MEETING CHINA'S FUTURE ENERGY NEEDS AND ENVIRONMENTAL COMMITMENTS: IS INCREASING NUCLEAR POWER THE BEST WAY TO GO?

David F. von Hippel

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Executive Summary

After three decades of rapid economic growth, with attendant increases in energy use and in the environmental consequences of same, as of 2018 China arguably sits at a point of decision, inflection, or possibly both in the evolution of its electricity generation system, its nuclear power future, and possibly the future of its energy sector as a whole. As a source of electric power that is essentially free of the air pollutant and greenhouse gas emissions that plague the coal-fired generation that produces up about 70 percent of China's electricity, nuclear power has been touted as a solution to China's environmental challenges. Scenarios of nuclear power development in China, including those presented in this paper, span the range from modest growth to 80-100 GWe (gigawatts of electricity generation capacity) by 2050 (from about 34 GWe today) to growth to 300 to 400 or more GWe of nuclear power by 2050. China's nominal plans for its nuclear sector include the use of spent fuel reprocessing to extract plutonium (Pu), the use of mixed-oxide (MOx—a mixture of plutonium and uranium isotopes) nuclear fuel in light water reactors, and ultimately, the development and use of fast-breeder reactors that produce and use plutonium fuel. These technologies potentially pose risks for the international non-proliferation regime by creating large stocks and flows of plutonium that, if diverted, could be used in nuclear weapons or "dirty bombs". This paper explores the potential for China to meet its development needs and environmental goals through three alternative paths of nuclear power development through 2050, and explores the relative physical, economic, environmental, and socio-political consequences of the paths.

A comparison of alternative paths for the Chinese nuclear and electricity sectors—namely a "BAU" or Reference path reflecting recent trends and plans, a "MAX" path with fairly aggressive expansion of nuclear generation capacity, and a "MIN" path in which nuclear power capacity expands more slowly, and construction largely stops after 2040, with energy efficiency and renewable energy sources becoming a major focus—suggests that it will be possible to meet China's economic development, GHG and air pollutant emissions reduction, and other goals without an extended or massive build-out of LWR capacity, and without expansions of uranium enrichment or reprocessing capacity beyond projects now underway.

In particular, the "Minimum Nuclear" (MIN) path means that China will likely not become a major exporter of nuclear power technologies but will continue along its current trend of being

perhaps a dominant provider of renewable power systems. In addition, the MIN path nuclear sector costs are much lower (both in aggregate and per unit output), than in the MAX and BAU paths. Although nuclear costs are only a small part of overall cost of providing energy services to the Chinese economy, past experience in China and elsewhere, as well as other studies of Chinese energy futures, have indicated that emphases on energy efficiency and renewable energy offers China the ability to effectively address environmental concerns without significant (if any) additional costs, relative to a reference path. In addition, a path with less nuclear power, and fewer nuclear fuel supply and enrichment ("front-end") and nuclear spent fuel handling, transport, and reprocessing ("back-end") facilities is arguably easier to deploy in social and political terms, particularly if expectations for a stronger voice in how China's future unfolds continue to grow among the Chinese citizenry (although that is not a given as of this writing). The MIN path provides significant benefits over MAX/BAU paths in terms of Pu production and stocks, and thus offers a significantly lower risk of nuclear weapons proliferation than the other two paths.

In order for the MIN path (or a similar energy trajectory) to become reality in China, national policy support for energy efficiency and renewable energy will need to take precedence over policy support for nuclear power and technological and cost trends in energy efficiency and renewable energy will need to continue or accelerate. Trends in recent years have pointed toward the enhanced practicality of a low-nuclear path for the Chinese energy sector. These trends include a slow-down in reactor construction, and a re-thinking of nuclear safety regulations in the post-Fukushima era, ongoing structural change in the Chinese economy away from heavy industry, with attendant much-reduced growth in electricity needs, and exceedance of even the State's own ambitious targets for renewable energy.

The nations of the international community can help to influence a Chinese transition to a low-nuclear future through the acknowledgment of the benefits of a MIN path (or similar) for China by international political and trading partners, through international policies encouraging low-nuclear paths, and by embracing energy paths of their own that de-emphasize nuclear power, enrichment, and reprocessing, and encourage nuclear sector safety and transparency, would encourage China to move toward a low-nuclear future.

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1 Introduction: China's Energy and Environmental Challenges

1.1 Projections of Economic Development and Energy Use in China, and Their Environmental Price

China's emergence as a global economic powerhouse from what was a largely rural and agrarian society even as of the 1980 has been a defining characteristic of the past few decades. The rate of growth in gross domestic product (GDP) in China exceeded 7 percent per annum in each year between 1991 and 2015, dipping only slightly below 7 percent in 2015 and 2016.[1] The result of this rapid growth has been that China's economy is more than 11 times larger today than it was in 1990, and nearly 30 times larger than it was in 1980. An increase in energy production and use, and especially electricity generation, has fueled the growth in China's economy. Primary energy use, a measure of all of the fuels that go into providing energy for an economy, has increased by nearly a factor of five since 1990, as has oil and oil products consumption, and electricity generation has grown nearly 10-fold in the same period. China edged the United States as the world's largest producer of coal in the mid-1980s. In 1990 coal production in China was over a billion tonnes (metric tons) per year, and rose to nearly 4 billion tonnes by 2013, before declining somewhat in recent years.

Although it has significant energy resources of its own, China has been obliged to turn to imports to help fuel its massive economic growth. China became a net importer of oil and oil products in the early 1990s, and a net importer of gas, as mostly as liquefied natural gas (LNG), in about 2006. By 2016, China was the world's third-largest importer of LNG, after Japan and the ROK. China's oil imports broke a monthly record early in 2017, with its imports exceeding those of the US to be the world's highest.[2] China sources its oil imports from a diverse array of nations; by 2014, 14 countries each supplied at least 2 percent of China's total oil imports, with Saudi Arabia its leading supplier at 16 percent.[3] China's energy imports dependency continues to increase, as consumption continues to rise while production of coal and oil, in particular, are relatively static. China's energy imports dependency is not yet, however, at the 90-plus percent level found in the ROK and Japan.

The large and rapid increase in China's energy use has been accompanied by a variety of environmental challenges. In 2006, China passed the United States to become the largest emitter of greenhouse gases (GHGs) among nations,[4] and by 2014 emitted 30 percent of global anthropogenic GHG emissions, although its per capita emissions remain less than those in the

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[1] World Bank (2017), "GDP Growth, Annual (%)", graph and data available at http://data.worldbank.org/indicator/NY.GDP.MKTP.KD.ZG?locations=CN.

[2] See, for example, Gordon Kristopher (2017), "China's Crude Oil Imports Hit a New Record Market Realist, April 19, 2017, available as http://marketrealist.com/2017/04/chinas-crude-oil-imports-hit-new-record/.

[3] United States Department of Energy, Energy Information Administration (2015), *China*, last updated May 14, 2015, and available as https://energy.gov/sites/prod/files/2016/04/f30/China_International_Analysis_US.pdf.

[4] See, for example, Carbon Brief, "Global Historical Emissions Map", available as https://www.carbonbrief.org/interactive-map-historical-emissions-around-the-world.

US and many other industrialized nations.[5] In addition, increased energy use in China has led to emissions of local and regional air pollutants high enough to be a significant danger to health much of the year in many Chinese cities, including Beijing,[6] and has contributed to water pollution, soil degradation, and numerous other environmental problems.

Although China has markedly improved energy use efficiency in recent years, particularly as measured in energy use per unit of GDP, shifting away from coal use to reduce global, regional, and local environmental problems has continued to be a priority in Chinese policy. This shift is to be in part accomplished by moving some of the most polluting industries out of the major southern and eastern Chinese cities to other areas of China, as well as moving some of those industries to other nations as the Chinese economy moves more toward high value-added manufacturing and services. In the electricity sector, this means a combination of improved efficiency in existing and new coal fired power plants and increasing the share of power generated from non-fossil resources, including renewable energy sources (particularly hydroelectric, wind, and solar power) and nuclear power.

China's nuclear sector is young by comparison to that of Japan and the ROK, but is and has been growing fast, as most of the reactors built worldwide at present are being built in China. With a large land area and a not-yet-powerful civil society sector, siting of nuclear plants and spent fuel facilities has not yet been a major problem for China, though it may grow to be so in the future.

1.2 Past and Projected Patterns of Growth of the Chinese Electricity Sector

Total Electricity generation in China in 1990 was approximately 650 terawatt hours (TWh, or billion kilowatt-hours), including Hong Kong, which is about the same as present-day Germany, with about 7 percent of China's population.[7] By 2016, electricity output and consumption in China had grown nearly 10-fold, supplanting the United States in 2011 as the nation with the largest electricity consumption (see Figure 1-1). Overall generation capacity grew even more rapidly, particularly in recent years, with growth in capacity averaging over 9 percent annually from 1990 through 2005, and 11 percent annually from 2005 through 2016 (see Figure 1-2).[8] Generation capacity in China now exceeds 1600 GW (gigawatts, or million kilowatts), nearly 60 percent more than the United States, where generation capacity stood at a bit over 1000 GW as of 2016.[9]

Thermal power, and specifically coal-fired power, has been the mainstay of Chinese electricity generation. Thermal power provided about 80 percent of generation in 1990, remaining near that

[5] United States Environmental Protection Agency (USEPA, 2016), "Global Greenhouse Gas Emissions Data", available as https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.

[6] See, for example, South China Morning Post (2017), "China orders cities to reduce emissions, as capital braces for another bout of heavy smog", dated February 13, 2017, and available as http://www.scmp.com/news/china/policies-politics/article/2070392/china-orders-cities-reduce-emissions-capital-braces.

[7] British Petroleum (2017), *BP Statistical Review of World Energy June 2017*, excel workbook accompanying volume available at http://www.bp.com/statisticalreview.

[8] Some of the even more rapid growth in the post-2005 period was due to the addition of large amounts of wind and solar power generation capacity, which have lower capacity factors, and thus generate less energy annually per unit of capacity than, for example, coal-fired and nuclear power plants.

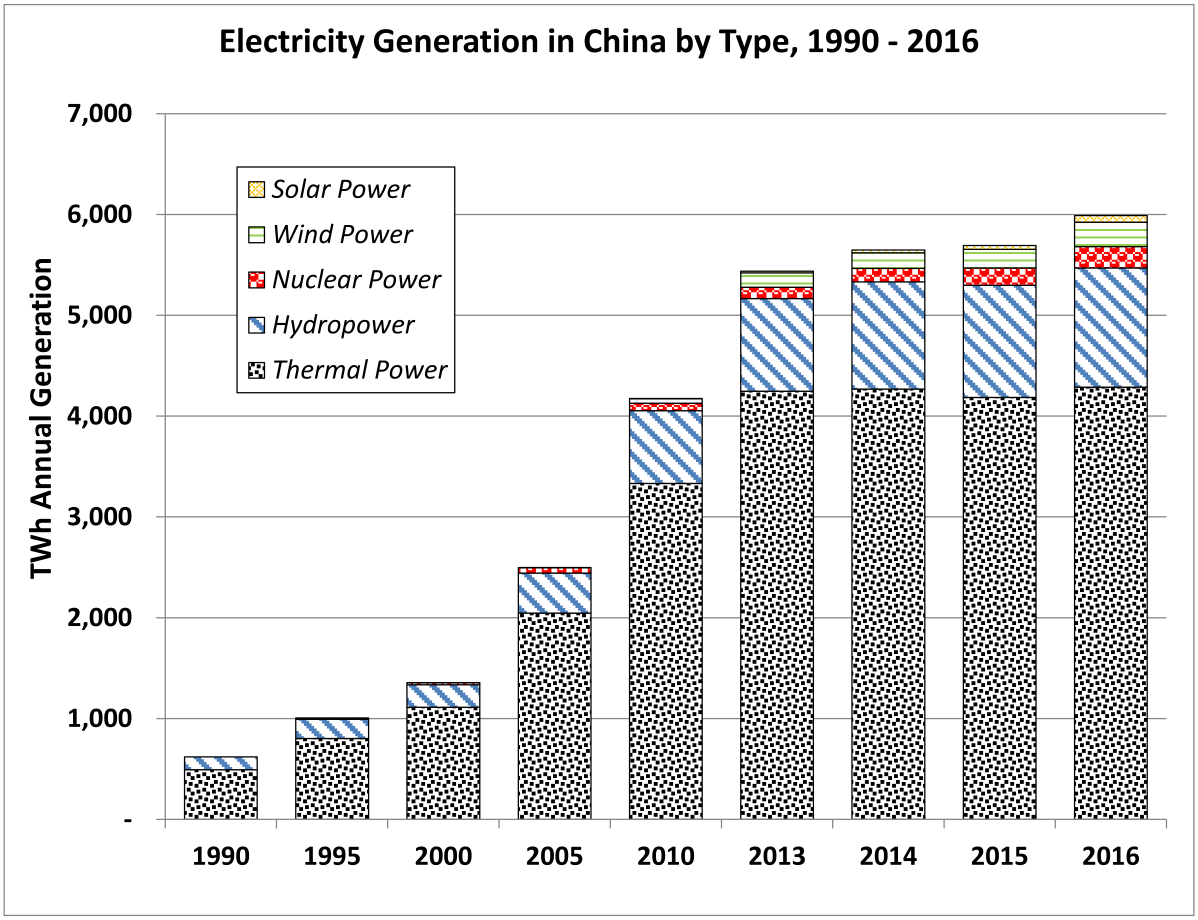
[9] United States Department of Energy, Energy Information Administration (USDOE EIA, 2017), "Electricity in the United States", available as https://www.eia.gov/energyexplained/index.cfm?page=electricity_in_the_united_states#tab2.

level though 2010, falling only in recent years to under 72 percent by 2016. Despite rapid growth in nuclear capacity, nuclear power accounted for only 3.6 percent of electricity output by 2016, somewhat less than wind power in that year. Construction of hydroelectric capacity has been rapid in the past decade, and continues today with, nearly 12 GWe of capacity added in 2016 alone to a total of 330 GWe (of which about 27 GWe are pumped-storage plants used for peak power provision).[10] Electricity consumption in China has been dominated by the industrial sector, which consumed nearly 77 percent of power in 1990. The importance of the industrial sector has waned somewhat—to about 70 percent of total consumption in 2014, as residential and commercial/services electricity use has grown—but still remains the major user of electricity in the Chinese economy.

The rapid overall growth in electricity consumption in the last decade, however, masks much slower growth in recent years—just over 3 percent annually between 2013 and 2016, as shown in the last four bars of Figure 1-2—as the Chinese economy has slowed somewhat, and greater emphases have been placed on improvements in energy efficiency, development of the services sector, and the reduction of heavy industry.

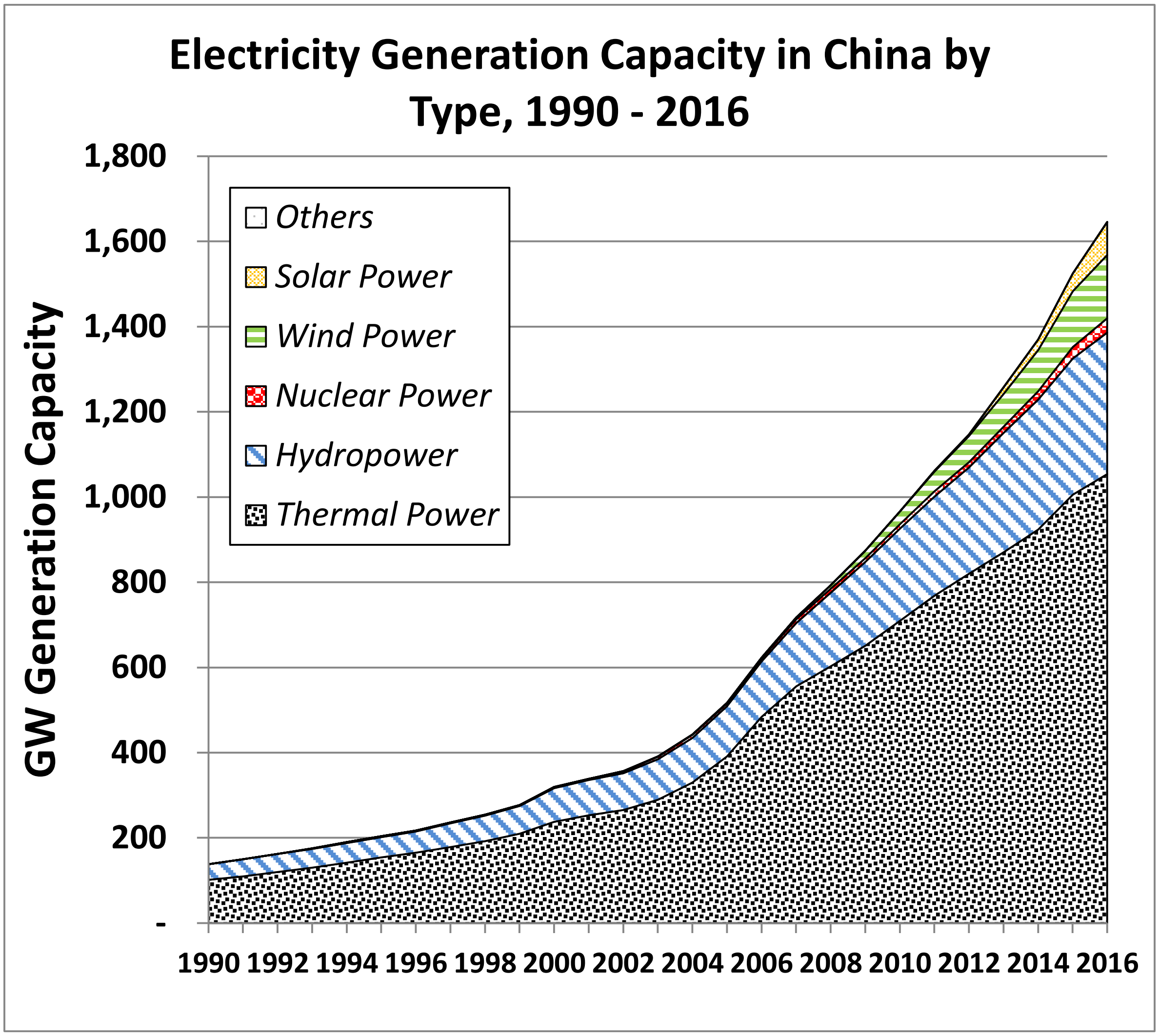
[10] International Hydropower Association (2017), "China", last updated May, 2017, and available as https://www.hydropower.org/country-profiles/china. This reference highlights the construction of the "Wudongde project on the Jinsha River in the south- west, which will provide 10.2 GW installed capacity when complete" in 2020, and will be the sixth-largest hydro plant in the world.

