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China's Industrial Energy Revolution: Renewable targets just became even more demanding (Part 1)　中国の工業用エネルギー革命--再生可能目標は以前に増して困難

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China's Industrial Energy Revolution: Renewable targets just became even more demanding (Part 1)

See the link to Part 2 of China's Industrial Energy Revolution

John Mathews and Hao Tan

China is undergoing the most astonishing energy transformation underpinning the industrial revolution that is making it the workshop of the world. It is building its 'black' energy system at a prodigious rate – building the equivalent of a 1-GW thermal power station every 10 days, and burning vast amounts of coal in doing so. But at the same time it is building a 'green' energy system based on non-fossil sources (renewables and nuclear) faster than any other country on earth. China's green revolution is reflected in its targets for building renewable energy systems, which are being expanded as fast as is humanly and technically possible – in the name of energy security and nation-building infrastructure as much as for decarbonizing the economy. Which wins in this close race between black and green development is a matter of the highest importance, for China and for the world.

In October China's State Council released its *Energy Policy* white paper, locking in some stringent goals prior to the leadership transition that moved ahead in November, and updating previous targets that had been spelt out in the 12th Five Year Plan, covering the years 2011 to 2015. In the White paper, China committed itself to achieving by 2015 no less than 30% of its electric power generation coming from non-fossil fuel sources. China's electric power system, already the world's largest and operating at just over 1 TW in 2011, is expected to grow to 1.5 TW by 2015. Of this, 450 GW (30%) is to be accounted for by non-fossil sources. The remarkable growth in non-fossil and renewable power sources—if achieved—will start to match that of thermal (coal-burning) sources. This is a truly historic milestone. It means that China's carbon emissions – 50% of which come from power generation – are coming under control.

We have just published a review of China's achievements in overhauling and expanding its electric power system in the journal *Energy Policy*. (See the paper here) Based on current thinking in China, we anticipated in our paper that the 30% goal for renewables would not be achieved until 2020. Now the 2012 energy white paper brings that date forward to 2015, at the conclusion of the current 12th Five Year plan. China's leadership is clearly in a hurry to switch its vast energy system behind non-fossil sources (and particularly renewables), to get off the treadmill of dependence on fossil fuels as its energy consumption continues at a torrid pace. And it believes that it can do so without sacrificing hyper-growth.

The following Table displays the targets outlined in the Energy WP for non-fossil sources of electric power, and the additions implied (GW). The White Paper reveals that China's total electric power system in 2011 had reached a scale of 1,060 GW, or just over 1 TW (1 trillion watts)– making it comparable to the US 1 TW electric power system. Non-fossil and nuclear sources accounted for 292.5 GW in 2011 (amounting to 27.6% of the installed electricity generating capacity). This puts the 2015 target of 30% in some perspective – but the goals are no less amazing.

Non-fossil sources	2011	2015	Increase	Increase (%)
Hydro	230	290	60	26%
Nuclear	12.5	40	27.5	220%
Wind	47	100	53	113%
Solar PV	3	21	18	600%
Total electric power from non-fossil sources	292.5	451	158.5	54%

Source: Adapted from 2012 Energy White Paper

In summary, over the next three years, China will be building 60 GW of new hydro power, 27.5 GW of nuclear, 53 GW of wind power and 18 GW of solar PV. These are by a long way the most ambitious goals for growing non-fossil energy systems in the world.

Now let us add in the (evolving) targets for 2020, as revealed in the new White paper and from semi-official sources such as the Energy Research Institute (ERI) and the State Grid Energy Research Institute (SGERI). The latest planning documents for energy in 2020 (supplementing the 12th FYP) list the following targets for fossil and non-fossil sources:

	2020 targets	Increase from the 2011 level (%)
Total electric power capacity	1786[1] GW	68.4%
Of which:		
Hydro	340 GW	47.8%
Wind	150 GW	219.1%

Source: Zeng et al. (2012), available here, which is based on data from the China Electricity Council and the State Grid Energy Research Institute.

Note:

1. Total electric power capacity also includes capacities of power stations using other sources such as pumped storage and oil that are not detailed in the table.

