, emissions, and contamination of water resources by fertilizer runoff [107].

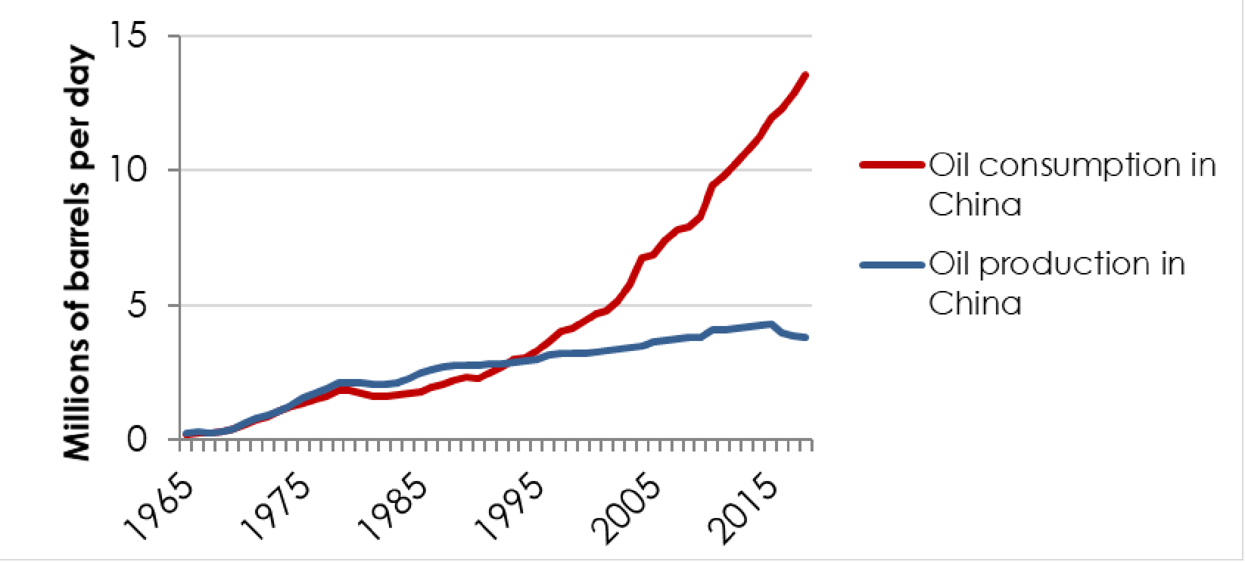
Exposure to mercury via contaminated rice is a growing public health concern in China, and coal-fired power plants are a dominant atmospheric source of mercury emissions in China [108]. These air emissions are eventually deposited, negatively affecting land and surface water quality.

ENERGY SECURITY

Du Xiangwan, senior energy expert in China, argues renewable energy is the key to China's energy security, pointing to ample domestic supplies and the insecurity inherent in a future of runaway global warming [109]. Energy security has economic implications. Renewable energy prices are not subject to the same fluctuations as petroleum, for which prices vary based on the world oil market. Yet the national security implications of dependence on imported energy often rise to the top.

Chinese policymakers profess increasing concern about China's growing dependence on imported fossil energy. The share of imports in China's energy mix doubled from 9 percent in 2014 to more than 20 percent in 2018 [110]. Since 2017, China has been the world's largest oil importer [111]. Rising fuel demand in the transportation sector and lack of domestic resources have created a growing imbalance in domestic supply and demand for petroleum, as illustrated in Figure 17.

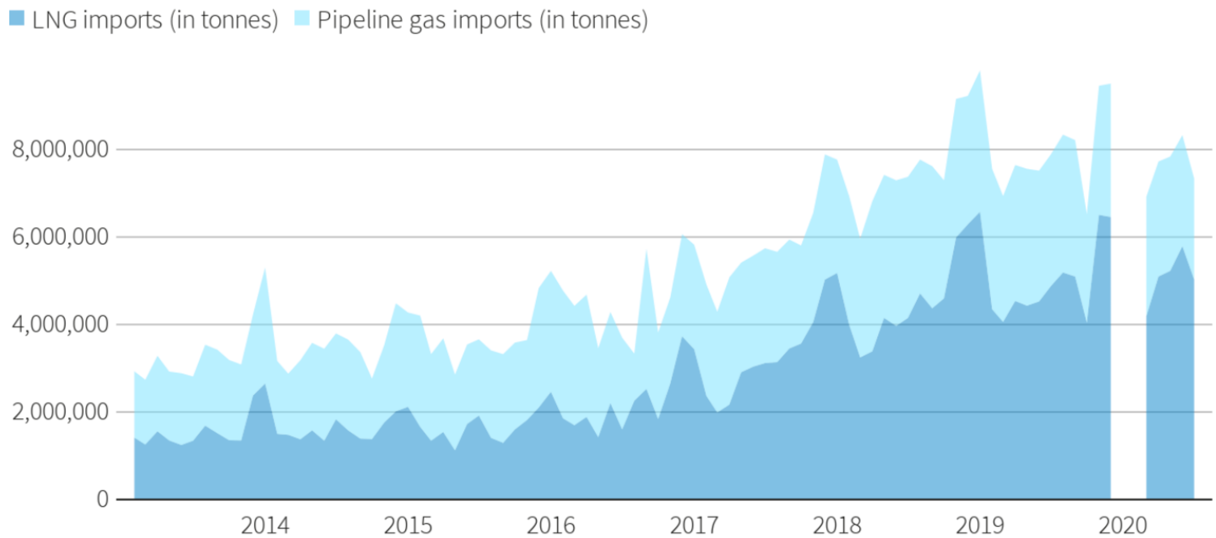
Figure 17. Rising consumption led China to become the world's largest oil importer in 2017



Source: British Petroleum [112]

China's overall natural gas imports are not among the largest globally, but the country's liquefied natural gas imports have been the fastest growing in the world. Natural gas demand is expected to grow year-over-year in 2020 despite the global economic weakening stemming from the COVID-19 pandemic. The strongest growth is expected in liquefied natural gas, putting China on track to surpass Japan as the world's largest importer of natural gas in 2022 [113].