Figure 1-1: Electricity Generation in China by Type, 1990 through 2016[11]



[11] Sources: Figures through 2014 from *China Statistical Yearbook, 2016*, available as http://www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm, with 2015 and 2016 data from John A. Mathews and Hao Tan (2017) "China's Continuing Green Shift in the Electric Power Sector: Evidence from 2016 data", *The Asia-Pacific Journal | Japan Focus*, Volume 15, Issue 10, Number 4, May 15, 2017, available as http://apjjf.org/-John-A--Mathews--Hao-Tan/5038/article.pdf.

Figure 1-2: Electricity Generation Capacity in China by Type, 1900 through 2016[12]



Although electricity in the 1990s and 2000s was transmitted and distributed through mostly six regional grid "clusters", recent years have seen massive investments in transmission lines designed to tie the national grid together. In addition to several point-to-point UHV DC (Ultra-high voltage Direct Current) lines, China has invested and is investing tens of billions of dollars in UHV AC (alternating current) lines.[13] Together, these UHV DC and UHV AC lines are designed to move electricity from coal-fired, hydroelectric, and wind power plants in China's North and West to the major consuming cities in central and eastern China. An additional goal of these transmission projects is to reduce coal-fired power generation, with its attendant air

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[12] Sources of data are as indicated for Figure 1-1.

[13] UHV DC lines are 800 kV (kilovolts) or more, and UHV AC lines are 1000 kV or more. By way of comparison, large high-voltage transmission lines in most countries are rated at about 500 kV. The higher the voltage, the more power can be carried by a given line. See, for example, *China Daily* (2014), "China Exclusive: China to build 12 power transmission lines", dated 2014-05-14, and available as http://shanxi.chinadaily.com.cn/2014-05/14/content_17505983.htm.

pollution problems, in the vicinity of big coastal cities. China is reportedly investing hundreds of billions of dollars in total in electricity transmission and distribution between 2015 and 2020, doubling the 2014 length of the lines in China's transmission system to over one million kilometers.[14] Nearly half of global additions to high-voltage transmission networks during 2014 through 2020 are expected to be in China.

Massive investments in manufacturing of electricity sector equipment in China have accompanied investments in transmission and distribution infrastructure, and have made China a world leader in the production of many types of power plants. China's largest wind turbine manufacturer, Goldwing, was third among global wind power firms in 2016, with an output of 6.4 GW (almost all installed in China), after leading the world the previous year.[15] China's solar photovoltaic (PV) firms produced 71 percent of the world's PV modules in 2016—and most of their modules were installed in China, as well as exporting panels to the rest of the world.[16] Almost by definition, China leads the world in production of coal-fired power plants, installed both in China and, increasingly, in other nations.[17] And China has slowly transitioned its nuclear industry from plants built with mostly foreign technology to plants designed and built in-country (see below).

The emphasis on manufacturing of renewable energy equipment has accompanied aggressive national goals for renewable energy deployment. Progress toward, and even past, these goals has been impressive. Deployment of solar photovoltaic power has been so rapid—topping 10 GW in a single recent month—that China's goal for solar deployment by 2020 under its 13th Five-Year Plan (FYP) has been nearly doubled, from 105 GW (already achieved) to 230 GW.[18] Progress toward wind power deployment goals has been nearly as impressive, with 129 GW of wind power capacity deployed by 2015, already over half of the 2020 target of 210 GW set in China's

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[14] See, for example, Reuters (2015), "UPDATE 1-China targets $300 bln power grid spend over 2015-20 – report", dated August 31, 201, and available as http://www.reuters.com/article/china-power-transmission-idUSL4N1171UP20150901, and Cision PR Newswire (2015), "Global Transmission and Distribution Market 2015 Report Says China Leading Power Transmission Line Additions to 2020", dated June 11, 2015, and available as http://www.prnewswire.com/news-releases/global-transmission-and-distribution-market-2015-report-says-china-leading-power-transmission-line-additions-to-2020-506906491.html. By way of comparison, the United States transmission grid includes about 700 thousand kilometers of high voltage lines (US Department of Energy (2014), "Top 9 Things You Didn't Know About America's Power Grid", dated November 20, 2014, and available as https://energy.gov/articles/top-9-things-you-didnt-know-about-americas-power-grid).

[15] See, for example, Bloomberg New Energy Finance (2017), "Vestas reclaims top spot in annual ranking of wind turbine makers", dated February 22, 2017, and available as https://about.bnef.com/blog/vestas-reclaims-top-spot-annual-ranking-wind-turbine-makers/.

[16] Jeffrey Ball, Dan Reicher, Xiaojing Sun, and Caitlin Pollock (2017), *The New Solar System: China's Evolving Solar Industry And Its Implications for Competitive Solar Power In the United States and the World*, Stanford University Steyer-Taylor Center for Energy Policy and Finance, dated March, 2017, and available as https://www-cdn.law.stanford.edu/wp-content/uploads/2017/03/2017-03-20-Stanford-China-Report.pdf.

[17] See, for example, Hiroko Tabuchi (2017), "As Beijing Joins Climate Fight, Chinese Companies Build Coal Plants", *New York Times*, July 1, 2017, available as https://www.nytimes.com/2017/07/01/climate/china-energy-companies-coal-plants-climate-change.html?mcubz=0&_r=0.

[18] See, for example, Joshua S Hill (2017), "China Continues Massive Solar Installations With 10.52 GW In July, Already Exceeds 2020 Target", Cleantechnica, dated August 22nd, 2017, and available as https://cleantechnica.com/2017/08/22/china-continues-massive-solar-installations-10-52-gw-july-already-exceeds-2020-target/; and Mark Osborne (2017), "China's solar boom to continue through 2020 as install targets revised", PVTech, dated July 28, 2017, and available as https://www.pv-tech.org/news/chinas-solar-boom-to-continue-through-2020-as-install-targets-revised.

13th FYP for energy. For some wind-rich provinces, wind and solar power already provided up to 15 percent of total generation by 2020.

China's renewable energy industries have not been without growing pains. Many wind generators, particularly in northern and western provinces, were built in anticipation of local electricity demand and/or construction of transmission facilities that have yet to catch up with wind power capacity, and as a result, wind energy output worth billions of dollars has been curtailed, far more than in other wind-rich areas of the world (such as Texas). The transmission line projects described above are expected to significantly lower curtailment rates in coming years, allowing wind energy from the North and West of China to displace coal-fired power for the cities of the East and South.[19]

Accompanying this drive to use more renewable energy has been a drive toward energy efficiency in multiple sectors. China's National 13th FYP includes a reduction of 15 percent in energy use per unit of GDP relative to the level in 2015, and a reduction of 18 percent in carbon dioxide emissions per unit of GDP.[20] It should be noted that energy (and CO_2) per unit of GDP are indicators dependent on several factors, most notably, the composition of industry in China, the types of products produced, and the value of those products, as well as the actual energy efficiency per unit of physical output. CO_2 per unit of GDP additionally factors in the composition of the energy sources used by an economy. As a result, a reduction in energy use (and CO_2 emissions) per unit of GDP can be accomplished by a combination of true energy efficiency improvements, greater value added in products produced, offshoring of heavy (energy intensive/polluting) industries, and a shift toward production of more services, all of which are currently in play in China.

China's 13th Five-year Plan lays out a number of goals for electricity sector development by 2020 (see Table 1-1). These include overall electricity consumption (given as a range), development of various types of generation, and other parameters. Along with the aggressive targets for renewable power development described above, the 13th FYP shows growth in electricity generation/consumption, as well as generation capacity, slowing markedly relative to experience over the past decade.

Although longer-term official forecasts of electricity demand were not available for this paper, the trend of declining growth in Chinese electricity generation and consumption is echoed and extended in a number of forecasts by other analysts. For example, in the US Department of Energy's (US DOE's) *International Energy Outlook 2016*, the growth rate of electricity use in China progressively decreases from about 3.6 percent annually in 2015-2020 to 1.4 percent/yr in 2035 through 2040 (see Figure 1-3). As China's population growth will, based on the United Nations' "Medium Variant" estimate, have reached its peak just before 2030,[21] continued growth in electricity consumption late in the US DOE forecast means continued growth in electricity use per person. Overall, the USDOE forecast calls for average annual growth in electricity use of just under 2.5 percent from 2012 through 2040, resulting in a doubling of 2012 electricity use in China by 2040.

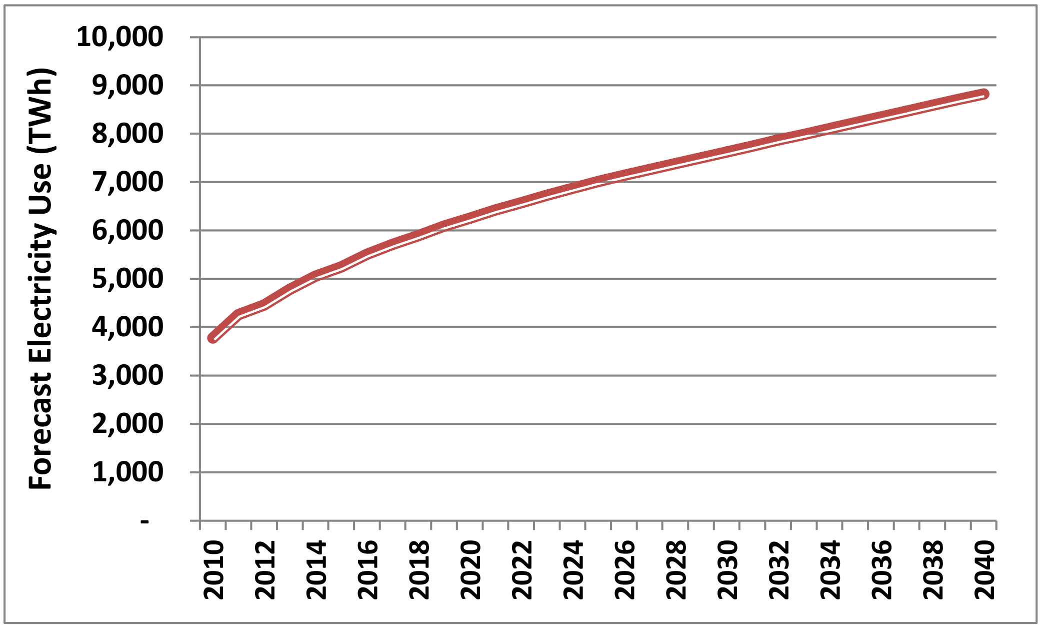
[19] See, for example, Li Ying (2016), "Blowing in the wind", Chinadialogue, dated May, 31, 2016, and available as https://www.chinadialogue.net/article/show/single/en/8965-Blowing-in-the-wind.
[20] Ma Tianjie (2017), "China's Ambitious New Clean Energy Targets", *The Diplomat*, dated January 14, 2017, and available as http://thediplomat.com/2017/01/chinas-ambitious-new-clean-energy-targets/.
[21] Data downloaded from United Nations DESA, "World Population Prospects 2017", available from https://esa.un.org/unpd/wpp/Download/Standard/Population/.

Table 1-1: Thirteenth Five-Year Plan Main Objectives of Power Industry Development[22]

Category	2015 Value	2020 Target	Annual average Growth Rate [or change]
Installed Capacity (100 million kilowatts)	15.3	20	5.50%
West to East [Transmission Capacity] (100 million kilowatts)	1.4	2.7	14.04%
Total electricity consumption (trillion kilowatt hours)	5.69	6.8 - 7.2	3.6 - 4.8%
Electricity accounted for the proportion of terminal energy consumption	25.80%	27%	[1.2%]
Per capita installed capacity (kW / person)	1.11	1.4	4.75%
Per capita electricity consumption (kWh / person)	4142	4860 - 5140	3.2 - 4.4%
Non-fossil energy consumption share	12.00%	15%	[3%]
Non - fossil generation share of installed capacity	35.00%	39%	[4%]
Conventional hydropower (100 million kilowatts)	2.97	3.4	2.80%
Pumped Storage hydro (10 thousand kilowatts)	2303	4000	11.70%
Nuclear power (100 million kilowatts)	0.27	0.58	16.50%
Wind power (100 million kilowatts)	1.31	2.1	9.90%
Solar power (100 million kilowatts)	0.42	1.1	21.20%
Fossil energy power generation installed proportion	65%	61%	[-4%]
Proportion of installed capacity as coal-fired power	59%	55%	[-4%]
Coal-fired generation capacity (hundred million kilowatts)	9	<11	4.10%
Gas-fired generation capacity (hundred million kilowatts)	0.66	1.1	10.80%
Average coal consumption of new coal-fired units (grams of standard coal / kWh)		300	
Average coal consumption of active coal-fired units (grams of standard coal / kWh)	318	310	[-8]
Transmission Line Loss Rate	6.64%	<6.5%	
Charging Facilities Construction	Meet requirements for charging 5 million electric cars		
Electricity from Alternative Sources (100 million kWh) [Presumably for Transport]		4500	

[22] Rough translation of "Box 2" from [China] National Development and Reform Commission, National Energy Board, *The Thirteenth Five-Year Plan for Electricity Development (2016-2020),* available as http://www.ndrc.gov.cn/zcfb/zcfbghwb/201612/P020161222570036010274.pdf.

Figure 1-3: Forecast for Electricity Use in China, 2010-2040 (US Department of Energy International Energy Outlook)[23]



The current setting for China's nuclear power sector is thus characterized by rapid (by the standards of most countries) but slowing economic growth, increasing energy efficiency, and substantial progress on many development goals. In combination, these factors are resulting in demand for electric power that will continue to grow, but at progressively lower rates as the decades pass. At the same time, an aggressive drive to use electricity from renewable sources and reduce electricity generation (and its attendant environmental emissions) from coal creates a significant drive toward nuclear power as carbon- and air pollutant-emissions-free electricity source, but also significant competition for nuclear power among low-emissions electricity options.

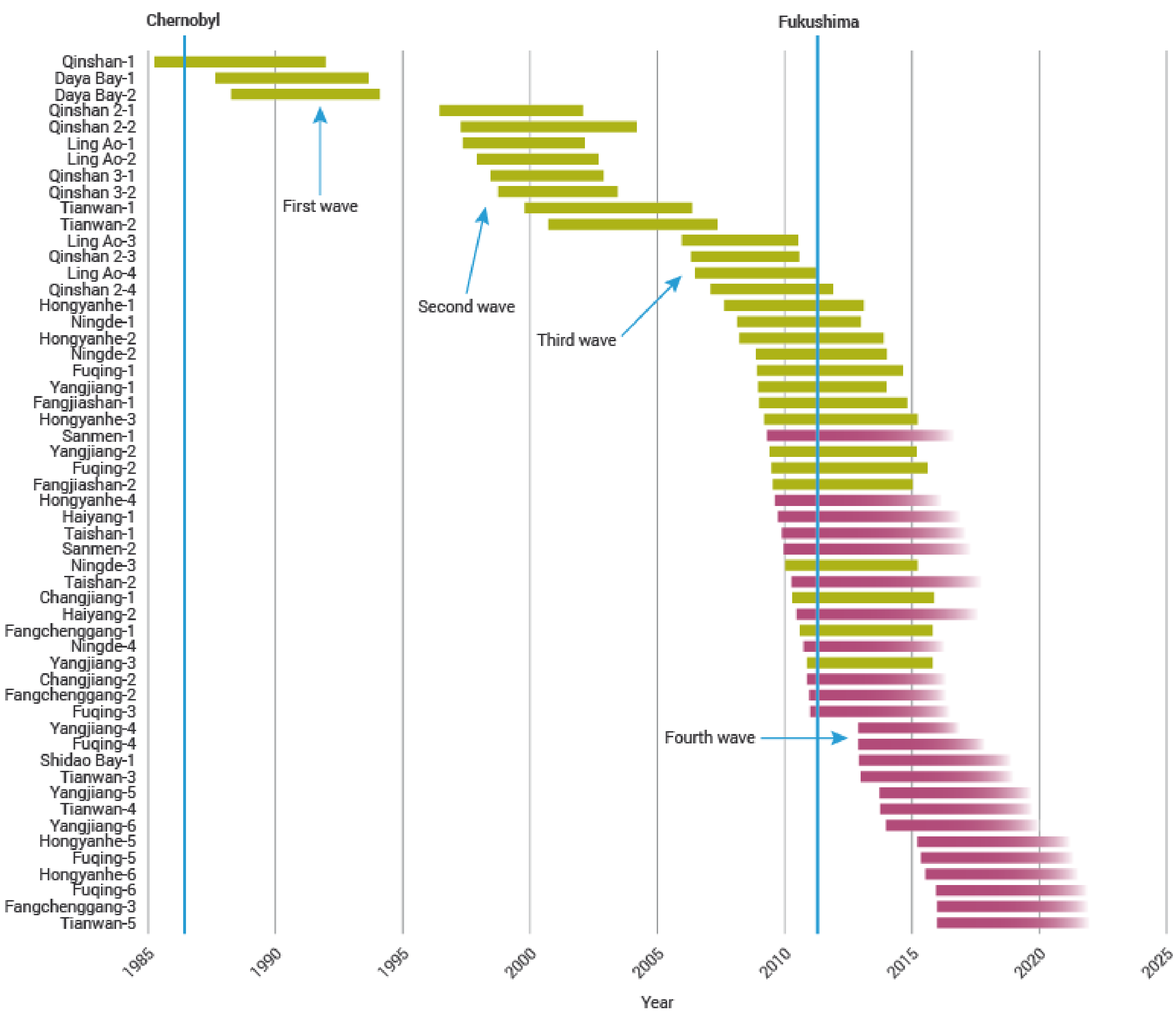
1.3 China's Current and Planned Nuclear Sector: 1990s through 2040

Though the decision to develop civilian nuclear energy in China dates back to the 1970s, concrete efforts to construct nuclear power plants began only in the late 1980s. China's civilian nuclear power development began with the construction of the French-built reactors at Daya Bay, near Guangzhou, and providing power to Hong Kong and other cities in the region. This pair of 944 MWe reactors were constructed starting in 1987, and began operation in 1994. At about the same time, the smaller (298 MWe) Qinshan-1 unit was built with a combination of imported and domestic technology. These three reactors constituted the "first wave" of reactor

[23] Figure prepared using data from US Department of Energy's Energy Information Administration (2016), detailed tables for *International Energy Outlook 2016*, "Table: Delivered energy consumption by end-use sector and fuel; Case: Reference case | Region: China", available from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=15-IEO2016&region=4-12&cases=Reference&start=2010&end=2040&f=A&linechart=Reference-d021916a.2-15-IEO2016.4-12&map=&sourcekey=0.

construction in China, as described by the World Nuclear Association (see Figure 1-4).[24] A second wave of reactor construction began in the late 1990s, and included four additional reactors at Qinshan, near Shanghai, this time in the 600 MWe class, and produced as stepping stones to development of a "Chinese standard" 1000 MWe-class unit, the CNP-1000. Two additional units at the Ling Ao power plant, very close to the original Daya Bay reactors. Like the Daya Bay plant, the Ling Ao reactors are based on French technology. A pair of reactors in northern Jiangsu province, between Shanghai and Beijing, the first set of Tianwan units, were built using Russian reactor technology but with control equipment supplied by an international consortium. These first two Tianwan units were completed as the third wave of reactor construction began.