This new Table shows the 2020 targets as raising

Biomass	15 GW	782.4%
Solar	24 GW	700.0%
Nuclear	80.8 GW	546.4%
Coal	1030 GW	54.4%
Gas	58.9 GW	63.6%[2]

overall electric power capacity from 1.0 TW (1000 GW) in 2011 to almost 1.8 TW in 2020. Of this, 610 GW would come from non-fossil sources, out of 1800 GW installed electric power -- or 34% -- meaning that the proportion of non-fossil sources is anticipated to rise from 30% to 34% over the remainder of the decade. Indeed if China continues its expansion of renewables at the same pace as it projects to 2015, we would suggest that a target for wind power in 2020 would be 200 GW, and for solar PV the target would be more like 50 GW (given that the 2015 target is already at 21 GW). So these revised targets would raise the overall non-fossil targets for 2020 by about 80 GW, to 685 GW – which is 38.4% of 1,785 GW (1.8 TW). The genuinely renewable sources – wind, solar, hydro, biomass – would account for 34% of electric power generation by 2020. The increase in renewable generating capacity from 2011 to 2020 would be of the order of 246 GW – or around a 1-GW power station every two weeks.

On the other hand, the fossil fuel-based electric generating capacity will also grow, with coal rising from a generating capacity of 667 GW in 2011 to a projected 1030 GW by 2020, or an increase of 54%. The increase in generating capacity would be of the order of 363 GW – or a 1-GW thermal power station every 10 days. But while coal's contribution to generating capacity continues to expand, its significance as a source of electric power is diminishing – from accounting for around 76% of electric power generation in 2001 to 63% of electric power in 2011 down to around 58% by 2020. If coal and renewables continue these comparative trends, one would expect that China would be generating more electric power from renewables than from coal before 2030. This is a truly amazing achievement, and one that reflects the determination and investment drive behind these bland Chinese planning documents. It can be expected to have multiple effects, including driving down the price of renewables to well below costs of fossil-fuelled power – and creation of millions of jobs, particularly in rural areas where the renewable energy sources may be found. But China's carbon emissions will continue to rise, for at least another decade -- and then can be expected to fall. And once they start falling, they will fall rapidly. We return to the likely trajectory of carbon emissions below.

According to China's 12th Five Year Plan, its seven designated strategic industries (two of which are renewable energies and electric vehicles) are anticipated to raise their contribution to overall GDP from 4% in 2010 to 8% in 2015 and to no less than 15% by 2020 – meaning that these industries would be growing at more than 20% per year and would become the central pillars of the Chinese economy. No other country comes even close to these targets. (Reuters reported at the end of 2010 that China was considering investing up to $1.5 trillion in the seven strategic industries by 2015.)

If all this comes to pass, China will be utilizing non-fossil sources for 34% of its electrical power generation by 2020 – within the decade – rising from around 27% in 2011, while starting to phase out fossil sources. What an extraordinary achievement – and one with far-reaching implications for driving down the costs of renewables for all countries, and for getting carbon emissions under control. While power generation from fossil-fuel sources including coal will continue to grow for at least the next decade, the substitution of fossil fuels by renewable sources in generating electric power can be expected to substantially reduce the amounts of carbon emissions that would otherwise be incurred. A crude conversion between different forms of energy based on heat content of fuels indicates that the installed electric power capacity using non-fossil fuels in 2020 could produce 253.5 million tonnes of coal equivalent (tce) of electricity in the year, or save up to 400 GW of conventional coal-fired power generating capacity in one year. [1]

Logistic industrial dynamics

Now let us probe more deeply into the question as to where these trends are taking China. Let us elaborate on our comment that China's overall energy supplies are rising then plateauing, while renewable sources are rapidly rising, following a logistic trajectory. The conventional way of depicting energy substitution is by straight lines, but this fails to capture the real industrial dynamics involved. As investment in the renewables value chain accumulates, so it makes the uptake of renewables all the more likely, and increases the economic clout of the sector as a whole. We wish to capture this effect in depicting energy transitions in China using a parabolic curve for the total energy (a convex curve that flattens out) and logistic curve for non-fossil energy uptake (and particularly depicting renewables uptake, excluding nuclear).