Figure 18. China's growing imports of liquefied natural gas (LNG) drive total natural gas import growth



Source: Reuters [114][xiv]

Electrification—switching devices and equipment currently running on petroleum-based fuels or natural gas to electricity—is a fundamental decarbonization strategy. Electrification shifts reliance to domestically generated electricity, which can be sourced from zero emission domestic resources. EVs are a well-known zero emission option in transportation. In buildings, heat pump technology offers a cost-competitive, proven means for electrifying space and water heating.

AVOIDED CLIMATE CHANGE DAMAGE

China's size means that its climate risks encompass nearly the full global range of afflictions that unmitigated climate change would visit upon humanity, such as drought and desertification in the north; flooding in the south; and agricultural disruption, massive infrastructure costs, and the spread of tropical and other infectious disease throughout the country. Climate impacts are emerging sooner and more intensely than scientists had predicted. Several social and psychological factors have contributed to climate scientists underestimating risks [115]. Research finds that the scientific community's premium on reaching consensus and experts' reluctance to venture opinions except when empirical data provides clear signals have the effect of weakening conclusions. Another factor is the prevailing view among climate scientists that there is little reputational threat to underestimating a threat but a significant risk of losing credibility if they overestimate a threat.

[xiv] Regarding missing data, this Reuters article cites China's General Administration of Customs as the original data source and notes that no information was reported for January and February 2020.

Growing evidence of similar dynamics in the economics literature is compounding the problem for climate policymakers. Economic studies have "omitted or grossly underestimated" many of the most serious climate risks [116]. Substantive difficulties facing economists include insufficient data and the prospect of significant change that is far beyond marginal changes—and even beyond recorded human experience. Beyond the analytical difficulties, the same asymmetric perception risk exists as in the natural sciences, with underestimation perceived as safer and overestimation carrying a threat to reputation.

For these reasons, in evaluating climate risk, policymakers must assume the probability and magnitude of climate damage have been systematically underestimated in both natural science and social science studies. This is a sobering realization given that even the existing scientific literature presents substantial evidence of current damages and high confidence of a grim-to-catastrophic future absent much faster decarbonization progress.

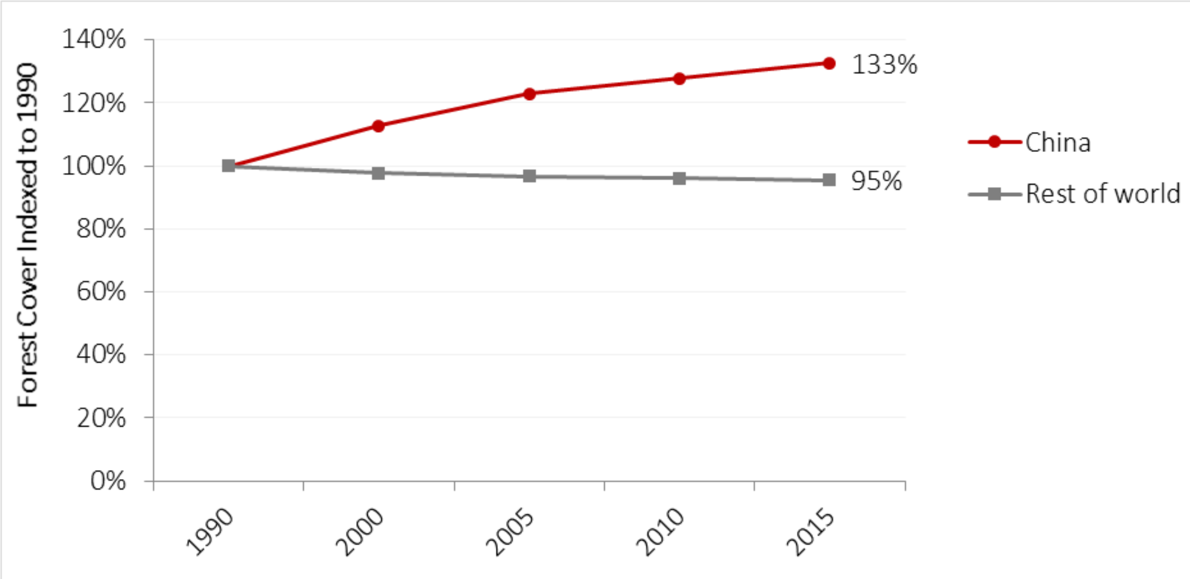
LAND-BASED CLIMATE SOLUTIONS

This paper's discussion of technology has thus far focused on energy technologies. Natural solutions, defined to include emission reductions driven by land-based actions in forestry and agriculture, offer another important approach to lowering the concentration of GHGs in the atmosphere. When trees and other plants grow, they absorb carbon dioxide from the atmosphere, retaining the carbon while supplying oxygen to the atmosphere. Roughly 20 percent of human-caused emissions globally are attributable to land change, principally due to the conversion of forests and other natural landscapes to agriculture and other human uses.

Natural solutions are widely recognized as an important, low-cost way to manage global GHG emissions and can be broken down into two types of projects: avoided emissions and sequestration. Avoided emissions projects avert land changes that would otherwise add to human-caused emissions, thus conserving existing carbon storage. Sequestration projects lock up greater amounts of carbon dioxide.

Expanding forest cover, whether by avoiding deforestation or enhancing regrowth, has been a foundational element of efforts to manage GHG emissions for decades. International efforts have centered on conserving tropical forests, which are home to disproportionately high shares of global biodiversity. In addition to climate benefits, forestry projects in China offer protection against desertification and flood control. Figure 19 below shows the decades-long trend of forestland expansion in China. Chinese forests have expanded 33 percent since 1990 while the rest of the world has seen shrinkage.

Figure 19. China's record of expanding forest cover contrasts with deforestation elsewhere



Source: Food and Agriculture Organization of the United Nations [117]

China's domestic efforts to improve forest and land management have so far yielded net climate benefits on the order of 500 million to 1 billion metric tons of carbon dioxide emissions annually. Stronger measures could increase annual sequestration to 1.7-3.7 billion metric tons of carbon dioxide per year [118].

Turning to agricultural climate solutions, better cropping strategies can increase the amount of carbon sequestered in soils. There are also opportunities to capture methane from improved livestock management, as well as growing interest in using waste from agricultural or forestry operations as a feedstock to electricity generation. Augmented with carbon capture sequestration, such bioenergy combustion offers a technically achievable path to produce a net-negative-emissions source of flexible, on-demand electricity generation [119]. Because the carbon dioxide released when plants are combusted had been absorbed in the process of plant growth, biofuel-related combustion is typically treated as making zero or minimal net contribution to climate change. When bioenergy combustion is combined with carbon capture technology, carbon is captured at the smokestack and then stored in natural underground repositories.