Figure 1-4: Nuclear Reactor Construction in China to Date



[24] Figure and related data from World Nuclear Association (2017a), "Nuclear Power in China", updated September 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.

The third wave of Chinese reactor construction is considered to have begun in about 2006, with ground broken on the last few of the 30 third wave reactors just before the Fukushima accident in Japan in March of 2011. The Chinese nuclear establishment's response to the Fukushima accident was to order a delay in new reactor starts while reactor safety provisions were reviewed and strengthened, and reactor deployment plans were reviewed. Subsequent to these reviews, a fourth wave of reactor construction is considered to have begun in 2012 and 2013, and has included at least 16 reactor units to date.

1.3.1 Current Fleet of Chinese Reactors

The current fleet of operating Chinese reactors, resulting from the first three waves of reactor construction described above (the fourth wave and some of the third wave plants being not yet operational) consists of 37 units totaling 33.7 GW of electricity generating capacity. Two of these units, Qinshan Phase III, units 1 and 2, are based on the CANDU heavy water/natural uranium technology (PHWRs); all the rest of the current fleet are light water reactors using low-enriched uranium fuel.[25] As shown in Figure 1-5, all existing and under-construction reactors in China are in coastal locations, and all but three nuclear plants listed as "planned" are also in coastal locations. Plants planned for inland locations, which must use river water for cooling, have been a focus of regulatory review for Chinese authorities, particularly post-Fukushima, with the reliable availability of sufficient cooling water, particularly in a changing climate regime, being a significant concern, as well as the possible pollution of rivers in the event of an accident. China's regulatory review of inland sites may have contributed to a general impression among the Chinese public that the consequences of a nuclear accident at a reactor located at an inland site will result in radioactive contamination of the river used for cooling that would be much worse than contamination of a coastal site. This impression, to the extent that it persists, may make it more difficult for reactors to be built in non-coastal areas.

[25] Light water reactors, or LWRs, use regular water (H_2O) as the reactor coolant. The two primary light water reactor designs are pressurized water reactors (PWRs), which are dominant in China, and boiling water reactors (BWRs), which are also common worldwide (and of which the units at the damaged Fukushima Daiichi plant are examples). China is also building a 210 MWe high-temperature gas-cooled reactor (Model "HTR-PM") in Shandong province. The HTR-PM uses fuel spheres ("pebbles") rather than fuel encased in long metal tubes (fuel rods) like the other reactor types.

***Figure 1-5: Location of Nuclear Power Plants Existing, Under Construction, and Planned in China*[26]**

The World Nuclear Association characterizes China's nuclear policy as:

"China has set the following points as key elements of its nuclear energy policy:

- PWRs will be the mainstream but not sole reactor type.
- Nuclear fuel assemblies are fabricated and supplied indigenously.
- Domestic manufacturing of plant and equipment will be maximised, with self-reliance in design and project management.
- International cooperation is nevertheless encouraged."

The World Nuclear Association also notes that "[t]he technology base for future reactors remains officially undefined, though two designs are currently predominant in construction plans: CAP1000 and Hualong One, after plans for more CPR-1000 units were scaled back post-Fukushima. Beyond them, high-temperature gas-cooled reactors and fast reactors appear to be the main priorities." For the present, China's use of many different kinds of reactors, ordered

[26] World Nuclear Association (2017a), ibid.

and funded by different provinces, and only loosely coordinated with power grid development, may prove to be problematic soon, and may complicate nationally coordinated management of spent fuel.[27]

The combination of current electricity generation over-capacity, particularly in east coast areas where many reactors are located, plus the variety of reactors under construction, the poor record of many imported reactor technologies, and China's ambitions to export reactors itself, combine to yield picture of China's nuclear future that is significantly muddled relative to stated policy. The text box below, co-authored by Professor Stephen Thomas of the University of Greenwich, United Kingdom, briefly explores these issues.[28]

Box 1: China's Nuclear Export Ambitions: Prospects and Challenges[29]

China's lack of focus on one or a very few reactor designs has resulted in a technologically challenging situation as a major reactor build-out continues. China's original plan as of 2007 was to use the 1970s/1980s French reactor design for a few years, but import and indigenize state-of-the-art foreign technologies, with the goal of making reactors affordable for domestic use and for export to countries new to nuclear power, as well as to established nuclear energy users. The indigenizing of foreign technologies was to have been done through the adaptation of the Westinghouse AP1000 and to a lesser extent the French (Areva) EPR designs. Both technologies have failed badly, so China's two major reactor vendors, CGN and CNNC, have returned to the old French technology used for, for example, the units at Daya Bay, updating it and adding new features to develop the ACP-1000 and ACPR-1000 designs, which are being "merged" to yield the Hualong One. Whether this design will be safe enough to convince foreign regulators (it is being tested in the United Kingdom, which has been considering importing Chinese reactors), and still be inexpensive enough to attract buyers, remains to be seen. Another, somewhat weaker Chinese nuclear utility, SNPTC, which was set up to indigenize the AP1000 design, is scaling it up to the 1400 MWe CAP1400 design to try to make the economics more attractive, but whether doing so will be successful or not is unclear.

Despite a substantial interest in exporting reactors, and substantial effort to do so, China has been unable to reach firm agreements except for its deal with Pakistan and an agreement, but not yet a

[27] In addition, China's nuclear energy sector involves dozens of different firms and entities. Some of these are national in scope, some regional or provincial, and some organized specifically to implement a particular nuclear project. Ownership of nuclear entities is similarly complex, with national and provincial utilities being mostly state-owned, but with a variety of joint ventures and subsidiaries involving publically traded companies, private entities, and others. See World Nuclear Association (2017b), "Government Structure and Ownership: Nuclear Power in China Appendix 1", updated September 2017, available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/appendices/nuclear-power-in-china-appendix-1-government-struc.aspx.

[28] For additional detail, see Steve Thomas (2017), "China's nuclear export drive: Trojan Horse or Marshall Plan?", *Energy Policy*, volume 101 (2017), pages 683–691.

[29] See also Matthew Cottee (2017), "China's nuclear export ambitions run into friction", *Financial Times*, dated August 2, 2017, and available as https://www.ft.com/content/84c25750-75da-11e7-90c0-90a9d1bc9691. Interestingly this article includes the following passage about Russia's allegedly waning interest in nuclear exports: "The current leader in the nuclear export market, Russia's Rosatom, is reportedly shifting focus to hydropower and wind turbines rather than its usual reactor business. Speaking at the 'Technoprom-2017' conference in Novosibirsk, the deputy general director of Rosatom, Vyacheslav Pershukov, suggested that the export market for nuclear reactors has been exhausted."

contract, to construct (or rather, to resume construction on) two CANDU units in Romania.[30] Both of these export ventures are receiving or thought to be receiving significant Chinese financing for the purchases. A number of other deals are reportedly under discussion. The lack of additional firm contracts may be because China has only entered the field of nuclear vendors during this decade, because there is reluctance to buy from China (for reasons not completely understood) or because there is simply little actual market for reactors outside of China. The contrast between Russia, which lacks the wherewithal to provide financing and significant portions of the required the supply chain to support reactor exports, but has about 30 firm orders, and China which does have the money and supply chain but has no orders, is marked.

The size of China makes analysis of its economic and technological situations hard to carry out, because its industries can dominate international markets without being dominant at home. Nuclear represents a negligible part of China's electricity mix, yet reactors built in China account for the majority of the world's nuclear construction over the last decade. As a result, one might say that that global nuclear industry needs China, but China doesn't necessarily need nuclear power. As such, the opposition by some citizen groups to building nuclear power at inland sites is very important, because it limits reactor development to the coastal areas, and in some coastal regions there is already significant generation overcapacity. Overcapacity in some parts of the coast has meant that reactors are being used for load-following—which A) they are not built for, and B) has a negative impact on their capacity factors and thus on their profitability—and new plants have even been delayed in entering service because there is insufficient electricity demand, further affecting the economics of nuclear investments.[31]

Given the challenges above, it is unclear to the authors how long the China government will put its weight behind its nuclear export industry, when the nation as a whole could win much more business and gain more political influence by putting its weight behind other technologies such as high-speed rail, in which it has had remarkable domestic success, and renewable energy, in which it has substantial and sometimes dominant market shares both at home and abroad.

1.3.2 Nuclear Fuel Cycle Facilities

China obtains portions, in some cases most, of its uranium, fuel conversion, enrichment, and fuel fabrication needs (the "front end" of the fuel cycle) from domestic resources and facilities. As a nuclear weapons state, some of these facilities were originally developed in support of China's nuclear weapons program. The World Nuclear Association describes China's policy on uranium acquisition for its nuclear power program as targeting "about one-third of uranium supply domestically, one-third from Chinese equity in foreign mines, and one-third on the open

[30] See, for example, World Nuclear Association (2017c), "Nuclear Power in Romania", last updated October, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-o-s/romania.aspx; and Stephen Stapczynski and Aibing Guo (2015), "China Widens Nuclear Exports With $7.7 Billion Romania Plant", *Bloomberg*, dated November 9, 2017, and available as https://www.bloomberg.com/news/articles/2015-11-10/china-keeps-nuclear-exports-going-with-7-7-billion-romania-deal.

[31] See C.F. Yu (2016), "CHINA: Beijing Drafts Rule to Put Reactors In Load-Following Mode", *Nuclear Intelligence Weekly*, Volume 10, No. 33, August 19, 2016, available from http://www.energyintel.com/pages/about_uiw.aspx.

market".[32] China has seven operating uranium mines, two of which date from the 1960s and 70s, as well as uranium resources in many other locations. China has purchased a significant amount of uranium from a number of supplier nations, and two Chinese firms hold equity in uranium mines in central Asia, Africa, and Canada.

Enrichment of uranium is the process of concentrating the fraction of the U-235 isotope found in natural uranium (about 0.7 percent) to the fraction needed in LWR fuel, typically 3 to 5 percent. A preliminary step to enrichment is conversion of natural uranium oxide, a solid, to gaseous uranium hexafluoride (UF_6). The World Nuclear Association lists China's conversion capacity as somewhat uncertain, with a report of a 5000 t/yr plant in Gansu province operating at 80 percent of capacity, with another 9000 t/yr plant due to come on line this year or next. A smaller plant (500 tU/yr) plant is reported in northwest Gansu province. Another plant with a capacity of 3000 t/yr is reportedly being built by China Nuclear Fuel Corp in Hunan province, and will be on line in 2018.

Enrichment of uranium in China takes place at larger plants in Shanxi and Gansu provinces, and at two smaller plants in Sichuan province. The total capacity of these plants is estimated at 5.7 to 7.0 million SWU (separative work units, a measure of enrichment capacity) per year in 2015, and a projected range of 10.7 to 12.0 million SWU/yr in 2020. By way of comparison, annual enrichment demand for Chinese reactors was expected to total 9 million SWU in 2020. Enriched uranium has also been imported to China, particularly for reactors of foreign design, with enrichment services provided in Europe and Russia. Centrifuges used for enrichment were provided by Russia in the past, but indigenous centrifuges technology has been used for recent capacity expansions, starting in 2010.[33]

The fabrication of fuel for Chinese reactors is done mostly in China, with some reactors supplied by France and Russia under contract to receive fuel from those nations sufficient for the first reactor core loading and a number of subsequent loadings. A plant in Yibin, Sichuan province, with a total capacity of 900 tU/yr, makes fuel for PWRs and for the Russian VVER design. A second major plant in Inner Mongolia, at Baotou, fabricates fuel for China's pair of CANDU reactors as well as for various PWR models,[34] and will reportedly have total annual capacity of 1600 tU/yr by 2020. A facility at the Baotou plant is also making fuel for the high-temperature gas reactor being completed in Shandong province. Fuel pellets for the fuel assemblies for some reactor models are also sourced from Kazakhstan's Ulba Metallurgical Plant.

Most spent PWR fuel in China is currently stored in pools on reactor sites. Generally, the on-site spent fuel storage capacity at operational nuclear power plants can accommodate 10 years of spent fuel. Taking into account ongoing trends in nuclear fuel management, such as increasingly high rates of fuel burnup (which reduce the number of refueling cycles necessary), extensions of reload cycles, and the use of dense-pack storage in spent fuel pools into consideration, it is estimated that the storage capacity of present facilities can be enlarged to hold approximately 20

[32] World Nuclear Association (2017b), "China's Nuclear Fuel Cycle", updated July 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx.

[33] Hui Zhang (2015), *China's Uranium Enrichment Capacity: Rapid Expansion to Meet Commercial Needs*, Project on Managing the Atom, Discussion Paper No. 2015-03, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated August, 2015, and available as http://www.belfercenter.org/sites/default/files/legacy/files/chinasuraniumenrichmentcapacity.pdf.

[34] Including the AP1000 and its Chinese variant the CAP1000, based on Westinghouse designs and intended to be the "main basis of China's move to Generation III technology" (see World Nuclear Association 2017a, ibid).

years' worth of spent fuel. Currently, all PWR spent fuel is in fact stored at reactor sites except for some of the spent fuel removed from the Daya Bay reactors, the first units in commercial operation in China. Since 2003, shipments of spent fuel from Daya Bay have been transported approximately twice annually to the centralized interim storage facility in Gansu province, where it is placed in wet storage facilities (away-from-reactor spent fuel pools).[35]

The facility in Gansu province, the Jiuquan Atomic Energy Complex (JAEC) as noted above, was initially developed in the 1950s and 60s to support China's nuclear weapons program. Since then, facilities for storage of civilian nuclear spent fuel have been added, as well as a pilot-scale reprocessing plant, constructed starting in 1986 but not operational until 2010, that can handle 60 tons of spent nuclear fuel (expressed as the mass of heavy metal—mostly uranium plus plutonium—abbreviated as tHM) annually.[36]

1.3.3 Plans and Projections for Reactor Deployment

The World Nuclear Association lists a total of 20 reactors in China as "under construction" and 30 to 40 more as "planned", mostly with an expected construction start before 2019. The under construction and planned units total 66.7 GWe.[37] In addition, the same reference lists 100 units, totaling 114.2 GWe, as "proposed", and an additional 79 units, and 90.8 GWe, proposed for the more distant future. Together, these listings plus the reactors already in operation total well over 300 GWe, over three times the size of the United States reactor fleet at its historic maximum in 2012.[38]

One recent article, citing both the World Nuclear Association source referenced above and a Chinese-language study by the Chinese Academy of Engineering lists ranges of nuclear capacities of 83.8 to 200 GWe by 2030, and 250 to 400 GWe by 2050.[39] Other reported projections provide ranges of 340 to 500 GWe by 2050,[40] 1200 TWh of generation by 2040,[41] and on the order of 250-300 GWe, by 2050, the latter in a "two-degree" scenario where fossil

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[35] Liu Xuegang (2014), *Spent Nuclear Fuel Management in China*, Nautilus Institute NAPSNet Special Report, dated 5 August, 2014, and available as https://nautilus.org/napsnet/napsnet-special-reports/spent-nuclear-fuel-management-in-china/.

[36] See, for example, Nuclear Threat Initiative (2011), "Jiuquan Atomic Energy Complex", last updated September 29, 2011 , and available as http://www.nti.org/learn/facilities/722/.

[37] World Nuclear Association (2017a), ibid. For nuclear power plants, capacity is sometimes shown as GWe, or gigawatts of electric power, to differentiate from output expressed in terms of thermal power, which is typically about three times higher.

[38] Nuclear Energy Institute (2017), "US Nuclear Generating Statistics, 1971 – 2016", updated April, 2017, and available as https://www.nei.org/Knowledge-Center/Nuclear-Statistics/US-Nuclear-Power-Plants/US-Nuclear-Generating-Statistics.

[39] Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2016), "Nuclear Power in China: An Analysis of the Current and Near-Future Uranium Flows", *Energy Technology*, 2017, Volume 5, Issue 5, pages 681 – 691, available as http://onlinelibrary.wiley.com/doi/10.1002/ente.201600444/epdf.

[40] Brian Wang (2015), "China will complete five nuclear reactors in 2017 and double nuclear power generation to about 420 TWh by 2021", NextBigFuture, dated March 2, 2017, available as https://www.nextbigfuture.com/2017/03/china-will-complete-five-nuclear.html.