We suggest therefore that linear interpolations do not give an adequate representation of these ambitious goals. The true scale of the changes being planned and implemented only become apparent when we plot them according to logistic industrial dynamics. We capture the industrial dynamics of china's energy systems in terms of two curves – an outer parabola, representing total electric power installed capacity, and an inner logistic curve, representing non-fossil energy sources.

In our paper just published in *Energy Policy*, we depict two curves – a convex curve showing the increase then rapid decline of fossil sources, and the logistic uptake of non-fossil sources. The chart is intended to demonstrate the difference in industrial dynamics between the logistic uptake of renewables (non-fossil sources) and the parabolic rise and decline of fossil sources.

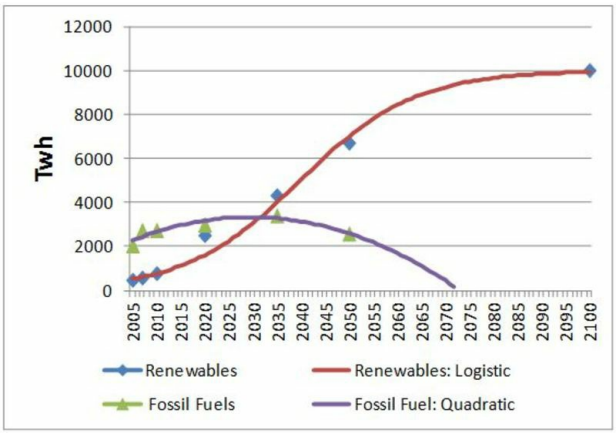


Chart 1. China's electric energy generation, 2005 to 2050 (projected)

Note that this chart measures electric energy in terms of million kilowatt-hours (or TWh), whereas we have been utilizing capacity measures (GW and TW) in our discussion above. So if we apply the notion to capacity measures using the updated estimates based on the latest development in the sector, we may add in an outer curve representing **total electric energy**, and draw the uptake of non-fossil sources as occurring within the envelope of the total energy supply. We build in assumptions that energy efficiency will improve by having this curve flatten out, even while renewable sources continue to rise. We also focus on the immediate future by cutting the chart off at the year 2040. We also draw two logistic curves for renewables – one for all 'non-fossil fuel sources' (which include nuclear) and one for genuine renewables (hydro, solar, wind etc.).

We take the 2020 goals as previously spelt out, and fit an outer parabola that goes through 1 TW of electric power generation at 2010 and reaches 1.8 TW by 2020, flattening out and perhaps reaching a maximum of just over 2 TW by 2030. We also fit a logistic curve that grows from 2000 to 2011 to 2020 so that the gap between the outer and inner curves is seen to be narrowing, with a shape beyond 2020 that suggests rapid substitution according to logistic industrial dynamics. The revised and fresh chart (our master chart for Chinese electric power trends) is shown below.

The historical data up to 2011 are available from the International Energy Statistics database of the Energy Information Administration of the US. The targets between 2015 and 2020 are based on the China Energy White Paper. The estimates of the nuclear electric capacity in 2030 and 2040 are based on the

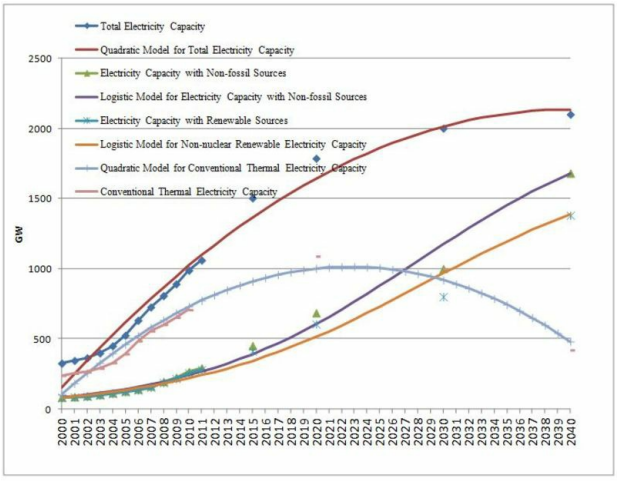


Chart 2. Industrial dynamics of electric power capacity in China: 2000-2040. Source: Authors.