The potential for bioenergy combustion with carbon capture and sequestration shows increasing convergence between natural solutions and clean technology. This hybrid opportunity of innovation and land-based decarbonization is hardly unique. New remote sensing technologies, perched on platforms from satellites to drones, are offering ever-greater ability to monitor and understand land change. More and more, technology is being used to optimize fertilizer and water use in agriculture, reducing energy by avoiding waste while also lowering emissions. Our supposition is that innovative technology is likely to enable increasingly cost-effective natural solutions, breaking down the distinction defined at the outset of this section and providing an opportunity for rural economic development.

POLICY IMPLICATIONS

The growing economic opportunities for China in clean tech support a more aggressive decarbonization agenda. A study led by Xie Zhenhua and Tsinghua University offers insights into what climate policy strengthening could look like. Released in October 2020, just weeks after China's 2060 carbon neutrality pledge, the study has substantial heft evidenced by its government sponsorship and input from 24 organizations across academia, government, and the private sector.

Specifically, the Tsinghua study recommends setting an absolute cap on GHG emissions in the 2021-2025 Five-Year Plan, suggesting an economy wide GHG emissions cap of 10.5 billion tonnes in 2025 [120]. The cap would represent a significant political milestone for China yet would allow annual emissions to rise by nearly 500 million tonnes over the next five years—an increase on par with total carbon dioxide emissions from entire countries like Brazil, Indonesia, and Mexico. The head of the Energy Foundation China, Zou Ji, has suggested an advisory target for total emissions in the range of 10-10.3 billion tonnes per year [121].

Successful decarbonization will hinge on effective policy design and implementation. The national ETS, which will establish a price for carbon dioxide emissions, has captured much attention in recent years. The lack of a price on carbon emissions has been referred to as the greatest market failure of all time. Markets work when government-set rules effectively channel the dynamism that the profit motive engenders in socially beneficial ways. When consequential costs or benefits are not factored into market prices, the resource efficiency potential is not realized. A well-designed national ETS in China will help to level the playing field for renewable energy with fossil fuel incumbents. Because pricing carbon allows firms to creatively seek heterogeneous ways to abate carbon, a carbon price promotes development of low-cost options [122].

Though carbon pricing is a potentially strong instrument, particularly in industry and the power sector, it is not a silver bullet. Market failures and other barriers limit the supply of mitigation responsive to carbon prices [123], [124]. Sector- or industry-specific performance standards are necessary to drive innovation in areas where the imperative of targeted technological progress is well established [125]. Subsidies are also important to support consumer demand at the earliest stages of an advanced technology's maturation to full market readiness. Standards and incentives often work synergistically, for example in China's well-conceived approach to promoting electric transportation, which combines ever-stronger requirements for EV sales with financial incentives that encourage EV purchases.

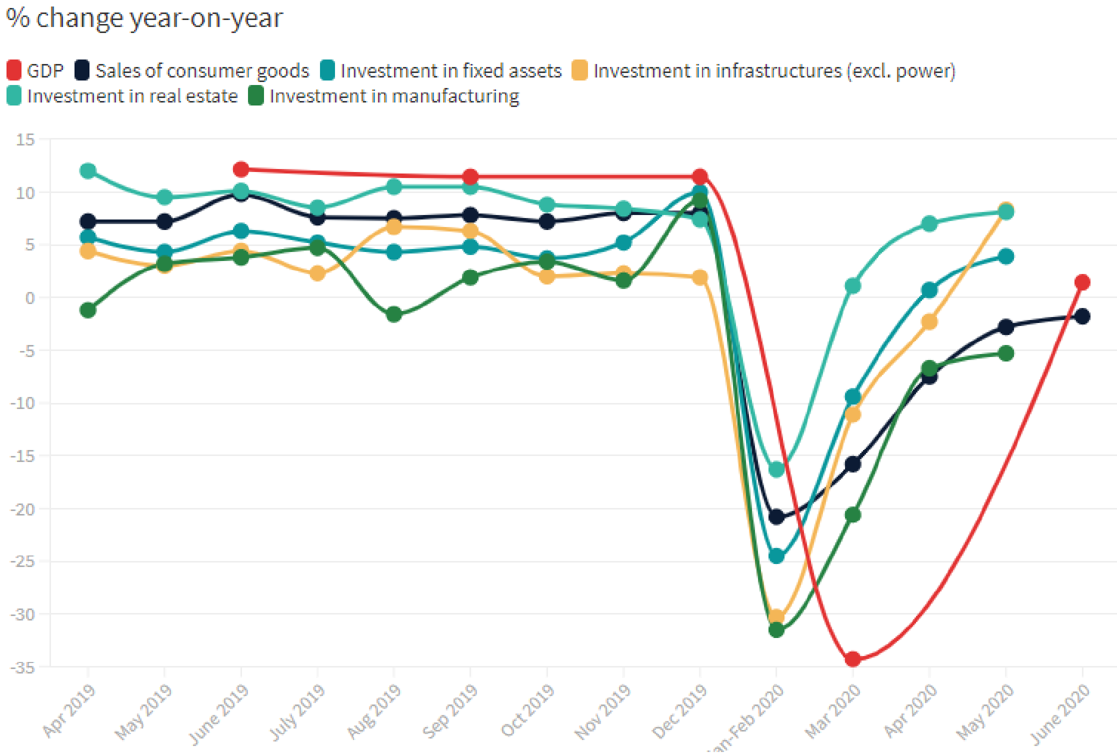
The effectiveness of China's national ETS will be closely related to progress in power market reform, in particular concerning the rules grid operators use to decide which power sources to dispatch (i.e., which sources are selected from among various options, distinguished by location and technology used to generate power). Dispatch is currently governed by the "three equals system" that allocates each plant a guaranteed share based on technology, not cost. Without dispatch reform, the effects of carbon pricing would be superseded by other rules governing system operation and planning.