[41] US Department of Energy, Energy Information Administration (2016), "China expected to account for more than half of world growth in nuclear power through 2040", dated September 28, 2016, and available as https://www.eia.gov/todayinenergy/detail.php?id=28132, 1200 TWh at an average annual capacity factor of 80 percent would translate into about 170 GWe of nuclear generation capacity.

fuel use is largely phased out except with the use of carbon capture and storage technologies.[42] These projections for massive growth in nuclear capacity are tempered by reports identifying the significant challenges to the Chinese nuclear sector in the years to come,[43] and focusing on renewable power and efficiency as alternatives to both fossil- and nuclear generation.[44]

1.3.4 Plans for Future Nuclear Fuel Cycle Facilities

The World Nuclear Association has summarized China's known plant for future development of "front-end" (nuclear fuel supply) and "back-end" (spent fuel management) fuel cycle facilities.[45] China looks to expand a number of mining activities, including, interestingly, extraction of uranium from coal ash from a power station in Yunnan province. Even with such expansions, based on at least one analysis,[46] it seems unlikely that China will be able to produce one-third of its uranium needs domestically, thus the significant emphasis by Chinese firms on investments in and joint ventures with companies prospecting for and producing uranium abroad.

Hui Zhang of Harvard University's Project on Managing the Atom, in a 2015 report, suggests, based on interviews with Chinese experts, that Chinese capacity to expand its enrichment capacity in the late 2010s was about 1 million SWU per year.[47] Given existing capacity, ongoing expansion, and the importation of initial cores for several reactors built with imported technology, Zhang estimates that China will easily have sufficient enrichment capacity to meet domestic needs through 2020, and perhaps will be able to sell surplus enrichment services internationally, "consistent with the government's stated policy of 'self-sufficiency' and 'targeting the international markets' in the supply of enrichment services". Information on China's plans for expansion of enrichment capacity beyond 2020 was not immediately available, but it seems likely that continued expansion of domestic facilities, coupled with the availability of capacity internationally, will be sufficient to fuel China's reactors on an ongoing basis.

Data provided by the World Nuclear Association suggests that China will have fuel fabrication facilities for PWRs of about 2400 tU/yr by 2020, sufficient to meet demand by that year. Some fabricated fuel is imported, particularly, as noted above, for the new cores of reactors built with imported technology. Information on plans for expansion of fuel fabrication facilities, as with enrichment, was not immediately available, but it is assumed that the China National Nuclear

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[42] International Energy Agency/Nuclear Energy Agency (2015), *Technology Roadmaps: Nuclear Energy, 2015 Edition*, available as https://www.iea.org/media/freepublications/technologyroadmaps/TechnologyRoadmapNuclearEnergy.pdf.

[43] See, for example, Xu Yi-chong (2016), "China's contested nuclear future: The expansion of China's nuclear power production faces some serious challenges", Asia Pacific Policy Forum, dated 5 February 2016, and available as https://www.policyforum.net/chinas-contested-nuclear-future/. This article cites challenges to nuclear build-out including difficulties in reactor siting, the use of multiple technologies as an impediment to cost reduction and regulation, other challenges in organizing and making effective the regulation of the industry, and competitive realities associated with the slowdown in the growth of electricity demand coupled with the growth of deployment of and ongoing cost reduction in the renewable power industries.

[44] Energy Research Institute, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute (2016), *Reinventing Fire: China, Executive Summary* dated September 2016, and available as https://www.rmi.org/wp-content/uploads/2017/05/OCS_Report_ReinventingFireChina_2016.pdf. Graphics in this document suggest that under a "Reinventing Fire" scenario, China's electricity generation from nuclear power in 2050 would be about 1300-1400 TWh, or the equivalent of about 190 GWe of capacity at an average capacity factor of 80 percent.

[45] World Nuclear Association (2017b), ibid.

[46] Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2016), ibid.

[47] Zhang (2015), ibid.

Corporation (CNNC), as the entity responsible for fuel fabrication in China, will continue to expand capacity to meet domestic demand, and possibly some fuel exports as well.

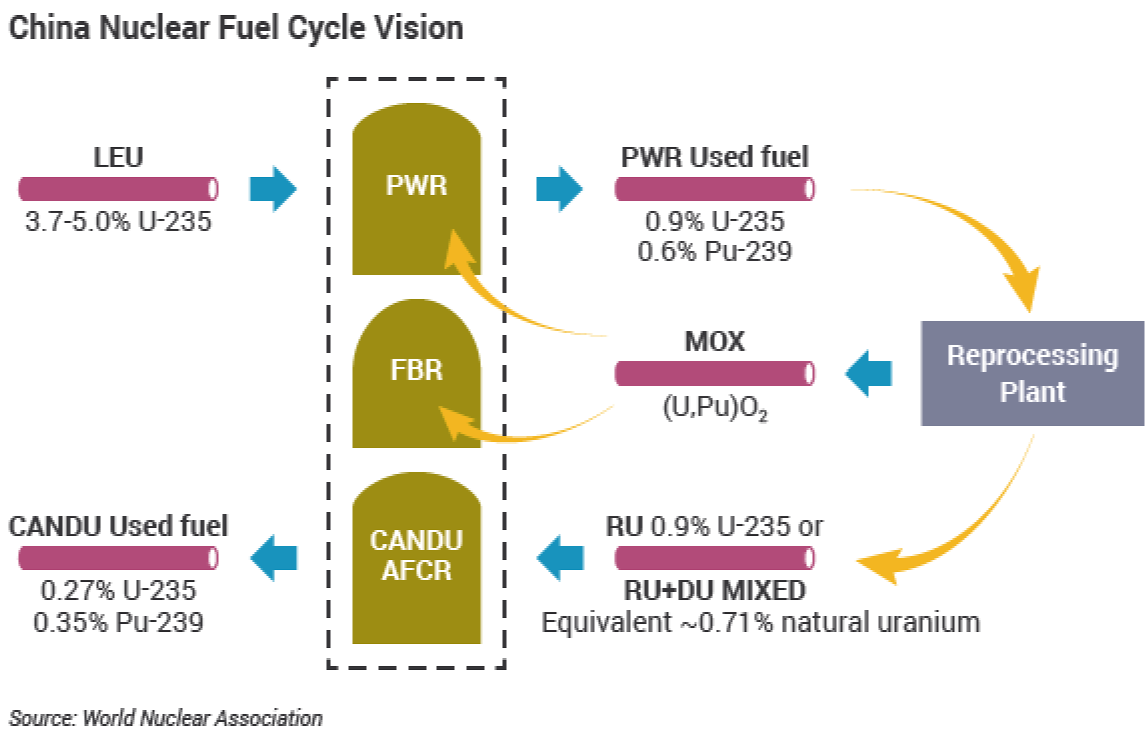
Reports indicate at least two ongoing efforts by China to build new facilities for reprocessing spent PWR fuel to separate plutonium for use in mixed-oxide fuel and, eventually, for use in fast reactors. A "medium scale" facility with a capacity of 200 tHM/yr is to be built at a site in Gansu province about 100 km away from the existing pilot-scale reprocessing plant described above. The medium-scale plant is part of an overall project of CNNC called "Long Teng 2020" (Dragon Soars 2020). The overall project was reported to have an expected cost 100 billion RMB (about USD 16 billion), [48] of which the reprocessing plant is an unspecified fraction, although an independent estimate provides a range of USD 3.2 to 5.7 billion (capital costs only).[49] In addition, CNNC is also negotiating with the multinational nuclear fuel cycle vendor Areva to develop an 800 tHM/yr reprocessing facility at a site on China's east coast. At 800 tHM/yr, this facility would be the size of Japan's Rokkasho reprocessing facility.

Overall, as reported by the World Nuclear Association, China is researching (in a program dating back to 1964) and plans use of "recycled" fuel on three tracks, as summarized in Figure 1-6. First, mixed-oxide fuel (MOX), which blends uranium with plutonium recovered from spent fuel during reprocessing, will be used in existing and new PWRs. Second, MOX will ultimately be used for fuel a new set of Fast Neutron, or Fast Breeder Reactors (FBRs in the Figure below). A small test fast reactor, the Chinese Experimental Fast Reactor, was built near Beijing was with Russian collaboration, and started operation in 2011. A larger test fast reactor (600 MWe) is scheduled to be constructed stating in December 2017, with operation in 2023. Assuming a positive decision for deployment in 2020, China's first commercial fast reactor (the Chinese Commercial Fast Reactor, listed at 1000 to 1200 MWe) will be constructed starting in 2028, with commissioning in 2034. Fast reactor capacity of 40 GWe is "envisaged" by 2050. Third, a blend of plutonium and recycled uranium from reprocessing of PWR fuel, plus and depleted uranium from enrichment, will be used in pressurized heavy water reactors (CANDU units, or PHWRs). A test of the use of blended recycled fuels in unit 1 of the Qinshan Phase III PHWRs was carried out, and deployment of the recycled fuels in both PHWR units was planned for 2018.

[48] Hui Zhang (2015), "China is said to be building a demonstration commercial reprocessing plant", International Panel on Fissile Materials, dated September 23, 2015, and available as http://fissilematerials.org/blog/2015/09/china_is_said_to_be_build.html.

[49] Matthew Bunn, Hui Zhang, and Li Kang (2016), *The Cost of Reprocessing in China*, Project on Managing the Atom Report, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated January, 2016, and available as http://www.belfercenter.org/sites/default/files/legacy/files/The%20Cost%20of%20Reprocessing.pdf.

Figure 1-6: Nuclear Fuel Cycles Planned for China[50]



Apart from reprocessing, with regard to spent fuel management in China, a report on spent fuel storage by Professor Liu Xuegang concluded, in part:[51]

"Dry storage is currently only used for CANDU reactors in China, and will be implemented for HTR spent fuel. These two reactor models account for only a minor portion of the whole Chinese nuclear fleet. But the utilization of dry storage and its performance will have a great impact on future decision-making for the sector. Though some experts consider that the pool capacity at reactors in China is large enough to accommodate spent fuel for the next 5 to 10 years, there are strong voices supporting the building of a large-scale centralized spent fuel storage facility soon. In part, it is argued, the current practice of pool storage for spent fuel in highly dense packed arrays has been subject to criticism following the Fukushima accident. In case dense-racking is ultimately not chosen as a means of spent fuel storage in China, the decrease in potential spent fuel storage density will result in a lack of storage space at Chinese reactors relatively soon. For at-reactor storage, it is difficult to build new pools to store spent fuel due to the complexity of the pool systems. Dry storage is very promising in those cases. For centralized storage away from reactors, dry storage is still a strong competitor to pool-type storage due to advantages such as low investment, modular design, and easy maintenance. As a result, though dry storage has not been adopted for PWR spent fuel storage in China, the utilization of dry storage facilities is a strong possibility in the short or medium-term."

In essence, it is clear that China is still keeping multiple options open, from once-through fuel cycles with medium-term spent fuel storage in dry casks to fast reactor options with reprocessing

[50] World Nuclear Association (2017b), ibid.
[51] Liu Xuegang (2014), ibid.

of spent PWR fuel, and authorities have not yet converged on a single path for the nuclear sector. But as spent fuel builds up at existing reactors, reaching decisions regarding the future management of nuclear spent fuel will become more imperative.

2 Summary of Business-As-Usual/Baseline/Reference Electricity Sector Scenario for China

2.1 Introduction

The current status of and recent trends in China's electricity sector, as described above, forms the basis from which the sector, and the nuclear energy components thereof, will evolve in the future. Although many types of "disruptive" events can occur to suddenly change how the electricity system may evolve—an accident at (as in Fukushima) or attack on a nuclear facility being a prime, but hardly exclusive, example—in general projections of electricity futures assume continuations of existing trends, informed by expected changes in demographics, economic development, regional, national, and international policies, and other "drivers". To systematically compare policy-driven scenarios for electricity sector development, it is important to start with a "reference" case for development of the sector (and the economy in which it is embedded) to provide a consistent basis for comparison of both qualitative and quantitative attributes between scenarios. Such a reference, or "business as usual" (BAU) case is described briefly below, prepared as a composite of several studies of China's electricity future. This BAU case serves as the basis for exploration of the alternative scenarios presented in Section 3 of this paper.

2.2 Description of Composite BAU Scenario

The BAU (or reference) scenario presented here represents a composite of a number of literature sources, including work by the US DOE EIA, British Petroleum, Lawrence Berkeley National Laboratory, and others as described in Section 3. The focus is on the future of electricity generation in China, and in particular, nuclear energy's role in same, but more general economy-wide metrics are provided as points of reference and comparison with other studies.

Some of the key general parameters of the BAU Scenario for China are as follows:

- Reflecting the maturing Chinese economy, gross domestic product (GDP) growth slows over time, averaging 5.8 percent annually from 2015 through 2020 and 5.4%/yr from 2020 through 2030, but slowing to 3.5%/yr from 2030 through 2050, and 2.5%/yr from 2040 through 2050.[52]
- As projected by the United Nations, China's population growth slows through 2030, when it peaks at about 1.45 billion, declining thereafter to about 1.37 billion by 2050.[53]

[52] Projections shown here are consistent with those included in the US DOE Energy Information Administration (USDOE EIA, 2017) *International Energy Outlook, 2017*, as included in the downloaded table "World gross domestic product (GDP) by region expressed in market exchange rates", available from https://www.eia.gov/outlooks/aeo/data/browser/#/?id=4-IEO2016&cases=Reference&sourcekey=0. Note that GDP growth values are not used as direct drivers of electricity consumption in the BAU scenario presented here, but are provided for reference.

[53] United Nations Department of Economic and Social Affairs, Population Division (2017), *World Population Prospects: The 2017 Revision*, dated June, 2017. Data shown are based on data for China in table "Medium fertility variant, 2015 – 2100". Downloaded File WPP2017_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.xlsx.

- Growth in electricity generation also slows, continuing recent trends. Generation (and thus consumption, which is equal to generation less transmission and distribution losses) growth falls from 6.8 percent annually in the first half of the 2010s to 3.5%/yr from 2015 through 2020, then to 1.75%/yr from 2020 through 2030, 1.3%/yr from 2030 through 2040, and 0.8 percent annually thereafter through 2050.[54] This trend is another reflection of a maturing economy and, coupled with continuing (though declining) GDP growth, results in falling energy intensity per unit of GDP. The declining population after 2030, however, means that growth in electricity production (and use) per person grows faster than overall electricity use, increasing, for example, at 1.5%/yr from 2030 through 2040, and 1.2%/yr from 2040 through 2050.

- While total electricity generation nearly doubles, from about 5700 TWh in 2015 to over 10,000 TWh by 2050, shares of electricity generation in China continue to shift over time, as shown in Figure 2-1. The share of electricity output provided by coal-fired power declines from about 70 percent in 2015 to slightly over 40 percent by 2050, with growth in gas-fired, wind, and nuclear generation providing nearly all of the displacement. Hydroelectric generation, as a share of the total, changes relatively little over time, solar grows substantially but to only 4.1 percent of generation by 2050, and the use of liquid petroleum products, never a large fraction of generation in China, continues to decline. Nuclear power's share of generation grows to 13 percent by 2050, but most of the growth in its share of the power market occurs before 2030.

- Changes in generation capacity by type, as shown in Figure 2-2, reflect the same general trends as in electricity generation itself, except that wind and solar power, due to their lower capacity factors (operating fewer hours per year due the intermittent availability of wind and solar resources) relative to coal-fired and nuclear units, account for a larger share of added and total generation capacity. Natural-gas-fired power undergoes a shift from being mostly a peak resource, with low capacity factors (23 percent in 2015 and 2020) to being mostly a baseload resource (capacity factor of over 60 percent in 2050), reflecting a shift from simple-cycle gas turbines to more efficient combined-cycle plants.

- Total Nuclear generation capacity in the BAU case rises to about 140 GW in 2040, and 170 GW in 2050. As such, it assumes a slightly reduced growth trend, particularly after 2040, than the BAU projections for capacity provided in the USDOE's most recent *International Energy Outlook*, which calls for 139 GW of generation in 2040, and 187 GW in 2050.

Additional details on the nuclear fuel cycle elements of the BAU scenario are provided in section 3, below.

[54] These increases in electricity use are generally consistent with the BAU scenario for China included the USDOE EIA *International Energy Outlook, 2017* document, as referenced above.