OECD "China in Focus" report The projection data up to 2040 are generated by a quadratic model (for the total electricity capacity) and two logistic models (for electricity from all renewable sources including nuclear and for electricity from non-nuclear renewable sources respectively) by authors.

Let us explain clearly what this chart means. For the outer parabolic curve, we have a total electric power trajectory that follows historic points up to the year 2011 (shown as diamonds), and then further points spaced out to 2015 and 2020 according to the most recent official projects, and then to 2030 and 2040 based on publications from the Energy Research Institute. It reaches just over 2000 GW (2 TW) by 2040. We then draw through this our own smooth parabolic curve (Quadratic model for total electricity) to indicate the shape of China's likely total energy trajectory up to the year 2040. For the inner logistic curve, we depict firstly the historic points for non-fossil energy sources (including nuclear) up to the year 2011, and then show points beyond this date (as triangles) based on official projections. We draw our own logistic curve through all these points (logistic model for non-fossil sources). Then we have a pair of curves for non-fossil energy sources excluding nuclear, i.e. genuinely renewable sources – again shown as historic points up to 2011 and then projected outwards (shown as crosses) according to official sources, together with our own smooth logistic curve capturing the essence of the trajectory. This curve shows for example renewable sources as contributing 685 GW by 2020 (out of a total of 1785 GW) (or 38%, as mentioned above)) rising to 1600 GW out of a total of 2000 GW by 2030 – or 80%, and 1890 GW out of 2100 GW by 2040.

Finally we depict coal-burning thermal electric power generation on the chart, showing it increasing from 667 GW in 2011 to 1030 GW in 2020 then peaking and declining to 1000 GW in 2030 – i.e. peaking between 2020 and 2030. In accordance with logistic industrial dynamics for uptake of renewables, the significance of fossil sources can be anticipated to decline rapidly thereafter – as shown in our original chart 1 above, and in our new chart 2.

We submit that this new Chart provides a plausible and realistic model of China's likely greening of its electric power sector – the source of 50% of its carbon emissions. Inspection of our new Chart shows that renewables would account for half of the total power generated by 2022 or 2023 – just over a decade hence.

The outer parabolic curve gives a powerful impression of the growth and levelling-off of China's total electric power system. The logistic inner curves for electric power generation from non-fossil sources would approach 100% substitution by 2050 – when both curves would start to decline as energy efficiency measures kick in.[2] The inner logistic curves indicate that while nuclear remains an option in China, the real growth in the electric power sector will come from true renewables like wind and solar. (Of course China's overall energy system computed according to primary sources will change much more slowly than this.)

We base our estimates for China's adoption of nuclear power on those published by the OECD in the "China in Focus" report in 2012. (See the report here) While China put its nuclear ambitions on hold following the Japanese Fukushima nuclear disaster, it seems that it is now back on track to building new nuclear reactors – in competition with Korea and France and (possibly) Japan. The only positive thing one can say about this choice of national strategy is that in China it seems that the nuclear option does not crowd out other renewable options. Our sense of the logistic industrial dynamics is that renewables will rapidly supplant nuclear in China's energy mix.

We suggest that this new Chart gives a stronger sense of what is happening in China than can be achieved by use of Tables and linear projections – which is what the IEA and EIA and other official bodies do. It is essential to grasp that what China is executing is a veritable energy industrial revolution – as captured by the logistic industrial dynamics of the uptake of renewables. Logistic dynamics reflect the effect of cumulative capacity additions, and capture visually the strong sense of path-dependence and cumulative investment that will bias the total energy system more and more towards renewables.

Finally we need to consider how these projections would translate into carbon emissions.