In transportation, even though EVs are close to cost neutrality or better on an all-in cost-per-kilometer-traveled basis, consumers are known to irrationally undervalue fuel savings [126]. Consumers' inattention to fuel savings is just one example of the barriers and market failures that inhibit "the invisible hand" when it comes to energy markets and systems, particularly in the transportation and building sectors.[xv]

Figure 16, below, shows that fixed asset, real estate, and infrastructure spending is recovering. China appears to have put the worst of the COVID-19-related economic downturn behind it. On balance, indications thus far are that China's stimulus efforts have spurred traditional industry and energy more than clean energy or low-carbon infrastructure [127]. Strong policy is an essential ingredient for redirecting investments to clean energy and related infrastructure, and to making them the predominant choice for new investment. Strengthening the norms and rules of green finance is also key and is considered next.

[xv] For example, on transportation, Dan Sperling—member of the California Air Resources Board and founding director of the Institute for Transportation Studies at the University of California, Davis—and co-author Sonia Yeh write: "There are many market failures and market conditions that riddle the energy system, many of them unique to transportation, that result in consumer and business decisions not in the best interest of society. These market conditions include network effects of additional coordination among fuel producers, vehicle manufacturers, and fuel distributors energy security externalities related to petroleum imports; long time horizons needed for investments in fuel infrastructure; the lack of fuel-on-fuel competition; the diffuse nature of biofuel industries; and the market power of oil companies and OPEC countries. Energy markets are particularly inefficient and ineffective at addressing end use technology efficiency and demand reduction." S. Yeh & D. Sperling, "Low Carbon Fuel Policy and Analysis," *Energy Policy* 56: 1-4, https://www.sciencedirect.com/science/article/abs/pii/S0301421513000141?via%3Dihub

Figure 20. Economic trends in China by sector (April 2019 – June 2020)



Source: China Dialogue [128]

GREEN FINANCE

Clean tech, like all new technologies, is inevitably treated by traditional financiers as carrying greater risk, in simplest terms, because the technologies are new and lack a successful track record in the marketplace. As a result, clean tech firms face sub-optimally high interest rates when seeking loans from traditional finance sources.

Policy signals—both domestic, as discussed above, and international—are essential to shifting funding to the investments necessary for decarbonization. Public policy, as explained above, is needed for markets to reward clean technologies for the social costs and benefits they deliver—the externalities, in the vocabulary of environmental economics. Price signals are an important ingredient, but policy must overcome other points of resistance. To unlock the requisite investment and steer it to the best projects, it is necessary to continue building up the methods and institutional capacity of green finance.

Green finance standards help to avoid empty sustainability claims and protect good actors in the marketplace. These standards build confidence by increasing the quality and verifiability of environmental effects attributed to projects. Greater standardization of green finance will allow investors to compare projects across industries and countries. The Network for Greening the

Financial System's landmark work on global methods for environmental risk analysis, published in September 2020, serves as a reference on best practices and is an important step forward in distilling preferred, standard metrics [129].

Many climate solutions involve longer payoff periods, particularly infrastructure and large capital investments. Yet the duration of Chinese loans is about two years on average [130]. Ma Jun points to continued growth in green bonds funding as a promising way to overcome the hurdle created by the short duration typical for loans in China. China's green bonds market, the second largest globally, was worth $43 billion in 2018 [131].

The Belt and Road Initiative is one of China's signature foreign policy initiatives, involving a mix of grants and loans. Lending for energy projects under the Belt and Road Initiative emerged as a focus of green finance discussions in the last five years. Countries involved in the initiative account for about 20 percent of current GHG emissions, but if their trajectories follow historical patterns, their share could grow to half the global total by 2050 [132].

International interest has spawned the Green Investment Principles for the Belt and Road process, bringing together development banks, governments, and a cross-section of stakeholders to fast-track rules governing development and implementation. According to the Green Investment Principles secretariat, the process has grown to include the largest global financial institutions and international organizations, which cooperated in developing an online tool for project evaluation.[xvi] The availability of this free, online tool represents a step forward in the priority area of standard methods and capacity building. Despite this progress, concerns persist that the Belt and Road Initiative screening criteria for sustainability still allow for new investment in coal power plants. The fact that only the most highly efficient types of coal plants are eligible for support is far outweighed by the lack of any requirement for carbon capture and sequestration [133].

While stopping investment in new coal power plants is paramount, green finance standards must be applied to investments in every sector of the economy. Buildings and infrastructure projects are other types of long-lived investments with important implications for energy and emissions; for example, investments in roads can fuel urban sprawl and deforestation.

CHALLENGES

China has achieved the clean energy and efficiency goals it set in the 13th Five Year Plan. In 2019, renewable electricity reached 9 percent of total electricity supply and zero emission sources—defined to include nuclear and hydroelectric as well as renewable technologies—grew to

[xvi] Green Investment Principles' online tool, accessed November 17, 2020, is available at http://cerat.gipbr.net/

30 percent of total supply. Meanwhile, the share of coal in the electricity mix fell to 64 percent in 2019, down from 79 percent in 2010.

Innovation has created new opportunities for stronger climate policies to produce economic benefits today. Looking forward, the study of learning curves has improved forecasting of technological change, providing confidence that future innovation will deliver further performance improvement and cost reduction. For China, stronger action also dovetails with the national priority of pursuing quality development. Accordingly, the argument in favor of more rapid decarbonization is overwhelming, we respectfully submit.

Nonetheless, it would be a mistake to underestimate the challenges ahead. China is still the largest producer and consumer of coal on earth. The importance of coal to China's overall economy and some regions' reliance on coal are factors adding complexity and creating a certain amount of social, economic, and institutional inertia.

The continued development of new coal plants in China, and support for expansion in other countries, is another undeniable challenge. Despite the deteriorating profitability of coal power, in the first six months of 2020, China built more than half of the world's new coal-fired power plants. China currently has plans under development for 249.6 gigawatts of coal-fired capacity, which is more than the existing capacity of both the United States and India, with 246 gigawatts and 229 gigawatts of existing coal power capacity, respectively [134].

ENSURING RESOURCE ADEQUACY AND OVERCOMING RELIABILITY MYTHS

China's energy system, like the country itself, is large and diverse. The system has experienced large-scale change over the last decade, including efforts to improve air quality, to reduce industrial overcapacity, and to increase efficiency.