Figure 2-1:

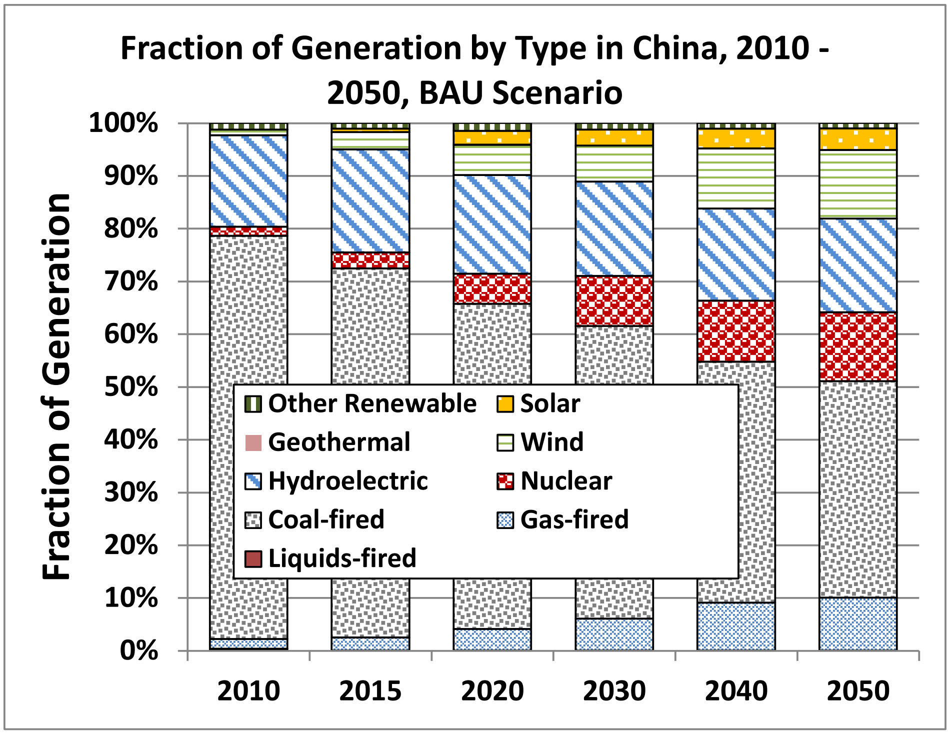
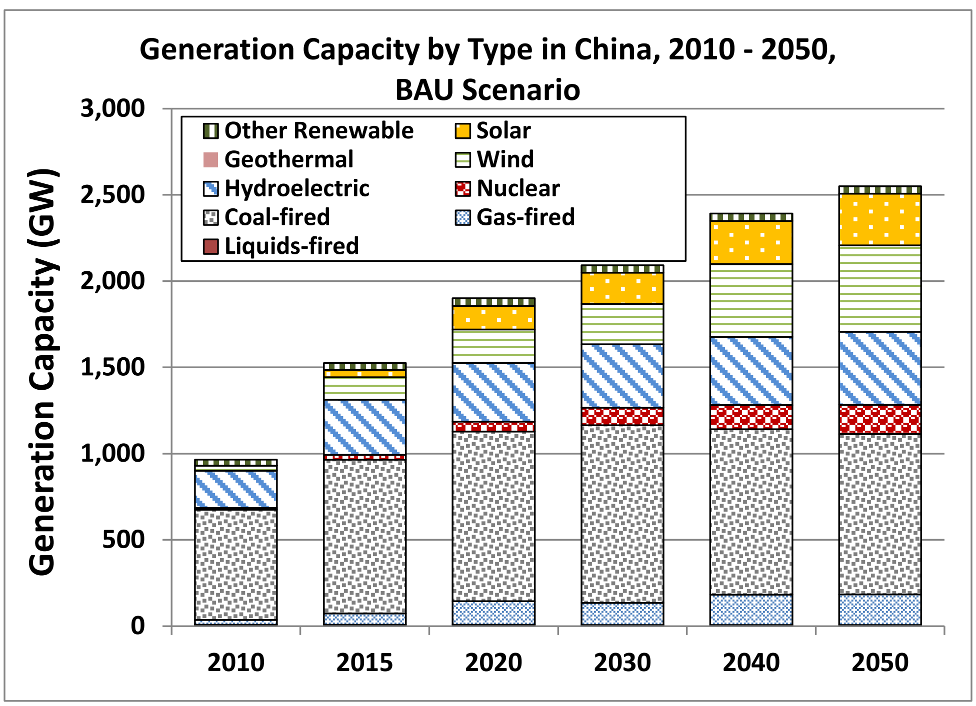


Figure 2-2:



3 Alternative Scenarios for China's Energy and Nuclear Future

3.1 Introduction—Focus of Alternative Scenarios and Key Examples

Alternative scenarios, or alternative projections (which are not necessarily the same thing), can be prepared to demonstrate different potential energy futures for a nation, state, province, city, region, or other jurisdiction. Scenarios and projections are thus tools that analysts, and the policymakers they serve or seek to influence, use to test how policies devised and implemented in the near or more distant future are likely to affect key metrics that are of concern to policymakers and to society as a whole. These metrics will typically include quantitative measures such as total energy or electricity use, total cost, and emissions of local and greenhouse gas pollutants, but may also include qualitative metrics such as the expected impact on energy or military security, environmental or political risk, or social impacts.

As there are literally an infinite number of future scenarios and projections that can be chosen, it is important for analysts to select examples for comparison that are plausible—though looking out more than 30 years into the future is by definition an exercise in speculation—yet are sufficiently different that the comparison of the different cases yield policy-relevant insights. At the same time, the different scenarios/projections should typically be configured to provide the same *energy services*, that is, for example, to support economies of roughly the same size and growth rate, to move the same number of people the same distance (if not always by the same modes), and to heat homes and cool to the same degree, though not always with the same energy sources. For the different China energy futures we describe below—focusing on electricity—we have defined scenarios/projections that support approximately the same economic structure and GDP growth rates, and the same populations, but are quite different in terms of how the energy systems, and especially the electricity and nuclear energy sectors, might evolve.

Given the global importance of the Chinese energy sector, a number of different groups have, over the past several years, prepared their own versions of how energy supply and demand in China might evolve through 2040 or 2050. Some notable examples include:

- The US Department of Energy's Energy Information Administration projections as a part of their *International Energy Outlook* series, the 2016 and 2017 versions of which have been used to help define the BAU case projections for the Chinese electricity sector presented in section 2 of this paper.
- Work by the China Energy Group of Lawrence Berkeley National Laboratory (LBNL), including studies developing and analyzing scenarios for the evolution of China's energy sector through 2050.
- Work by the Rocky Mountain Institute and LBNL under the "Reinventing Fire" project, which looks at scenarios to vastly reduce energy sector greenhouse gas emissions in several countries, including China.
- A study of scenarios of the Chinese power sector by a group from the Renewable and Appropriate Energy Laboratory of the University of California-Berkeley.

- Work by Greenpeace, including on the future of nuclear and coal-fired power in China, and scenarios of accelerated deployment of renewable energy systems.
- Scenarios of the evolution of the energy sector published by the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC).
- Continuing work under the China Renewable Energy Outlook project, implemented by ERI and the China National Renewable Energy Centre (CNREC), with cooperation from the Danish Energy Agency and the US National Renewable Energy Laboratory (NREL).

Brief summaries of each of these efforts are presented briefly below, followed by quantitative and qualitative comparisons of three "composite" scenarios that draw from these studies and others, and feature deployment of nuclear energy at different levels.

3.2 **Summary of Examples of Alternative Scenarios**

Alternative scenarios explore and project futures for China's energy sector that are different than a reference or business-as-usual case, and thus reflect the application of policies designed to steer the energy sector in a given direction, the influence of changes in the energy sector (or broader economy and society) not anticipated in the reference case, or both. Summaries of several alternative energy and, especially, electricity-sector scenarios for China are provided below. Most of these scenarios focus primarily on accelerated implementation of energy efficiency and/or renewable energy, relative to a reference case, but each could or would have significant implications for the nuclear energy sector as well.

3.2.1 Lawrence Berkeley National Laboratory (LBNL) China Energy Group

The researchers in the China Energy Group of the Energy Analysis and Environmental Impacts Division of LBNL have carried out a number of studies in which they have developed scenarios of China's energy future, usually focusing on energy efficiency and/or reducing greenhouse gas emissions.[55] A recent (2017) publication by the China Energy Group compares a "reference case" with alternative cases for electricity demand. A "Cost-effective Efficiency and Renewables Scenario" reduced year-2050 electricity demand by 21 percent, relative to the reference case, and a "Maximum Electrification Scenario"—based on the Cost-effective Efficiency and Renewables Scenario, but incorporating additional electrification in all sectors—still reduced 2050 electricity demand by 13 percent. Both of these scenarios resulted in a reduction of over 50 percent in national CO_2 emissions in year 2050 relative to the reference case (from 11.57 billion tonnes, or Gt, CO_2 to 4.79 and 4.72 Gt CO_2, respectively). A third alternative scenario, including maximum deployment of demand-side renewables, offered additional reductions, to 3.98 Gt CO_2 by 2050. By way of comparison, China's 2016 CO_2 emissions stood

[55] See, for example, Nina Khanna, David Fridley, Nan Zhou, Nihan Karali, Jingjing Zhang, and Wei Feng (2017), "China's Trajectories beyond Efficiency: CO_2 Implications of Maximizing Electrification and Renewable Resources through 2050", dated May, 2017, prepared for the European Council for an Energy Efficient Economy's 2017 Summer Study, and available as https://china.lbl.gov/sites/default/files/1-142-17_zheng_khanna_final.pdf. The China Energy Group uses the LEAP (Long-range Energy Alternatives Planning) software tool developed by the Stockholm Environment Institute—United States to quantitatively model energy flows, emissions, and other parameters for China in LBNL's China 2050 Demand Resources Energy Analysis Model (DREAM).

at about 10 Gt, so each of the alternative scenarios represents a significant reduction, by 2050, relative to current emissions.[56]

In a 2016 study focused on energy demand and CO2 emissions in China's cities—which produce on the order of 75-80 percent of China's national CO2 emissions in recent years—LBNL China Energy Group researchers evaluated a "Low Carbon" scenario representing "a pathway in which commercially-available cost-effective efficiency and renewable energy technologies are fully deployed". [57] The measures included in the Low Carbon scenario reduced year 2050 reference case urban emissions by approximately two-thirds, a result consistent with the findings in the 2017 study detailed above.

In a 2016 study focusing on the implications of power-sector policies on coal-fired generation and CO_2 emissions in China, the China Energy Group projected that a "Strengthened renewable MMS [mandatory market share] with green dispatch scenario" could reduce coal-fired generation to 14 percent of total generation by 2050.[58] In the same scenario, renewable power generation (biomass, wind, solar, and hydro) provides about 63 percent of generation in 2050, with output of "renewables" (inferred in this case to mean wind, solar, and biomass) reported at 4472 TWh, and nuclear power providing about 20 percent of total generation. At that level of nuclear generation, the implied capacity of nuclear power assumed in the Strengthened renewable MMS with green dispatch scenario would be nearly 300 GW.[59]

3.2.2 Rocky Mountain Institute, LBNL, and Energy Research Institute "Reinventing Fire" Project

An ongoing collaboration between the Rocky Mountain Institute (RMI), LBNL, and the Energy Research Institute (ERI) of the of the National Development and Reform Commission of China (see below), the "Reinventing Fire" project seeks to identify pathways of deep carbon dioxide emissions reduction through a combination of energy efficiency, electrification of end-uses that currently use fossil fuels, and expanded deployment of renewable electricity. The collaboration draws on work by all three partners, including the LBNL and ERI described above and below, respectively. An Executive Summary of the *Reinventing Fire* report from 2016 shows a reference case in which electricity generation rises to 12,800 TWh by 2050, up from 4,700 TWh

[56] See, for example, Zhu Liu (2016), *China's Carbon Emissions Report 2016: Regional Carbon Emissions and the Implication for China's Low Carbon Development*, Environment & Natural Resources Program, Belfer Center for Science and International Affairs, Harvard Kennedy School, dated October, 2016, and available as https://www.belfercenter.org/sites/default/files/files/publication/China%20Carbon%20Emissions%202016%20final%20web.pdf; and David Fridley, Hongyou Lu, and Xu Liu (2017), *Key China Energy Statistics 2016*, available as https://china.lbl.gov/sites/default/files/ced-9-2017-final.pdf.

[57] Nina Z. Khanna, David Fridley, Lynn Price, Nan Zhou, and Stephanie Ohshita (2016), "Estimating China's Urban Energy Demand and CO2 Emissions: A Bottom-up Modeling Perspective", 2016 ACEEE Summer Study on Energy Efficiency in Buildings, available as https://china.lbl.gov/sites/default/files/11_129.pdf,

[58] Nina Zheng Khanna, Nan Zhou, David Fridley, and Jing Ke (2016), "Quantifying the potential impacts of China's power-sector policies on coal input and CO_2 emissions through 2050: A bottom-up perspective", *Utilities Policy*, Volume 41, August 2016, Pages 128-138, available as available from https://eta.lbl.gov/publications/quantifying-potential-impacts-chinas.

[59] Estimate of implied nuclear capacity by the author of this paper is based on review of Figure 3 in Khanna et al, 2016 (ibid), and assuming an average capacity factor for nuclear generation in 2050 of 85 percent. Reference case generation in 2050 was reported as 10,730 TWh.

in a 2011 base year.[60] In the "Reinventing Fire" case, electricity generation in 2050 falls by 16 percent relative to the reference scenario, to 10,800 TWh, as a result of two partially offsetting sets of policies. Energy efficiency reduces 2050 electricity demand by on the order of 6,000 TWh, relative to the reference case, while electrification displacing fossil fuel use throughout the economy adds back 4,000 TWh to the 2050 total. Additional renewable electricity generation in the Reinventing Fire scenario displaces about 3,000 TWh of fossil and some nuclear generation in 2050, relative to the reference case. Nuclear generation in 2050 in the Reinventing Fire case is about 1,550 TWh, as opposed to about 2,400 TWh in the reference case. These values correspond to 2050 nuclear capacities of about 210 and 320 GW, respectively, assuming an average capacity factor for nuclear generation of 85 percent in 2050.[61]

Real GDP growth in both cases was assumed to be slightly higher than that included in the BAU case outlined in Section 2.2, above, at annual averages of 7.18 percent from 2010-2020, 5.60 percent from 2020-2030, 4.12 percent from 2030-2040, and 2.94 percent from 2040-2050. Population growth assumptions were similar to those in the United Nations "Medium Variant" projections reported above.

The net result of the Reinventing Fire scenario is to essentially cut in half year 2050 primary energy requirements relative to the reference case, bringing overall primary energy use by the Chinese economy back to 2050 levels. Overall 2050 CO_2 emissions similarly fall by nearly half in the Reinventing Fire case, relative to the Reference case. Emissions of the local and regional air pollutants sulfur and nitrogen oxides fall by factors of approximately 8 and 12, respectively, relative to 2010 level, in the Reinventing Fire scenario. Further, the authors of the report find a net direct economic benefit due to the transition to the Reinventing Fire scenario. The Reinventing Fire Scenario will

> "…save China 21 trillion RMB in energy costs. From 2010 to 2050, implementing the Reinventing Fire Scenario yields a potential energy savings of 56 trillion RMB ($8.3 trillion) relative to the Reference Scenario. Incremental new investment required beyond the Reference Scenario to realize these energy savings is estimated to be 35 trillion RMB ($5.2 trillion), yielding a net present value savings of 21 trillion RMB ($3.1 trillion, all figures 2010 real)."

3.2.3 "SWITCH-China" Modeling by UC Berkeley Renewable and Appropriate Energy Laboratory

SWITCH-China is an integrated model of the Chinese electricity sector prepared by researchers at the University of California's Renewable and Appropriate Energy Laboratory (RAEL) and their colleagues.[62] In a 2016 study, the SWITCH-China model was used to investigate four

[60] ERI, LBNL, and RMI (2016), *Reinventing Fire: China, A Roadmap For China's Revolution in Energy Consumption and Production To 2050, Executive Summary*, dated September, 2016, and available from https://www.rmi.org/insights/reports/reinventing-fire-china/.

[61] Nuclear generation values estimated by the author of this paper from data presented in Figure ES-14 in ERI, LBNL, and RMI (2016), ibid.

[62] Gang He, Anne-Perrine Avrin, James H. Nelson, Josiah Johnston, Ana Mileva, Jianwei Tian, and Daniel M. Kammen (2016), "SWITCH-China: A Systems Approach to Decarbonizing China's Power System", *Environmental Science and Technology*, 2016, 50 (11), pp 5467–5473, available as http://pubs.acs.org/doi/abs/10.1021/acs.est.6b01345.

scenarios of the evolution of carbon emissions by the Chinese power sector. The most stringent of these, the "IPCC Scenario", includes on the order of 250-300 GWe of nuclear generation capacity by 2050,[63] meeting 14 percent of total electricity demand, along with about 1500 GWe of wind power, about 1900 GWe of solar power, and 500 GWe of electricity storage. By 2050, about 90 percent of coal-fired generation (providing in total 29 percent of China's 2050 electricity needs) is coupled with carbon capture and sequestration (CCS) systems. CCS systems collect carbon dioxide from power plant exhaust gases (using considerable energy in the process) for sequestration in (typically) underground strata.

The SWITCH-China IPCC case results in a reduction of power-sector CO_2 emissions to 80 percent of 1990 levels. The authors of the study report that the annual additional cost of the scenario is over $2 trillion per year by 2050, which is offset at least partially ("22 to 42 percent) by the avoided external costs of coal production and use in the IPCC scenario. Placed in context, $2 trillion is about 5-7 percent of projected Chinese GDP in 2050. It should be noted that the SWITCH-China Reference Case appears to call for considerably higher growth in overall generation capacity, and thus likely in generation, relative to the composite BAU scenario described in section 2.2 of this paper.

3.2.4 Commentary on Plans for Nuclear and Coal-fired Power Development by Greenpeace

Although the author of this paper was unable to find long-range projections of the evolution of the Chinese energy sector authored by Greenpeace that are similar to the studies described above, a number of Greenpeace publications have commented on the future of the Chinese coal and nuclear sectors. A 2012 article suggests that China should focus on renewable energy and energy efficiency to reduce greenhouse gas emissions, and that

> "…building enough nuclear power stations to make a meaningful reduction in greenhouse gas emissions would cost trillions of dollars, create tens of thousands of tons of lethal high-level radioactive waste, contribute to further proliferation of nuclear weapons materials, and result in a Chernobyl-scale accident once every decade. Perhaps most significantly, it will squander the resources necessary to implement meaningful climate change solutions."[64]

A late 2017 article notes that China has recently canceled or delayed work on more than 150 planned or under-construction coal-fired power plants due to the "flat-lining" of demand for coal-fired power due to overcapacity of coal-fired generation. The article cites the environmental benefits of not moving forward with coal-fired power, including air pollution and water consumption benefits, and indicates that newly-increased targets for deployment of solar and wind power sources will further reduce the need for coal-fired generation. The article also notes that "[t]he government's recent efforts to clamp down on the red-hot real estate sector and

[63] Capacity estimates are by the author of this paper based on review of figures in He et al (2016).
[64] Greenpeace East Asia (2012), "No nuclear in China - not anywhere", dated 10-31-2012, and available as http://www.greenpeace.org/eastasia/news/blog/no-nuclear-in-china-not-anywhere/blog/42752/.

local government debt spending – key drivers of China's heavy industry volumes and power demand – will also leave less space for coal-fired power generation."[65]

A Greenpeace report evaluated the co-benefits of renewable generation in China from 2015 through 2030.[66] Among other findings, the report:

- Finds that the external environmental benefits of renewable generation exceed the wind power subsidy provided even in 2016,[67] and will be more than twice the level of the subsidy by 2030.
- States that "Between 2015 and 2030, wind and solar PV power will contribute RMB 14.3 trillion to China's GDP".
- Estimates that the wind and solar industries will employ 7.7 million people by 2030.
- Indicates that solar energy has been a force in "energy poverty" alleviation by being a major tool for providing electricity to households that previously lacked grid access.
- Notes that wind and solar development has reduced water use by coal-fired power plants, with the reduction by 2030 "… expected to increase to 3.6 billion m^3, equivalent to the annual basic water consumption of 200 million people".