China's projected carbon emissions

What emissions are likely to be generated from China's massive burning of fossil fuels – before the substitution by renewables is completed? Using Chinese data on carbon emissions, we can now sketch the actual carbon emissions likely to be generated by China's electric power revolution.[3] We exclude potential carbon emissions from renewable and nuclear-based electric power stations in this calculation as we assume those would be minimal compared with those from the coal-fired power stations.[4] We estimate expected carbon emissions from China's electric power sector will continue to grow till around 2025, and then start to decline thanks to the take-off of the renewable energy used in the sector. This means that, for all its efforts to reduce energy intensity and carbon intensity, China is likely to be increasing its total carbon emissions from generating power for another decade or more.

We can round out these curves to show the point where it can be anticipated that China's carbon emissions will approach zero, as the country moves along logistic industrial dynamics to a point where its renewable energy utilization becomes dominant.

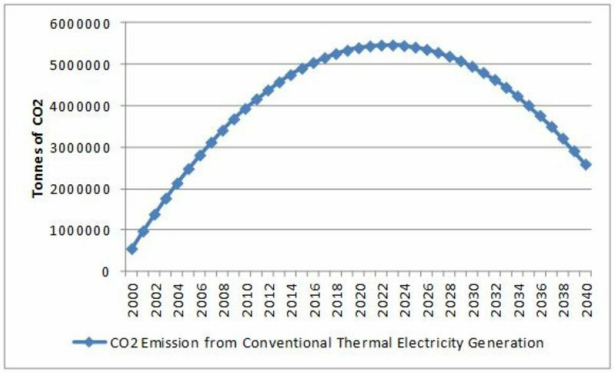


Chart 3. China: Projected carbon emissions from thermal power generation, 2000-2040. Source: Authors' calculation

This chart tells a remarkable story. By integrating under the curve, we estimate that total CO_2 emissions due to China's electric power generation over the next three decades between 2011 and 2040, would be about 140 billion tonnes. Yes, China's carbon emissions from electric power generation will continue to rise – but we anticipate that they will plateau in the 2020s and then start to decline – steeply, as thermal power generation declines.

What will be the impact on carbon dioxide levels of these extra gigatonnes of carbon emitted as a by-product of China's industrialization? We know (e.g. from the Carbon Mitigation Initiative at Princeton) that carbon dioxide levels rise by 0.22 ppm for each Gt carbon emitted.[5] Thus addition of around 140 Gt carbon dioxide from electric power generation up to the year 2040 would force carbon dioxide concentrations to rise by around 30 ppm.

So we have a clear outer limit to the 'carbon emissions' cost of China's energy revolution and associated industrialization, based on burning coal and other fossil fuels in the electric power sector (the largest user of coal in the Chinese economy). This outer limit of 140 Gt CO_2 up to 2040 is likely to drive up carbon dioxide concentrations by 30 ppm. Since the CO_2 concentration stands at 391 ppm (in 2012), China's net forcing from electric power generation can be expected to drive this up to 421 ppm – taking the world close to the 'prudent level' of

450 ppm established by the Inter-Governmenal Panel on Climate Change. Of course China's and other countries' carbon emissions have to be added to this to gain a global perspective. China's industrialization is the first where its carbon emissions implications can be anticipated in advance.

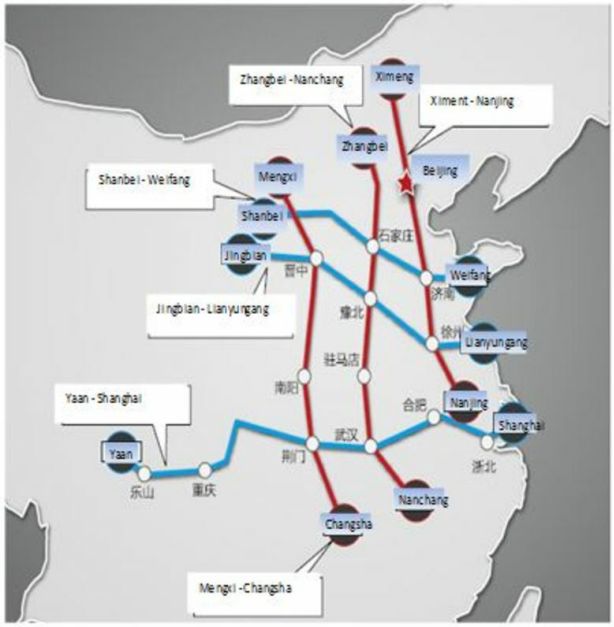
We do not wish to be misunderstood on this point. We are not advocating that China cease its industrialization because of the expected carbon emissions. This contribution from China needs to be compared with the cumulative contribution from the countries of the West as they industrialized; these countries emitted more than 350 Gt carbon over the 250 years from the Industrial Revolution to the year 2000, and drove up carbon dioxide concentrations from the pre-industrial level of 280 ppm to around 391 ppm by the year 2012.[6] Between 1751 and 1900 about 12 gigatonnes of carbon were released as carbon dioxide to the atmosphere from burning of fossil fuels. By contrast, from 1901 to 2008, according to the Carbon Dioxide Information Analysis Center, the figure was about 334 gigatonnes. This history of fossil fuel burning by the West puts China's present contribution into context. And China's accelerated uptake of renewable energy sources promises to curb carbon emissions more effectively than any other means.