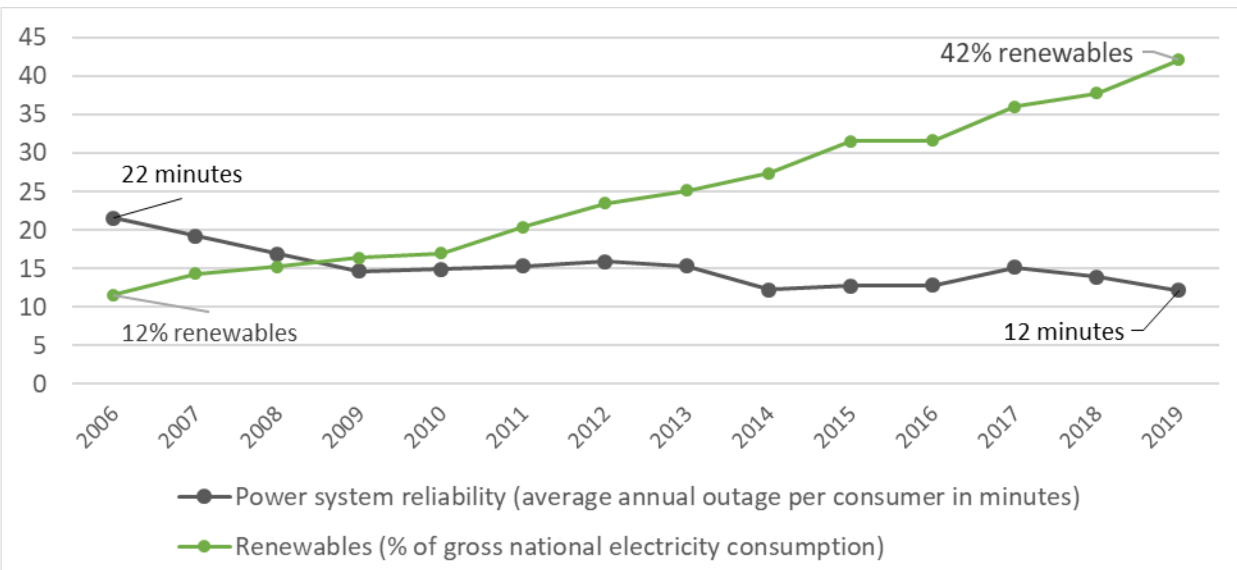
Growing complexity is another challenge. In the case of electricity, optimizing flexible supply and demand offers the potential of lower cost and cleaner systems but also requires grid managers to adapt to new technologies and paradigms. Instead of building centrally dispatched power plants to ensure any given level of peak demand will be met, managers must build a more flexible system, aiming to balance supply and demand across a portfolio of resources.

Although an energy mix dominated by renewable technologies does require a rethinking of grid management, China's plans to build additional coal power can be traced in no small part to persistent myths about the reliability of decarbonized electricity systems with high shares of renewable technologies. Yet California and Germany have successfully managed the variability of renewable technologies as renewables have become power system mainstays. California and Germany, two of the world's highest-performing economies, are proving that zero emission technologies are ready to step into a leading role in the heart of modern power systems.

If California were a country, its economy would rank fifth largest among nations. In 2019, renewable energy made up 36 percent of California's electricity mix, and zero emission resources (renewables plus large hydroelectric and nuclear power) accounted for 63 percent of the state's electricity supply [135]. California law commits the state to expanding shares of both renewables and zero emission resources, requiring at least 60 percent renewables in 2030 and complete decarbonization by 2045. The state's governor has suggested he would like to boost ambition in the electricity sector by increasing the 2030 renewable requirement and moving forward the target date for carbon neutrality.

The German economy, the world's fourth largest, is running on even higher shares of renewable energy. On reliability, German regulators find no impairment of service. To the contrary, "The energy revolution and the increasing share of distributed generation capacity continue to have no negative impact on quality," according to Jochen Homann, president of the Germany's federal grid agency. The improvement in reliability is evident in Figure 21, below, showing that average outages per consumer declined from 22 minutes in 2006 to 12 minutes in 2019 as renewable energy grew from 12 percent to 42 percent of Germany's energy mix.

Figure 21. Germany's power reliability improved as renewables grew to 42 percent of supply



Sources: German Federal Grid Agency [136], International Energy Agency [137]

Germany's security of supply is in Europe's top tier, according to the Council of European Energy Regulators, which found in a comparative analysis of power disruptions that Germany ranked second in the European Union for power reliability [138].

JUST TRANSITION

Given coal's centrality in China's current energy mix, a rapid transition away from coal raises questions about how to minimize impacts on affected workers, asset owners, and communities particularly dependent on coal-related economic activity. These challenges may be grouped together under the policy imperative of achieving a just, or fair, transition.

After years of restructuring to address overcapacity by closing lower-performing mines, coal mining employment in China is down from a high of almost 5.3 million jobs in 2014. Still, with an estimated workforce of 2.6 million in 2020, coal production is an important industry in China, particularly in coal's historical strongholds [139]. Consider the case of Shanxi, a province where coal production is responsible for nearly 30 percent of economic output and almost 50 percent of tax revenue. Places such as this require specific policy support, as do workers unable to adapt.

International best practices and China-specific studies point to two fundamental elements of a just transition strategy: (1) offering targeted support for displaced workers and the most affected communities, and (2) managing the financial impacts on capital owners and capital markets.

Worker retraining programs should retrain as many displaced workers as possible, including those who were directly employed in coal and those displaced from jobs indirectly related to coal [140]. Many displaced workers will face insurmountable education- or skill-related barriers to finding new work. These truly disadvantaged workers deserve a strengthened social safety net to avoid precipitous declines in living standards [141].

In coal-dependent places, community-level efforts should work to strengthen other parts of the local economy, including by supporting other industries—particularly innovative clean tech industries. Community programs should invest in education, infrastructure, and the physical environment, including rehabilitation of closed mines. In addition to improving physical capital, these programs should use targeted efforts to build social capital. Examples include encouraging entrepreneurship through support for technology associations, which can promote cooperation and information sharing, and pooling resources for shared investments such as foreign market development.

A report released in 2020, *How to Retire Early,* offers a practical guide to managing the financial aspects of a just transition, highlighting refinancing strategies for lowering the cost of outstanding debt [142]. One innovative policy recommendation is to use a voluntary reverse auction, inviting coal-plant owners holding outstanding debt to bid in through the auction, meaning they would signal through their bid the payment they would need to retire outstanding loans. "[A] reverse auction to acquire outstanding debt on coal plants in exchange for closure does not mandate participation—but it can serve as a powerful mechanism to reveal the true appetite for accelerated phaseout on which subsequent policies can be built" [143]. Reverse auctions can also provide information helpful to the stakeholder management process.