A 2016 article provided by Greenpeace identifies some of the issues affecting deployment of reactors in China based on imported designs, and suggests that these issues will make China's ambitious nuclear power development targets difficult to achieve.[68]

3.2.5 China National Renewable Energy Center's "China Renewable Energy Outlook 2016" (CREO)

The report *China Renewable Energy Outlook 2016*, prepared by the China Renewable Energy Center in collaboration with groups in China, Europe, and the United States, focuses on an alternative "High Renewable Energy (RE) Penetration" scenario to a "Stated Policies" reference case, both evaluated through 2030.[69] The two scenarios differ only modestly with regard to overall energy consumption, with the stated policies case reaching a slightly higher peak in overall energy consumption a few years later than the high RE penetration case, and having a somewhat slower decline in contribution of coal to primary energy use (47 percent of total

[65] Lauri Myllyvirta and Li Danqing (2017), China halts more than 150 coal-fired power plants", dated October 11, 2017, and available as https://unearthed.greenpeace.org/2017/10/11/china-halts-150-coal-fired-power-plants/.
[66] Greenpeace (2017), *Accelerating the Energy Transition The Co-benefits of Wind and Solar PV Power in China, Summary* dated April, 2017, and available as https://secured-static.greenpeace.org/eastasia/PageFiles/299371/Renewables%20co-benefits%20report,%20April%2017/Accelerating%20the%20Energy%20Transition_GPEA%20media%20briefing_0411.pdf.
[67] The subsidy location cited is n Zhangjiakou, Hebei Province, where the wind power generation subsidy was 0.14 RMB/kWh in 2016.
[68] Zachary Davies Boren (2016), "All is not well with nuclear in China", dated February 17, 2016, and available as http://energydesk.greenpeace.org/2016/02/17/not-even-china-likes-the-hinkley-epr-nuclear-reactor/.
[69] China National Renewable Energy Center and Energy Research Institute (CNREC and ERI, 2016), *China Renewable Energy Outlook 2016*, prepared with cooperation partners the Danish Energy Agency and the US National Renewable Energy Laboratory, and available as http://www.ea-energianalyse.dk/reports/1473_REO2016.pdf.

primary energy in 2030 in the Stated Policy scenario versus 42 percent in the High RE Penetration scenario, down from 65 percent in 2016). The High RE Penetration case, however, provides a third more RE energy production by 2030 than the Stated Policies case. This difference is accomplished mainly by adding over 1000 GW of mainly wind and solar generation capacity in the High RE Penetration scenario, over and above the amounts assumed for the Stated Policies case. Coal-fired capacity falls from a high of 960 GW in 2020 in both scenarios, to 710 GW in the Stated Policies case and 660 GW in the High RE Penetration scenario, Generation from coal-fired power plants falls more dramatically, however, and as a result CO_2 emissions are 1.25 billion tonnes lower (about 13 percent) in the High RE Penetration scenario, and local air pollution and its health effects fall much more rapidly as well. The CREO report estimated a small increase in GDP in the High RE Penetration case relative to the Stated Policies case, with a significant boost to employment in renewable energy-related occupations partially offset by a reduction in employment in the fossil fuels sectors, mostly coal mining.

With regard to the nuclear sector, the CREO report includes the following description:

> "According to the decisions by the previous as well as current government of China, construction of nuclear power plants in the inland and in large-scale construction in the Yangtze River Basin will not happen. The development of the western regions has priority for a "green mountains and clear water are as good as mountains of gold and silver", primarily based on renewable energy. Before the fourth generation of nuclear power technology is in commercial operation, it is assumed that China will not open the inland deployment of nuclear power. Based on this, we consider nuclear power development to be within the range of 100 GW in 2050, solely deployed in coastal areas."

Although nuclear deployment in the two scenarios considered in the CREO 2016 report does not different markedly, with nuclear development limited to 75 GW by 2030, CREO thus projects much less nuclear capacity than that implied by the roster of planned reactors presented by the World Nuclear Association (as described above), but still creates significant environmental benefits, relative to the Stated Policies case, through the High RE Penetration scenario.

The CREO project partners have been updating and expanded their analyses, and a "CREO 2017" report is forthcoming.

3.2.6 Energy Research Institute's "China 2050 High Renewable Energy Penetration Scenario And Roadmap Study"

The 2015 report *China 2050 High Renewable Energy Penetration Scenario And Roadmap Study*, prepared by the Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC), and funded by the Energy Foundation, presents scenario for the evolution of the Chinese energy sector that, like the CREO and LBNL studies, includes significant additional electrification, relatively modest growth in nuclear generation capacity and use, and continuing strong growth in the deployment of renewable power sources.[70] Key findings of the report, as relayed in its *Executive Summary*, include the following:

[70] Energy Research Institute (2015), *Executive Summary, China 2050 High Renewable Energy Penetration Scenario And Roadmap Study*, dated April, 2015, and available as http://www.efchina.org/Attachments/Report/report-20150420/China-2050-High-Renewable-Energy-Penetration-Scenario-and-Roadmap-Study-Executive-Summary.pdf.

- Total power generation in 2050 is higher than that in the BAU scenario presented in section 2 of this paper, due principally to higher growth in generation in the early years of the projection, though growth in the later years (2040-2050) is somewhat lower in the ERI projection.
- The fraction of generation provided by coal-fired power plants falls from nearly 75 percent in 2011 (the base year of the ERI study) to less than 7 percent in 2050.
- The fraction of generation provided by solar and wind power rises to nearly 54 percent of the national total by 2050, with hydropower providing another 14 percent.
- Nuclear power generation capacity grows to 100 GW by 2050, at which point it supplies 4.3 percent of total generation. In the ERI projection, nuclear power's share of generation stays between 4.8 percent and 3.7 percent from 2018 through 2050.
- Carbon dioxide emissions fall to about 3 GT CO2 by 2050.
- Emissions of the local and regional air pollutants nitrogen oxides and sulfur oxides (NOx and SOx) fall to approximately 1970 levels (NOx) and about half of 1970 levels (SOx), on the order of a tenth of peak emissions of both gases (reached in 2010 and 2005, respectively).
- The average costs of generating and delivering electricity in ERI's high renewables scenario are only very modestly higher than in ERI's reference case, ranging from 0.672 RMB/kWh in 2030 to 0.685 RMB/kWh (about 10.4 US cents/kWh at current exchange rates) in 2050 in the high renewables case, "while in [the] reference scenario the average cost between 2030-2050 will stay flat around RMB 0.67/kWh".[71]
- Under the high renewables scenario, about 10 million jobs are added in the renewable energy industries between 2015 and 2050.
- Relative to the reference case, ERI's macroeconomic analysis of the high renewables scenario indicates modest changes in key economic indicators in 2050. Government spending is lower, imports and exports higher, and residential consumption up, but all within the range of a 0.23 and 1.44 percent difference between cases. Price levels in the two cases are virtually the same in 2050.

Overall, ERI's results suggest that a shift to a high renewables penetration scenario can provide very significant environmental benefits at minimal overall costs to the economy—though of course some sectors will come out better than others—and without large growth in the deployment of nuclear power.

3.3 Quantitative and Qualitative Comparison of Alternative Scenarios with Baseline

The alternative scenarios of and commentary on China's near- and medium-term energy future presented above indicated that serious consideration is being given both inside and outside of

[71] Quote from ERI (2015), ibid. Note that projecting costs two or three decades into the future is necessarily an uncertain exercise, thus the main point here is that the costs in the high renewables case appear minimally different from those in the reference case.

China to policies to transform China's economy and energy sector towards a much lower-carbon, higher-renewables, and more efficient system than exists today. Some of the work described above (which certainly does not exhaust the universe of China energy futures studies) posit a relatively modest role for nuclear power in China's electricity sector by 2050, with little or no growth over time in nuclear's share of generation, while others suggest a more important role. In reviewing all of the projections above, and those presented in this paper, it is important to consider the breathtaking changes ongoing in the Chinese energy sector. Trends in just the past few years—marked reductions in deployment and use of coal-fired power, marked reductions in the rate of growth of electricity demand, and vast increases in wind and solar generation capacity (along with reductions in wind and solar costs) are shifting the baseline upon which scenarios are constructed. These trends may rapidly make readily achievable scenarios that look unachievable today.

Below we present, in the broader context of the overall electricity-sector scenarios described above and in section 2 of this paper, three alternative scenarios of nuclear power sector development in China, and offer a brief analysis of their relative benefits and costs, both quantitative and qualitative.[72]

3.3.1 Summary of Nuclear Capacity Scenarios

In order to explore the consequences of different scenarios of nuclear power capacity development in China, we have created three different capacity expansion cases. These are as follows:

- A "**Business as Usual**", or **BAU** case, that draws from a very recent listing of planned and proposed reactors in China prepared by the World Nuclear Association (WNA),[73] but assumes that the phase-in of new "planned" reactors will be somewhat slower than in the WNA listing,[74] and that about 55 GWe of the reactors listed as "proposed" by WNA will ultimately be built by 2050 (out of a total of 200 GWe of projects listed). Based on standard operating lifetimes, Existing LWRs are retired when they reach 40 years of service, and China's two "CANDU" reactor units are retired after 30 years of service. By 2050, nuclear generation capacity in the BAU case reaches a level that is slightly lower than the nuclear capacity projected in the USDOE EIA's *International Energy Outlook 2017* reference case, and also slightly lower than estimated 2050 nuclear capacity the *Reinventing Fire* China Reference case.
- A "**Maximum Nuclear**" or **MAX** case, which also draws from the WNA listing but assumes a faster phase-in than in the BAU case of under-construction and "planned" units, and also assumes that about 80 percent (160 GWe) of the reactors listed in the

[72] The analysis of benefits and costs defines "energy security" in a broad sense, including traditional energy supply security and net direct costs, but also including environmental, social and political, and military-related security. For a discussion of an analytical framework used with this broader concept of energy security, see for example, David von Hippel, Tatsujiro Suzuki, James H. Williams, Timothy Savage, and Peter Hayes (2011), Energy Security and Sustainability in Northeast Asia, published in the "Asian Energy Security" Special Section of *Energy Policy* Volume 39, Issue 11, November, 2011, pages 6719–6730.
[73] World Nuclear Association (2017), "Nuclear Power in China", updated July 2017, available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-power.aspx.
[74] Some authors see evidence that China's nuclear build-out is not proceeding as rapidly as initially planned. See, for example, Steve Thomas (2016), "China's Nuclear Power Plans Melting Down", *The Diplomat*, October 29, 2016, available as http://thediplomat.com/2016/10/chinas-nuclear-power-plans-melting-down/.

World Nuclear Association table as "proposed" (or replacements similar in total capacity) are ultimately built and are all phased in by 2050. Existing LWRs are retired when they reach 50 years of service, so 10 years of life extension is assumed. By 2050, nuclear generation capacity in the MAX case is lower than that implied in RMI's Reinventing Fire scenario.

- A "**Minimum Nuclear**" or **MIN** case, in which the reactors listed by the World Nuclear Association as under construction or planned are all ultimately phased in by 2038, though on a much slower schedule (for those plants for which an operational date is given) than listed. After 2038, no additional plants are built, and as in the BAU case, older plants are retired as they reach the end of their standard operating lives. This lower capacity scenario could arise due to a combination of factors, including minimal growth in electricity demand in the 2030s and beyond, increased price competition from renewable energy, the availability of new and cost-effective electricity storage technologies, and/or perhaps a social backlash against nuclear power, In the MIN case, nuclear capacity begins to slowly decline about 2050, reaching a level by 2050 that is somewhat below that of the ERI and CREO scenarios described in section 3.2.

Readers should note that none of these paths account explicitly for potential shocks to the Chinese nuclear power industry, and to Chinese society as a whole, that might arise from a serious accident in a Chinese nuclear power plant. Such an event could have potentially devastating consequences for large populations.[75] The timing of such an event, should it occur, is not knowable in advance, although there is an argument that it is statistically likely over the time frame of these paths, given historical rates of major accidents per year of reactor operation.[76]

Figure 3-1 and Figure 3-2, respectively, show the capacity and electricity output implied by each of the three nuclear scenarios above. In the BAU case, capacity increases to 170 GWe by 2050, while in the MAX case capacity rises to nearly 260 GWe. In the MIN case, capacity rises to about 91 GWe by 2040 (about 260% of existing capacity as of 2017), but no new plants are added thereafter, so capacity falls to about 85 GWe by 2050 as older plants are retired. By way of comparison, as noted above, China's current (2016) overall electricity generation capacity for all types was over 1600 GW, and overall generation was nearly 6200 TWh.[77]

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[75] The author of this paper prepared a rough estimate of the consequences of an incident involving (accident at or attack on) a reactor and spent fuel pool at the Ling'Ao nuclear plant in Guangdong province that suggested that "worst case" releases of Cesium-137 might result in exposures sufficient to cause hundreds of thousands of premature cancer deaths and almost certainly require the abandonment of one or several big cities, depending on the prevailing wind direction at the time of the incident (D. von Hippel and P. Hayes, 2016, unpublished).

[76] See, for example, He Zuoxiu, "Chinese nuclear disaster "highly probable" by 2030," *China Dialogue,* March 19, 2013, at: https://www.chinadialogue.net/article/show/single/en/5808, and S. Wheatley, B. Sovacool, D. Sornette (2017), "Of Disasters and Dragon Kings: A Statistical Analysis of Nuclear Power Incidents and Accidents," *Risk Analysis*, Volume 37, #1, pages 99-115, available as http://onlinelibrary.wiley.com/doi/10.1111/risa.12587/epdf.

[77] For electrical energy, see British Petroleum (2017), "BP Statistical Review of World Energy June 2017" workbook, available as http://www.bp.com/content/dam/bp/en/corporate/excel/energy-economics/statistical-review-2017/bp-statistical-review-of-world-energy-2017-underpinning-data.xlsx. For capacity, see, for example, "Installed capacity of electric power generation in China between 2010 and 2016 (in GW)", available as https://www.statista.com/statistics/302269/china-installed-power-generation-capacity/.

Figure 3-1: Three Scenarios of Nuclear Generation Capacity (GWe) for China through 2050

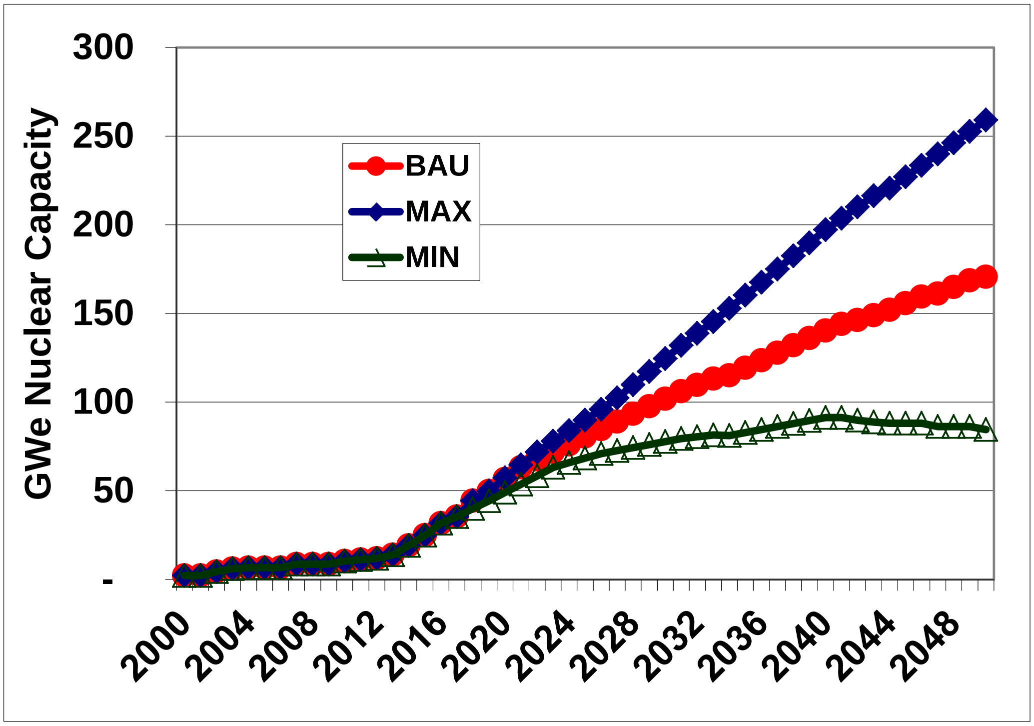
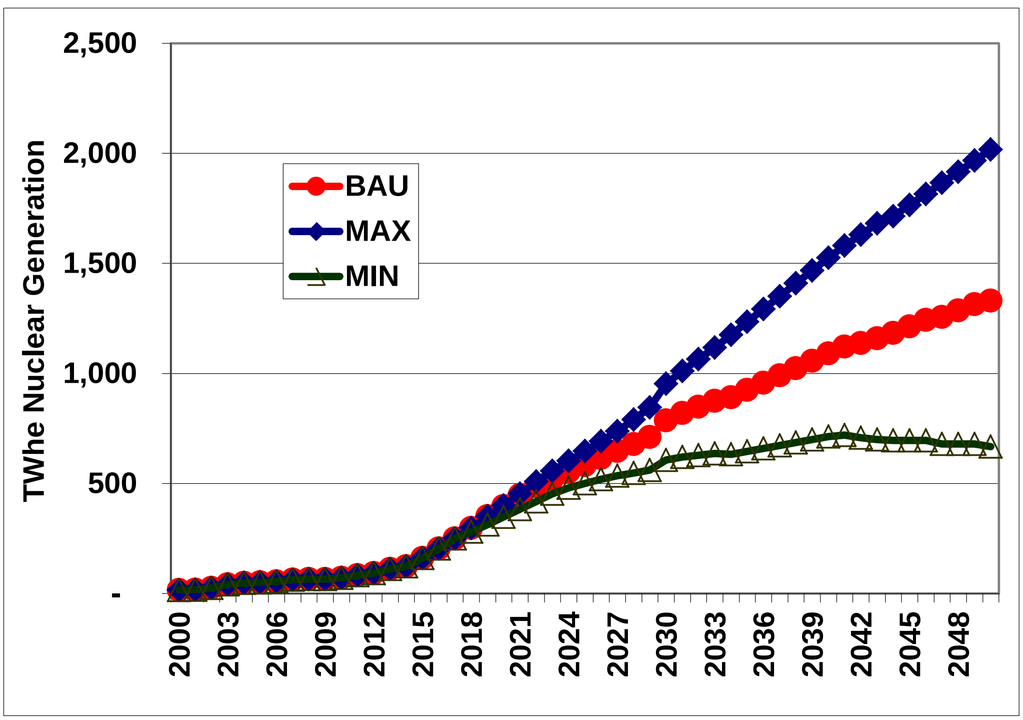


Figure 3-2: Three Scenarios of Nuclear Generation Output (TWhe) for China through 2050



3.3.2 Broader Energy and Nuclear Sectors Contexts for Nuclear Paths

Each of the nuclear generation capacity expansion paths could, in theory, be combined with a range of different trends and policies in the broader energy and electricity sectors, as well as in the overall nuclear sector, including front-end and back-end fuel cycle developments. In practice, competition for private and public investment resources, national and societal goals and preferences, and other criteria make some combinations more plausible than others. The assumed energy and nuclear/sector contexts for each of the paths described above is as follows.