Strong and smart grid

An energy industrial revolution is not concerned only with the promotion of renewable supplies. It is also concerned with the promotion of demand (e.g. through the use of feed-in tariffs, now diffusing through China) and through the upgrading of the grid, so that it can accommodate fluctuating supplies from renewables and match them to fluctuating demand.

The targets for investment in grid upgrading by the State Grid Corporation of China (SGCC) are emblematic of the huge push being made to accommodate renewables. SGCC is the world's largest utility, and one of the 10 largest companies worldwide – and yet it is still barely known outside China. Its grid covers over a billion people in China, complementing that supplied by the Guangzhou-based Southern Power Grid Co. As we stated in our joint paper for Energy Policy, SGCC has committed 4 trillion yuan investment over the course of the 12th and 13th Five Year Plans (i.e. up to 2020) – that is around US$642 billion, far more than is projected by any other country. Of this, 1.7 trillion yuan (US$273 billion) are to be allocated up to 2015, and 2.3 trillion yuan (US$369 billion) for the second five-year period. (Note: There have been other reports in the semi-official *China Daily* that SGCC announced in 2011 that it would invest $250 billion up to 2015, and a further $240 billion to 2020; see here)

The major element of China's upgrading is the building of long-distance power lines utilizing high-voltage direct current (HVDC) which loses much less power in transmission than conventional AC lines. We reproduce a chart from China that shows how the grid will change as the SGCC investments are implemented. The upgraded grid will have several east-west and north-south 'trunk routes' for carrying ultra-high voltage cables (depicted as red and blue). Clearly provinces that are not depicted as being connected to these HVDC long-distance links will nevertheless be connected to the upgraded grid.



Source: the State Grid Corporation of China (SGCC), available at Caixin.com

China's plans are to transfer technologies for the grid – smart meters, HVDC cables, digital substations, EV charging points etc – and build up domestic capabilities in these technologies as fast as possible. To this end Chinese standards are also being introduced, which will operate in tandem with standards developed in the US, EU and Japan – and where the headstart secured by China in building the strong and smart grid will put its firms in a good position in rolling out such standards. In our paper we discuss the role of standards for the smart-grid as representing an important area where China can be anticipated to move from a production mentality to an innovation mentality. Unlike the standards being developed currently in the US and EU, which are largely based on hypothetical developments, the Chinese standards will be backed by the real investments in real grid upgrades, which are necessitated by the anticipated uptake of renewable energy sources and the need for a grid that can accommodate them.

The infrastructure project that complements China's massive rollout of a strong and smart grid is that of a national high speed rail network. Here the scaling up is again being taken at a prodigious rate – even if set back by the tragic accident involving a collision in 2012 of two HSR trains in Wenzhou, Zhejiang. The proposed national HSR infrastructure mirrors that for the strong and smart grid – indeed the two complement each other as 21st century nation-building projects – as railways were for the 19th century and pipelines and road systems were for the 20th. China's HSR system is shown in the Chart, which we reproduce here solely to illustrate how high-speed rail complements strengthening and upgrading the grid, and that both projects need to be seen as China's major 21st century nation-building infrastructure projects that have powerful consequences for the country's likely future industrial capacity.