MANAGING UNCERTAINTY

Although additional innovation will be required to reach carbon neutrality, commercially available technologies are ready to immediately begin robust deployment, so technological feasibility is not a challenge. Admittedly, the nature of future innovation is not entirely certain. Despite strong confidence that learning curves will deliver steadily improving performance and lower costs, and despite enhanced predictability of the future rate of innovation, price forecasts inevitably involve error bounds. Given the coal economy's importance in some regions, Chinese policymakers are understandably on guard against politically unsustainable disruptions.

A growing body of research and practice provides guidance on how to design policy to capture the benefits of clean technology while minimizing economic risks [144]. Three options for building cost containment into policy design are technology neutrality, flexibility across polluters, and direct cost controls.

Technological neutrality means that a policy sets a performance requirement, such as a requirement that all producers meet a specific emission standard, while enabling compliance using different technologies. In other words, technology-neutral policy allows for a variety of compliance pathways. For example, trucks driven by either battery-electric power or hydrogen fuel cells qualify for California's zero emission truck requirements.[xvii]

Firm-level flexibility allows for heterogeneous responses by different polluters. For example, California's zero emission vehicle policy sets an average required percent of ZEV sales for each automaker, while offering flexibility through a credit trading approach, which works as follows: Automakers that exceed the industry average requirement receive credits, which they may sell. Automakers failing to reach the average requirement are required to buy credits to make up for underperformance.

Flexibility in technology and allowing for heterogeneity in firm-level response encourages discovery of the lowest-cost approaches and encourages the most innovative, cost-effective emitters to carry a larger share of the emission reduction effort.

Direct cost control can be achieved by offering an alternative compliance payment option—giving regulated companies the choice of paying a monetary fee to comply. If costs turn out to be unexpectedly high, an alternative compliance payment effectively caps the cost of complying with the regulation. If the demands of a regulation impose costs lower than the payment required under alternative compliance option, firms would be expected to undertake the actions

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[xvii] Referring to the Advanced Clean Trucks rule adopted by the California Air Resources Board in June 2020. In this case, "zero emission" refers to the lack of tailpipe emissions. There are emissions currently associated with generation of both electricity and hydrogen, though the technology to zero-out these "upstream" emissions is maturing.

envisioned by the policy. In this way, an alternative compliance payment threshold provides an automatic relief valve.

The setting of a price ceiling in an ETS is another example of direct controls on cost. Emission permits are often distributed at least in part through auctions. Auction design provides the simplest way to set a price ceiling. If bids received from potential buyers of emission permits at auction would have the effect of pushing the price above the price ceiling, additional permits are injected until supply matches demand at the price ceiling price.

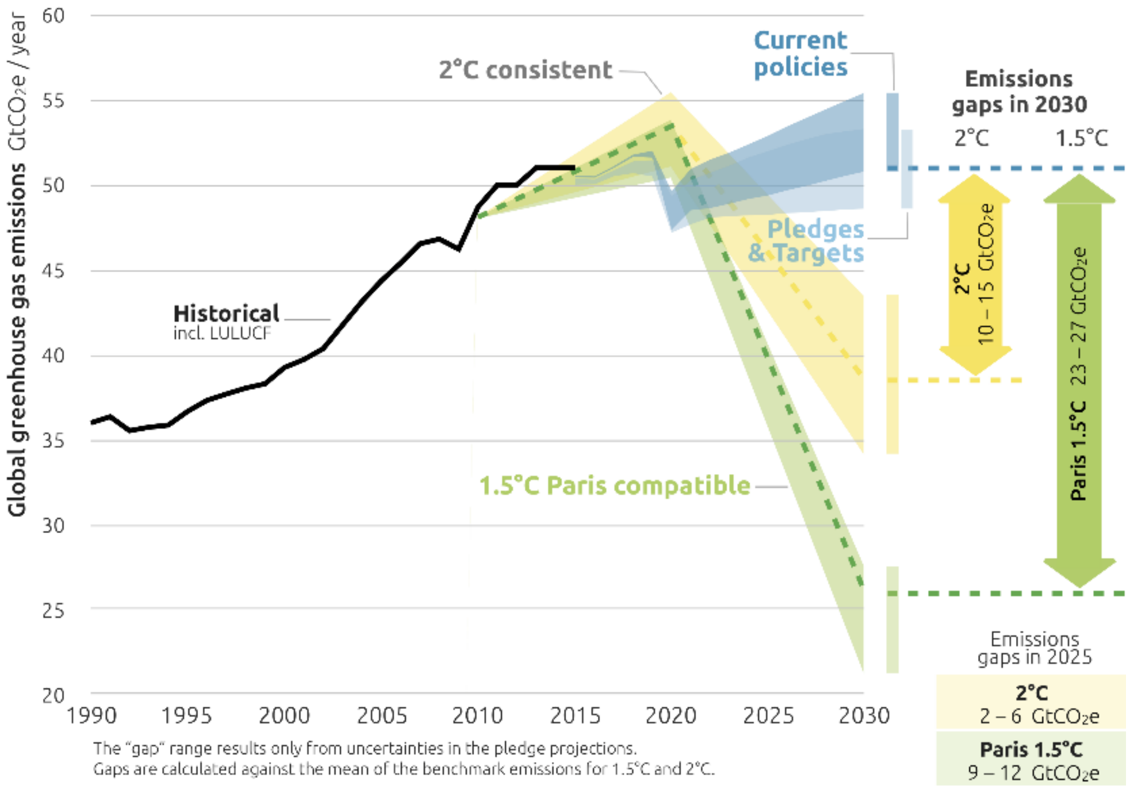
California's ETS has taken the approach of setting a price ceiling, though its price floor has proved more consequential. The initial emission reduction demand of California's ETS has been modest for reasons having to do with faster-than-expected technological progress and the effects of renewable portfolio standards and policies other than carbon pricing. The effect has been a build-up of surplus allowances, putting downward pressure on prices. California carbon permit prices have never approached the ceiling. By contrast, on five occasions, the price floor has come into play, limiting the number of permits released at auction due to weak demand [145]. The same dynamics have occurred in the European Union's ETS program, the U.S. Northeastern states' Regional Greenhouse Gas Initiative, and every other major program of which we are aware.