BAU Path

The BAU path is assumed to exist within a Chinese energy sector in which significant, but not aggressive, efforts to displace coal-fired power with renewable energy sources continue, energy efficiency improvements also continue, but are not major priorities of national energy policy, and some electrification of currently fossil-fuel-dominated sectors and end-uses, most notably transport, occurs, but is again aggressively pursued. In the BAU path, investment priorities in the energy sector are thus split between the nuclear and renewables sectors, with some development of coal- and gas-fired power continuing.

In the BAU path, as well as in the MAX and MIN paths as described below, China is assumed to source one-third of its uranium domestically.[78] In the nuclear sector under the BAU path, the development of uranium enrichment and reprocessing facilities, and the use of MOx fuel, proceeds roughly as described by the World Nuclear Association, but on a somewhat delayed schedule. For enrichment, this means that about 80 percent of China's enrichment needs are supplied domestically by 2020, with enrichment being entirely domestic by 2030. World (and Chinese) enrichment costs, driven in large part by Chinese nuclear expansion, follow a "medium" scenario, rising to about $75/kg SWU (about twice 2017 levels, but much lower than historical maxima) by 2050 (2009 dollars). Research and pilot development of fast reactor technologies continues, but also on a somewhat delayed schedule, such that commercialization of fast reactors is still at least several years off by 2050. MOx use is in LWRs assumed to start in 2025,[79] and 25 percent of reactors are assumed to use cores with 20% MOx fuel by 2050. Reprocessing also starts in 2025, with capacity and throughput ramping up sufficiently to process 50 percent of cooled spent fuel by 2040 and thereafter.

Spent fuel management in the BAU path, consistent with the path's emphasis on reprocessing, focuses mainly on interim spent fuel storage in spent fuel pools at reactors and at reprocessing facilities, although there is some dry cask storage of spent fuel.[80]

[78] From World Nuclear Association (2017), "China's Nuclear Fuel Cycle, updated September, 2017, and available as http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/china-nuclear-fuel-cycle.aspx. "China aims to produce one-third of its uranium domestically, obtain one-third through foreign equity in mines and joint ventures overseas, and to purchase one-third on the open market."

[79] See, for example, Qiang Yue, Jingke He, Laurence Stamford, and Adisa Azapagic (2017) "Nuclear Power in China: An Analysis of the Current and Near-Future Uranium Flows", *Energy Technologies*, 2017, Volume 5, pp. 681 –691, available as http://onlinelibrary.wiley.com/doi/10.1002/ente.201600444/epdf

[80] "Dry casks" refers to the spent fuel storage option, used in many countries, in which cooled spent fuel is isolated in massive casks designed to last for up to 100 years. Spent fuel assemblies are typically sealed into stainless steel containers several centimeters thick, which are then placed in "overpacks" made of steel or concrete. The resulting cask is on the order of 2 meters in diameter and 6 meters tall, weighs up to 50 tonnes, and is essentially impervious to any significant damage that could be caused by natural disasters or accidents, as well as to all but the most determined and well-equipped attempts at penetration by criminals or terrorists.

MAX Path

Consistent with, for example, the Reinventing Fire scenario described above, the MAX Path includes both significant investments in energy efficiency and in renewable generation, as well as in electricity transmission facilities. Electrification of the energy sector is also a priority, with the reduction of greenhouse gas emissions and local/regional air pollutants a driving policy impetus. Both the savings in year 2050 electricity needs due to energy efficiency improvements and additional electrification to displace fossil fuel at the end-use level are assumed to be about half that assumed in the Reinventing Fire study—about 25 and 17 percent, respectively. The lowered assumptions for these impacts are in part due to a lower reference case assumed here than assumed in the Reinventing Fire study, and in part to an assumption that a more aggressive build-out of the nuclear sector, and of, for example, reprocessing (see below) and enrichment, will to some extent crowd out investments in efficiency and renewable energy (for example). Investment to drive the nuclear sector comes to a large extent from public funding, while renewable power investments are mostly privately driven, but take advantage of necessarily higher prices for electricity required by nuclear investments.

The MAX path focuses on building national capacity in the nuclear sector, including aggressive build-outs of uranium enrichment and related capacity, as well as reprocessing capacity and MOx use. For enrichment, this means that about 90 percent of China's enrichment needs are supplied domestically by 2020, with enrichment being entirely domestic by 2025. Enrichment costs, again driven by Chinese demand, are assumed to follow a "high" scenario, rising to $104/kg SWU (still much lower than the $160/kg SWU historical maxima) by 2050. National capacity for manufacturing of key nuclear plant components grows rapidly, and the MAX path is likely to be also combined with an aggressive national effort to export nuclear reactors to other nations. MOx use is in LWRs assumed to start in 2022, and 40 percent of reactors are assumed to use cores with 20% MOx fuel by 2050. Reprocessing on a commercial scale likewise starts in 2022, with a target of 80 percent of cooled spent fuel reprocessed by 2035. Spent fuel management focuses on interim storage in spent fuel pools at reactors and at reprocessing facilities.

MIN Path

Consistent with paths projecting high rates of renewable energy penetration in the CREO and ERI studies, the MIN path couples nuclear capacity expansion at a rate that holds the nuclear share of generation roughly constant with aggressive development of renewable energy for power generation and for end-uses, plus aggressive energy efficiency programs. Electrification is also an emphasis, both for greenhouse gas emissions reduction and to bring down emissions of local and regional air pollutants. Energy efficiency efforts, and the use of more renewable energy sources at the end-use level, are assumed to reduce electricity needs by 33 percent by 2030 relative to BAU requirements, with electrification adding 20 percent back to electricity demand by 2050. Ongoing policies, including carbon markets and carbon taxes, preferentially target markets for renewable energy and energy efficiency, with the proceeds used to support investment in both, as well as in pollution control and environmental remediation. The MIN path does not explicitly include carbon capture and sequestration (CCS) for coal- and/or gas-fired power plants, as used in the "IPCC Target" scenario of the Gang He, et al (2016) study referenced above, but could include CCS if CCS technology is suitably advanced and if greenhouse gas emissions reduction policies in China required its use. China has been rapidly developing facilities for importing LNG, and LNG could play a more important role in power generation in China's future in a variant of a MIN path, with or without CCS. Greater gas-fired generation, perhaps displacing some planned nuclear plants, would be even more plausible if, for example, infrastructure for bringing North American gas to China at attractive prices can be developed. Also not explicitly modeled in the MIN path is the development and widespread use of electricity storage technologies, which would be needed to complement the aggressive development of renewable (wind and solar) electricity sources.

In the nuclear sector, reprocessing is not pursued beyond the existing and under-construction pilot plants, and MOx use in existing reactors is limited. Uranium enrichment facilities planned for the near-term are built by 2025, but no additional enrichment plants are built, and the remainder of China's required enrichment services are imported. With a smaller nuclear capacity expansion in China, and (assumed) reduced nuclear restarts in Japan, relative to other scenarios, international (and Chinese) enrichment costs follow a "low" trajectory, reaching $54/kg SWU by 2050, about 40 percent above 2017 levels. Efforts to export reactors continue, but are not heavily subsidized by the Chinese government. Research into fast reactors continues, but at a low level, and commercialization of fast reactors is still decades away by 2050. In part to provide fuel for fast reactor research, the smaller (200 tHM/yr) reprocessing facility reportedly (as of 2017) being built at Gansu is eventually completed, but is not run until 2025, and then at only partial capacity for several years. Pu from this facility is used to produce MOx fuel, which is used in 10 percent of LWRs by 2050, with phase-in occurring slowly starting in 2030. MOx fuel again makes up 20 percent of reactor cores in those units that use MOx. Cooled spent fuel is stored mostly in a mixture of at-reactor spent fuel pools and in dry casks, which may be located at or near reactors or at a centralized dry cask facility.

3.3.3 Flows of Nuclear Materials

Table 3-1 shows estimated total requirements for uranium and uranium ore in each of the three scenarios, both for the individual years 2010, 2030, and 2050, and on a cumulative basis from 2015 through 2050. The MAX path implies the use of over 50,000 tonnes of U annually by 2050, while less than a third as much is required in the MIN path. The extraction of 11 million tonnes of ore is required by 2050 in the MAX path, but placed in context, this is much less than a percent of the total volume of coal extracted to fuel China's power sector. By assumption, two thirds of Chinese uranium needs are sourced abroad, and one third are from domestic mines.

Table 3-1: Uranium Requirements by Nuclear Capacity Expansion Path

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Annual Total Metric Tons Natural Uranium (as U) Imported plus Domestic Production	2010	2,629	2,629	2,629
	2030	27,718	21,837	15,946
	2050	53,659	35,106	16,570
	Cumulative, 2015-2050	1,105,629	820,318	540,581
Annual Total Thousand Metric Tons Uranium Ore (from In-country and outside mines) to Supply All Domestic Uranium Needs	2010	546	546	546
	2030	5,752	4,532	3,309
	2050	11,136	7,286	3,439
	Cumulative, 2015-2050	229,457	170,245	112,190

Under the MAX expansion path, if China chose to provide all of its own enriched uranium, China alone would need to build new enrichment capacity by 2050 approximately equal to more than half of today's global capacity. China's annual requirement requirements by 2050 rise to nearly 42 Million kg SWU. Under the MIN expansion path, however, international enrichment facilities extant as of 2015 are likely sufficient to meet China's enrichment needs by 2050 (about 12 million kg SWU), even factoring in likely East Asia regional and out-of-region demand without significant expansion, assuming existing international enrichment facilities (or replacement facilities) continue to operate. Though the ROK and Japan have accounted for almost all enriched uranium in East Asia needs pre-Fukushima, the rapid growth of China's nuclear power sector and the slow process of restarting Japan's reactors means that China's demand for enrichment will likely outstrip needs in the rest of the region well before 2020.

The uranium oxide (UOx) and MOx fuel requirements under each scenario are summarized in Table 3-2. MOx fuel requirements in the BAU path by 2050 are less than half of those in the MAX path, and MIN path MOx use is less than a tenth of MAX path use by 2050.

Table 3-2: Requirements for UOx and MOx Fuel in Each of 3 Nuclear Paths

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Implied Total Requirements for UOx Fuel (excluding MOx) from All Sources (Metric tonnes heavy metal in fabricated fuel)	2010	267	267	267
	2030	2,929	2,327	1,711
	2050	5,417	3,620	1,763
	Cumulative, 2015-2050	115,040	86,601	57,961
Implied Requirements for MOx Fuel Blended and Fabricated from All Sources for Use in Domestic Reactors (Metric tonnes heavy metal in fabricated fuel)	2010	-	-	-
	2030	60	24	-
	2050	408	191	36
	Cumulative, 2015-2050	4,657	2,123	394

With widely varying use of reprocessing in the three scenarios, it is not surprising that plutonium production and uptake (as MOx) also is significantly different, as shown in Figure 3-3. Cumulative plutonium separation through reprocessing rises to over 450 tonnes of Pu in the MAX case by 2050, and about 9 tonnes of Pu inventory remains after MOx use in 2050. About 200 tonnes of Pu are produced by 2050 in the BAU case, but almost all stocks are used as MOx. In the MIN case, only about 27 tonnes of Pu are produced via reprocessing in China through 2050, and more than that amount of Pu is used as MOx, implying, for example, that some Pu from other nations (stocks from Russia, the UK, or France) is blended into fuel used in Chinese reactors, and/or military Pu from the Chinese weapons program is disposed of as MOx. Note that all of these calculations of net Pu inventories by 2050 are extremely sensitive to the combination of assumptions regarding the fraction of spent fuel reprocessed and the amount of fuel used as MOx. In practical terms, this means that if a reprocessing program is successful BUT MOx use is delayed, significant inventories of Pu can build up, and can serve as a proliferation target. As a sensitivity analysis, Figure 3-4 shows what might happen if reprocessing proceeds in each path as indicated above, but MOx use is delayed by 10 years in each path, and used in only half as many reactors—a plausible outcome given the difficulties in implementing MOx use that other nations have experienced to date. In this sensitivity case, inventories of Pu of about 300, 140, and 18 tonnes build up in the MAX, BAU, and MIN cases, respectively, by 2050, at which point Pu stocks are still continuing to accrue. The stocks building up in this sensitivity case in the MAX and BAU paths would suffice to build tens of thousands of nuclear weapons, and even the MIN case stocks represent thousands of times the mass of Pu contained in a nuclear warhead. Additionally, paths that produce high volumes of Pu, whether or not fully consumed as MOx, would tend to enhance the chance of significant volumes of Pu going astray, as the more Pu is produced, the easier it will be for weapons-relevant quantities (kilograms) of Pu, amounting to less than a tenth of a percent of MAX and BAU annual output from reprocessing facilities, to be diverted for criminal purposes.

Figure 3-3: Pu Separation and Stocks Net of MOx Fuel Use by Path

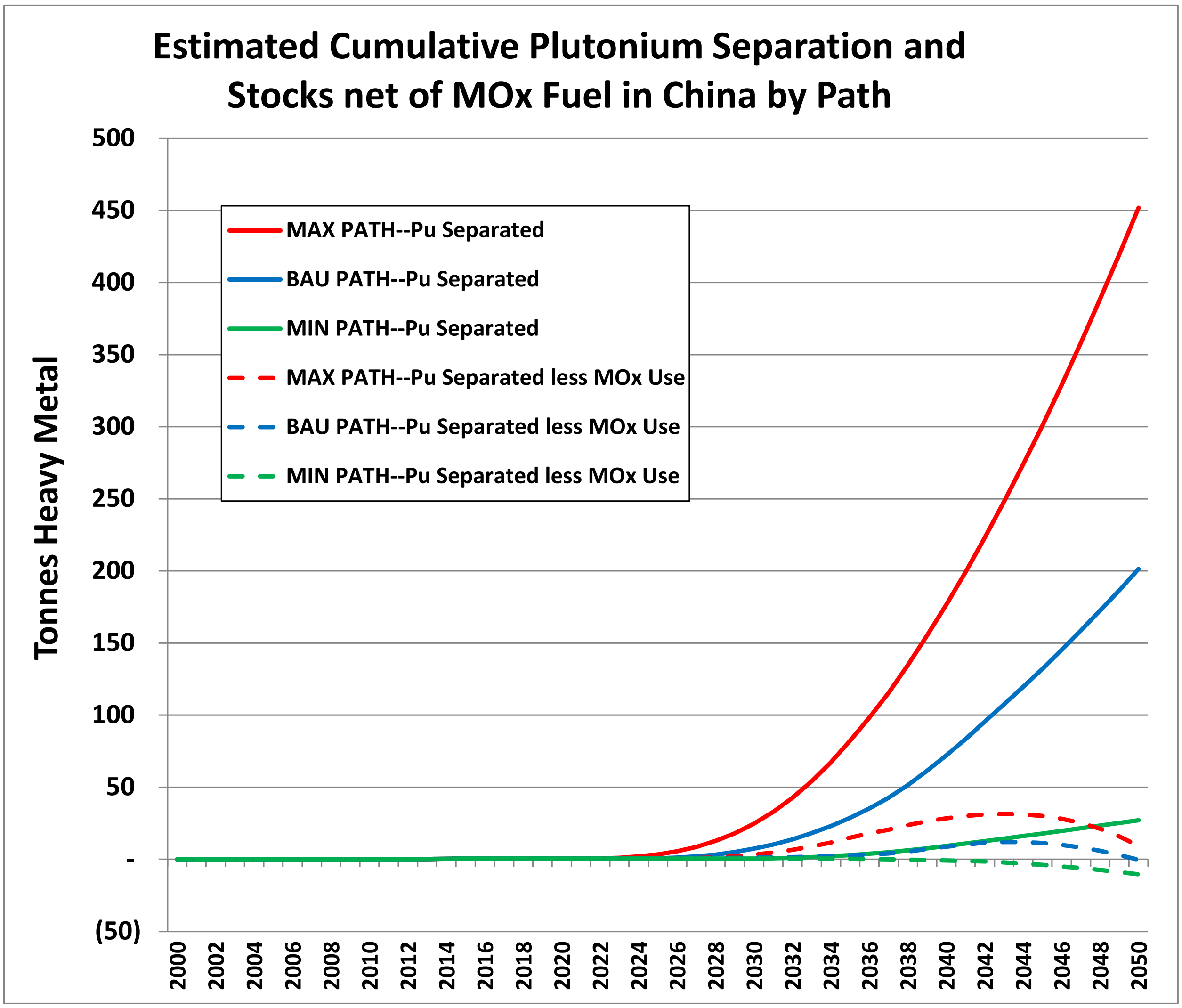


Figure 3-4: Sensitivity Analysis: Pu Separation and Stocks Net of MOx Fuel Use by Path if MOx Use is Delayed