Source: Ministry of Railways, China

We conclude:

As a relative latecomer in its energy-based industrial revolution, focused on the years since 2001 when China entered the WTO, Chinese firms and state agencies have been able to draw on the accumulated knowledge available in the developed world and apply this in their own large domestic market. Industrial

policy has been applied in selecting certain technologies for development, building domestic value-chains in the selected technologies, encouraging foreign direct investment in the targeted sectors, and building a domestic technological capacity in these (as evidenced in the standards developed for the interoperability of the smart and strong grid). The characteristic approach being pursued by China in relation to grid modernization, is to fashion the architecture and operation of the grid so that it can accommodate a growing proportion of renewable energy generation sources, with their fluctuating supply, and match them with fluctuating demand, from industry, commerce and transport. In this way, the strong and smart grid underpins every other policy development. But at the same time the Chinese leadership is intent on building strong industries in each of the areas of power generation, transmission and management, cultivating the firms concerned, and the standards needed for the technology, and using its strong domestic market as catalyst for these industries. This is an industrialization strategy that is hard to fault – unless other countries that see themselves being left behind seek redress through the World Trade Organization (as is threatened by the US), or through trade sanctions.

Our argument has been that China has demonstrated impressive understanding of its own limitations in terms of institutional and technological capacity, and has contrived through industrial policy to seek to make up for these deficiencies and achieve technological parity in key sectors including more efficient thermal power production, expansion of renewables generation, and the building of a 21st century infrastructure including a strong and smart grid and national high-speed rail system. In this way China promises to reduce its initial strong dependence on fossil fuel sources, and high carbon emissions, as it moves along logistic industrial dynamic pathways to see a rapid uptake of renewable and low-carbon energy systems. If successful in transforming the world's largest energy economy into one predominantly reliant on renewables, this will be good for China and for the world.

See Part 2 of China's Industrial Energy Revolution.

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Notes

[1] According to the State Grid Corporation of China's 'Green Development White Paper' in 2010, the annual utilization hours for hydropower, wind, nuclear and solar in China are 3500 hours, 2000 hours, 7500 hours and 1400 hours respectively. The annual utilization hours for thermal power stations are given as 5300 hours. Thus a 1 GW source of hydropower generates 3500 GWh in one year; a 1 GW source of wind power generates 2000 GWh; a 1 GW thermal power station generates 5300 GWh; a 1 GW nuclear power station generates 7500 GWh; and a solar PV source generates 1400 GWh in one year. If 1 tce contains 29.3 GJ, then 1 billion tce (1 gtce) contains 29.3 EJ, or 8.4 trillion kWh (8400 TWh). Therefore, the capacity of non-fossil fuel electricity in 2020 will produce 2130 TWh of electricity in one year, or 253.5 million tce of electricity.

[2] See ERI, 2009.China's Low Carbon Development Pathways by 2050: Scenario Analysis of Energy Demand and Carbon Emissions. NDRC Energy Research Institute Research Team. Science Press, Beijing (in Chinese)

[3] Following Liu, T. et al. (2011) 'Development forecast of renewable energy in China and its influence on the GHG control strategy of the country'. Renewable Energy, 26: 1284-1292, we use in this calculation the emission factors of 1017 g CO2/kWh for coal-fired power plants in China. Again, we utilize the annual utilization hours as indicated in the State Grid Corporation of China's 'Green Development White Paper' in 2010, i.e. 5300 hours per year for thermal power to translate the electricity capacity to electricity generation.

[4] This is supported by Liu et al. (2011) 'Development forecast of renewable energy in China and its influence on the GHG control strategy of the country'. Renewable Energy, 26: 1284-1292, who estimate that the emission factors of hydro, wind, solar and biomass-based electricity are 17, 36, 57, and 46 g CO_2 / kWh compared with 1017 g CO_2 / kWh by coal-fired power plants.

[5] See the Carbon Mitigation Initiative website, and the presentation on Stabilization wedges here.

[6] See the webpage of the Carbon Dioxide Information and Analysis Center. For the estimate of the cumulative carbon emissions over the 250 years 1750-200, see Allen et al (2009).