INTERNATIONAL CONTEXT

Climate Action Tracker evaluates whether countries' current policies and emission commitments with scientifically based targets. China's 2060 carbon neutrality pledge, if fulfilled, would lower global warming by 0.2 to 0.3 degrees Celsius in Climate Action Tracker's estimation—the single largest policy impact ever calculated by the organization.

Climate Action Tracker offers a current view of possible futures over the next decade and the implications for the battle against climate change, in Figure 22 below. The black line represents historical global emissions. In broad stroke, the dark blue and light blue bands can be thought of as representing the existing emissions trajectory. The darker blue band represents the low and high end of expected emissions based on analysis of current statutory and regulatory policies. Unlike the bottom-up accounting of current policy effects, the lighter blue band (Pledges & Targets) graphs stated emission goals without regard to whether current policy strategy is likely to lead to such an outcome.

Figure 22. Global emission pathways compatible with limiting warming to 1.5-2 degrees Celsius



Source: Climate Action Tracker [146]

Lacking a filter of expected policy effectiveness, the lighter blue band for Pledges & Targets portrays greater emission reductions. The yellow and green pathways represent the magnitude of global emission reductions needed over the next decade if we are to bequeath future generations any chance of preserving a hospitable planet. Specifically, the yellow pathway offers a chance to keep warming below 2 degrees Celsius. The green pathway offers a chance to keep warming below 1.5 degrees Celsius.

China's pledge to reach carbon neutrality, the first such pledge by a developing nation, is not the only recent development providing new optimism about prospects for international climate efforts. The European Union recently committed to ratcheting up its 2030 ambition, boosting its target to a 55 percent reduction below 1990 emissions.

The greatest obligation for more aggressive decarbonization rests with the United States. Symmetrically, the United States is the country best positioned to compete with China in clean tech. The innovative potential of the United States is unsurpassed given its combination of top universities, culture of entrepreneurship, and existing innovation ecosystem.

Indeed, the United States has staked an early claim as the leading country for EV exports through 2019, almost entirely due to Tesla exports from California [147]. EVs were California's second-most valuable manufacturing export in 2019 and are likely to claim the top spot in 2020, while also driving the state's auto-manufacturing employment to record levels [148]. EV export growth in California can be seen as a case study of the home market effect. The state has the strongest policies in the Western Hemisphere, recently announcing plans to phase out new sales of gasoline-powered cars by 2035. With 10 percent of the U.S. population, California is home to half of the country's EVs. Though engineers and entrepreneurs are the primary protagonists in this story, policymakers played an essential role. Through requirements for manufacturers and consumer incentives to develop market demand, California's policy helped to build the market for EVs.

CONCLUSION

Innovation has changed the economics of climate policy. When the potential for innovation is accounted for in full, it becomes evident that accelerating electricity system decarbonization in China is an opportunity to create not just a cleaner electricity system, but also a lower-cost one. Spurred on by technology advancement, trends in global markets are expanding economic opportunities, particularly for China, which has leading positions in the cleanest technologies—renewable power technologies and EVs. By upping the pace of its domestic clean energy transition, China will improve the international competitiveness of its clean energy firms, boosting exports in these and other industries of the future.

While emphasizing the new economic opportunities, this paper also surveys emerging evidence on the value of co-benefits yielded by decarbonization: improved health, greater energy security, better urban mobility and quality of life, cleaner water, and improved soil quality. New scientific evidence enhances our understanding of the value of co-benefits, as well as the implications of unmitigated climate change.

The science leaves no doubt: The biosphere has a limited ability to absorb more carbon without unleashing dangerous and possibly catastrophic climate change. Humanity must quickly transform the energy systems on which we depend. The specter of catastrophe, fortunately, is outshone by the ever-improving economics of clean energy. The clean technologies needed for rapid emission reductions are available, and their costs continue to plummet.

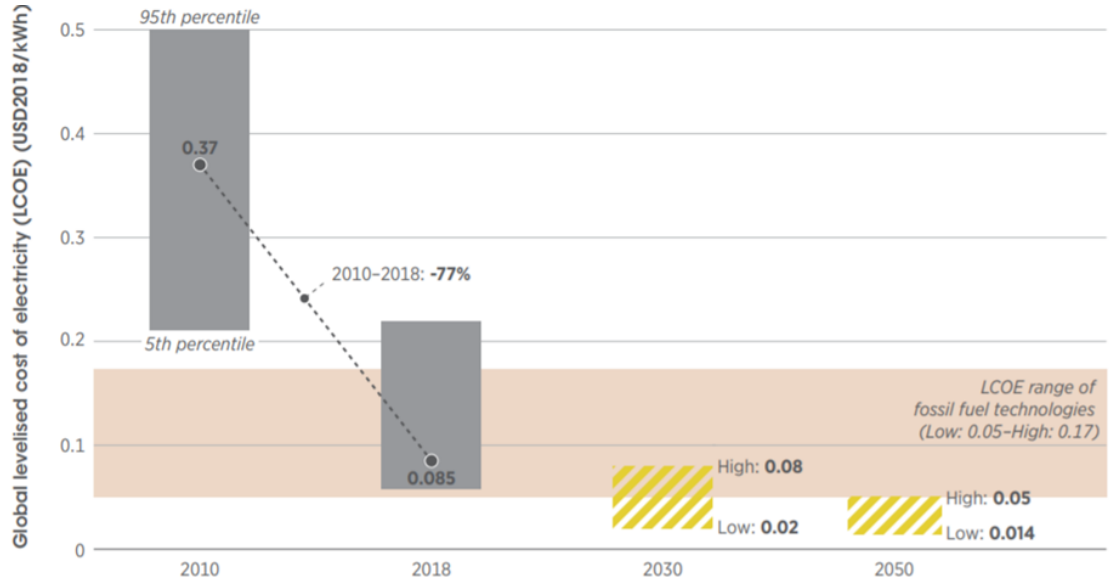
The new economics of climate policy indicate China can make faster progress on clean energy and other domestic priorities while galvanizing international action. To turn away from this opportunity at a time of increasing climate peril would be a decision lamented for many generations to come.

APPENDIX: FUTURE LEVELIZED COST METHODOLOGY

This Appendix outlines the approach used to project future costs for solar, wind, and coal power technologies as portrayed in Figure ES-1 and Figure 2. The International Renewable Energy

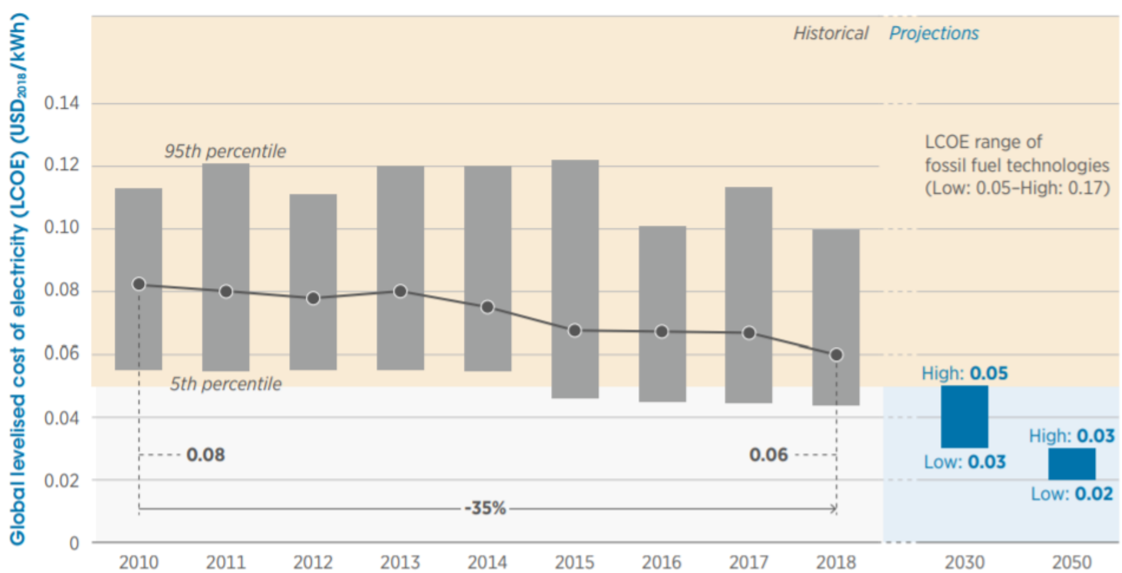
Agency's outlooks for solar and wind are shown in Figure 23 and Figure 24, respectively, and serve as an input to future cost expectations developed for this paper.

Figure 23. Future cost outlook for utility-scale solar PV power plants per the International Renewable Energy Agency



Source: International Renewable Energy Agency [149]

Figure 24. Future cost outlook for onshore wind power plants per the International Renewable Energy Agency



Source: International Renewable Energy Agency [150]

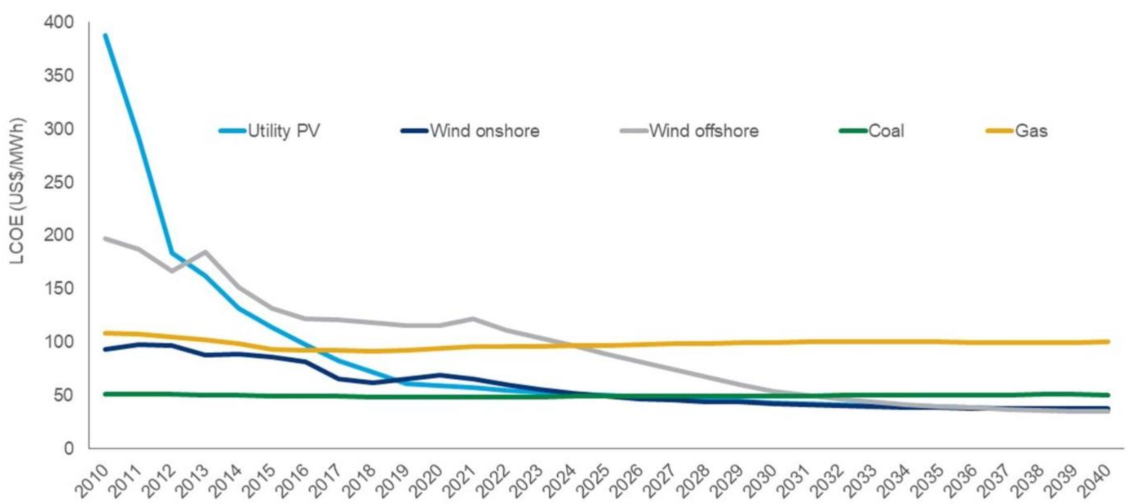
Specifically, for both solar and wind, we calculated an expected percent cost reduction in 2030 as the midpoint between the lower and upper bounds of the forecast. Then, we applied the calculated percentage reduction to historical data on China's average costs for each technology, to impute an expected value for 2030. We defined the time path forward using an exponential function to estimate annual prices, using the calculated expected value in 2030 and the historical value as endpoints.

Levelized cost of electricity for future coal includes low and high scenarios, hinging on assumptions about the future capacity factor, i.e., the level of actual generation over full technical potential. Excess capacity in China has led to declining capacity factors for coal power plants. The average capacity factor for coal power plants fell to about 50 percent in 2019 from more than 70 percent a decade earlier, as shown in Figure 3.

The price path shown for the "Coal – future (high)" scenario is what would be expected should capacity factors for coal continue to deteriorate. The "Coal – future (high)" scenario uses as an input the 2030 value forecast by Carbon Tracker International. Specifically, values were selected from the table entitled, "Summary of the results for the top three companies by capacity within each country," showing the average levelized cost for a generic new coal plant in China in 2018 as $49/MWh, rising to $64/MWh in 2030 due to declining capacity factors [151].

The "Coal – future (low)" scenario aligns with the price forecasts from the advisory firm Wood Mackenzie depicted in Figure 25. These forecasts show constant future costs, implying a stabilization of capacity factors. For completeness, we observe that Wood Mackenzie's utility solar and onshore wind forecasts are more pessimistic about the future rate of innovation in solar and wind, with cost declines falling at the high end of the range that the International Renewable Energy Agency considers possible.

Figure 25. Wood Mackenzie levelized cost of electricity in China by technology



Source: Wood Mackenzie [152]

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