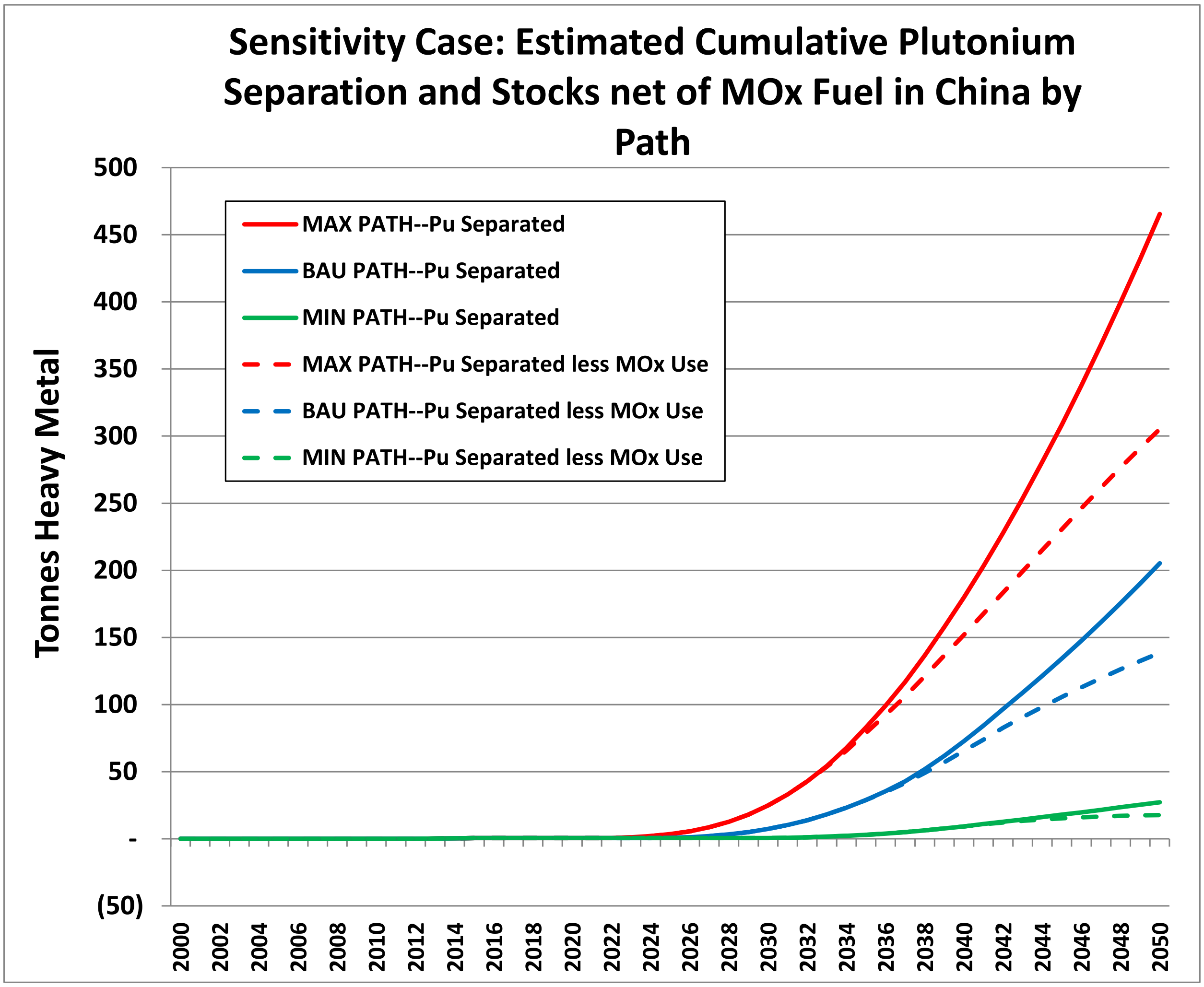


Table 3-3 presents annual and cumulative results for the production of cooled spent fuel[81] and high-level wastes from reprocessing, as well as the number of casks used for dry cask storage, in each of the three nuclear paths. Despite the large difference in 2050 nuclear generation capacity between the three paths, the cooled spent fuel produced over time is not all that different, because cooled spent fuel production lags changes in generation. The MAX scenario produces much more high-level waste (HLW) from reprocessing than the other cases. Though the volume of HLW is not large—5000 or so cubic meters could be contained in 25 or so average urban

[81] Spent LWR nuclear fuel must be cooled—typically for five to 10 years, in spent fuel pools before it can be either reprocessed, placed in dry casks for long-term (100 years or more) storage, or placed in long term storage/indefinite or permanent disposal in mined repositories, such as the canceled Yucca Mountain facility in the U.S., or in deep borehole disposal (a technology in the early phases of development—see, for example, Neil Chapman (2013), "Deep Borehole Disposal of Spent Fuel and Other Radioactive Wastes", NAPSNet Special Reports, July 25, 2013, https://nautilus.org/napsnet/napsnet-special-reports/deep-borehole-disposal-of-spent-fuel-and-other-radioactive-wastes/.

apartments—it is highly radioactive and, like spent fuel, remains so for thousands of years, meaning that special well-secured facilities capable of holding the wastes indefinitely must be constructed. In the MIN path, where the emphasis is on dry cask storage, on the order of 2600 casks would be required to accommodate the cooled spent fuel produced by 2050, not including the relatively small amount of spent fuel reprocessed in the MIN path. To put this number of casks in perspective, the total dry casks filled during the MIN path could be stored in an area of less than 10 hectares, just a bit bigger than area enclosed by the fence around the White House in Washington DC.

Table 3-3: Spent Fuel Management Results for Three Nuclear Paths

Parameter	YEAR	MAX Path	BAU Path	MIN Path
Annual New Spent LWR Fuel Cooled and Available for Reprocessing, Storage, or Disposal (excluding MOx spent fuel), Metric Tonnes Heavy Metal	2010	51	51	51
	2030	1,190	1,139	975
	2050	3,654	2,686	1,747
	Cumulative, 2015-2050	57,028	46,688	35,880
Annual Spent MOx Fuel Cooled and Available for Storage or Disposal, Metric Tonnes Heavy Metal	2010	-	-	-
	2030	-	-	-
	2050	239	112	23
	Cumulative, 2015-2050	2,020	883	150
Implied Amount of Spent LWR Fuel (UOx only) Reprocessed in Total for Use in Domestic Reactors (Metric tonnes heavy metal)	2010	1	1	1
	2030	612	214	9
	2050	2,923	1,343	175
	Cumulative, 2015-2050	41,045	18,276	2,438
Implied Volume of High-level Waste (as vitrified) from All Cooled Spent LWR Fuel (UOx only) Reprocessed for Use in Domestic Reactors (cubic meters)	2010	0.15	0.15	0.15
	2030	70.37	24.57	1.02
	2050	336.18	154.47	20.10
	Cumulative, 2015-2050	4,720.15	2,101.75	280.35
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR Fuel (UOx only) for Storage/Disposal, Net of Reprocessing (units)	2010	-	-	-
	2030	-	-	-
	2050	36	109	156
	Cumulative, 2015-2050	362	1,496	2,608
Total Annual Number of Casks Required for Dry Cask Storage of Cooled Spent LWR MOx Fuel for Storage/Disposal (units)	2010	-	-	-
	2030	-	-	-
	2050	24	11	2
	Cumulative, 2015-2050	202	88	15

3.3.4 Costs

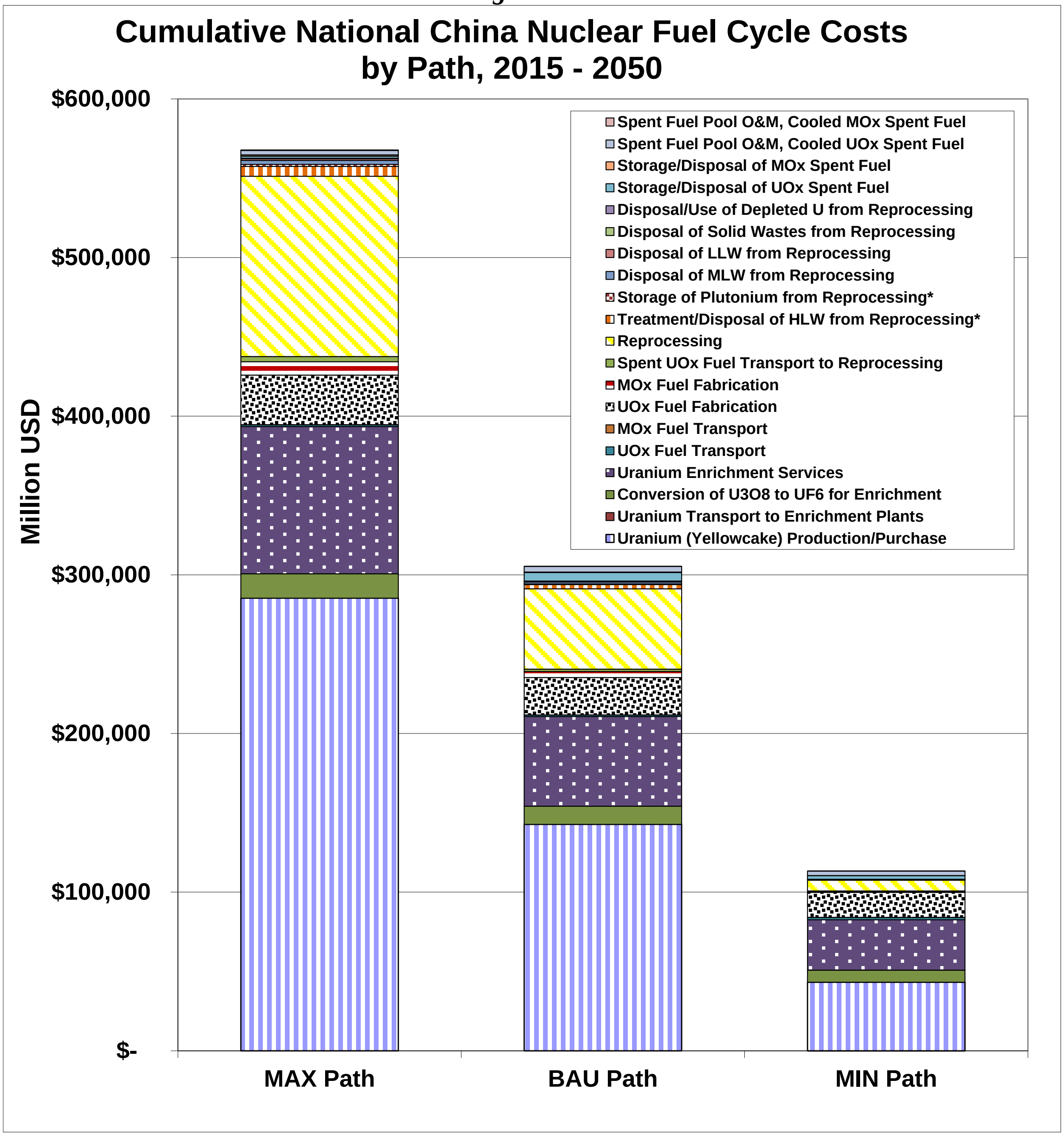
Although a full quantitative evaluation of the direct costs of the scenarios described above is beyond the scope of this paper, some of the considerations in comparing the costs between the three scenarios in qualitative terms are as follows:

- Fossil fuel costs for electricity generation will be highest for the BAU case, with annual costs in the MAX case about half of BAU levels by 2050, and in the MAX case about a quarter of BAU levels, due to displacement of fossil fuels by efficiency improvements, electrification, and use of renewable energy for direct end-uses and electricity generation.

- Overall fossil fuel costs, including “upstream” costs for oil refining, coal mining, and other fuel-cycle activities, will be lower due to electrification of end-uses in the MAX scenario, and even lower in the MIN case.
- There is likely to be very little growth in capital and operating and maintenance (O&M) costs for fossil-fueled power plants in any of the scenarios, though these costs will be lower in the MAX path, and lower still in the MIN path, as more coal-fired generation is displaced by nuclear (in the MAX path) and renewable generation/energy efficiency in both paths, In the MAX and especially the MIN path, at least more coal-fired capacity will likely be retired, providing a reduction in O&M costs. One factor that could cause power plant costs to rise, and could be applied to any of the three scenarios, is if more stringent controls are required to reduce local and regional air pollutants, and/or if carbon capture and sequestration is required on fossil-fueled plants.
- Costs for energy efficiency and increased deployment of end-use renewables will be higher in the MAX case than in the BAU case, and higher still in the MIN case, although previous experience in China and elsewhere suggests that in many cases energy efficiency provides electricity savings more cheaply than electricity case be generated by supply-side resources. Thus when the avoided costs of electricity generation and direct fuel use are factored in, efficiency investments will likely yield a net savings in overall direct costs. The much higher rate of renewables deployment in the MIN path will likely reduce the per-unit costs of renewable energy systems, and accompanying electricity storage systems. It is difficult to say whether the net costs of aggressive deployment of energy efficiency and renewable energy in the MIN path will be higher or lower than the costs of the conventional and nuclear energy systems that they displace in the BAU and MAX paths, but recent experience and at least some previous studies of energy futures suggest that the cost differences may be small relative to overall energy system costs and to the uncertainties of costs projected three decades into the future.
- The MAX scenario will have the highest overall costs for nuclear generation capacity, as well as for fixed and non-fuel variable operating and maintenance (O&M) costs, followed by the BAU case. MIN case total capacity costs and O&M will be substantially lower than in the other two cases. Costs for fast reactor research and development will be highest in the MAX case, and relatively limited in the MIN case.

Nuclear fuel cycle costs—exclusive of reactor capital and non-fuel O&M costs—have been quantified for each of the three nuclear paths described above. Not surprisingly, as shown in Figure 3-5, Nuclear fuel cycle costs are much higher in the MAX path, at a about $560 billion on a cumulative basis over 2015 through 2950. This total is nearly twice as much as for the BAU path, and on the order of five times that of the MIN path.   The three largest cost categories are raw uranium and uranium enrichment—higher in the MAX path due to higher cost escalation assumptions—and reprocessing costs, which are nearly avoided altogether in the MIN path.

Figure 3-5:



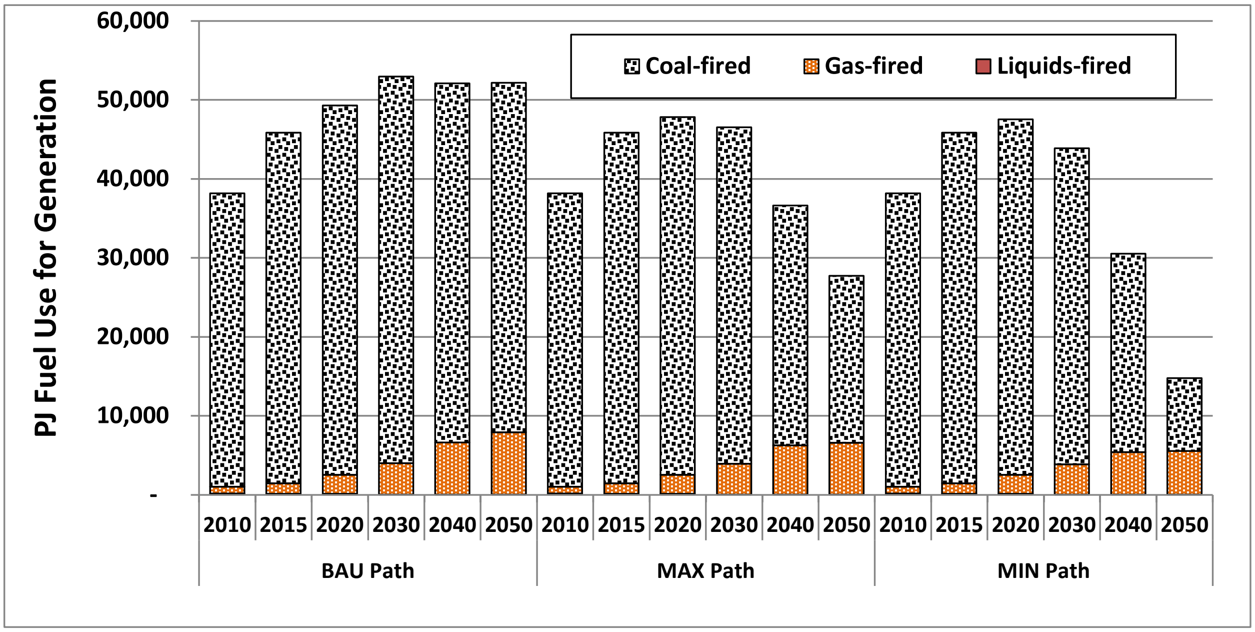
The relative indirect costs to the economy of alternative energy scenarios, and the policies that will drive them, are often a key consideration for policymakers. The perceived and projected impacts of different nuclear scenarios on, for example, GDP and employment at the provincial and national levels in China will have a considerable impact on the acceptability of particular scenarios and policies. In practice, there are always winners and losers—for example, with regard to employment in different sectors and even regions—when policies are shifted, but the net impact of these changes is very hard to know in advance, due to policy- and non-policy-related shifts in the economy and technology (and in underlying costs and factor prices) shifts over time, and to the general uncertainty associated with any economic prognostication. In many macroeconomic studies of different energy scenarios, changes to GDP and employment by, for example, 2050 come out looking like large numbers, but are invariably swamped by the underlying combination of the size of overall GDP by a target year, and the uncertainties inherent in the analysis.

That said, there will be certain sectors that will doubtless win and lose to different extents between the three nuclear scenarios. The nuclear sector, and particularly firms and government organizations associated with advanced fuel cycles and reprocessing, will be the losers in the MIN scenario, and to a lesser extent, the BAU case, relative to the MAX scenario, while the renewable energy industries will benefit most in the MIN case. Coal mining income and employment will be reduced substantially in the MIN case relative to the other cases, though coal mining in China is becoming less labor-intensive in general, following the historical trend in the US and other places. In general, many studies have found that scenarios that focus on renewable energy and energy efficiency produce more long-term jobs and similar if not greater national and regional net income than scenarios focused on supplies of conventional and nuclear energy, but, as noted, there will inevitably be subsectors and industries that are winners and losers in any case relative to any other.

3.3.5 Energy Supply Security

The traditional concept of energy supply security, in brief, is that the more a country can source its fuel requirements from its own territory—or failing that, the more a country can draw for its energy needs from a diversity of domestic resources and imports from large number of trading partners—the more energy supply security is enhanced. Under that definition, the MAX case, which uses more nuclear power and less oil (the reduction being mostly due to electrification of the transport and other sectors) coal, and natural gas, is provides arguably more energy security than the BAU case. The MIN case, with more use of domestic resources (wind, solar, and energy efficiency) than the other two cases, arguably comes out on top in terms of energy supply security. Figure 3-6 shows the relative use of fossil fuels, both cumulative and for selected years, under each case. By assumption, in each case, uranium is sourced from the same ratio of domestic and foreign sources, though in principle, a higher proportion of domestic U could be used in the BAU and, especially, the MIN cases, given the lower overall U requirements.

Figure 3-6: Annual Fossil Fuel Use for Electricity Generation by Type and Year for Three Paths

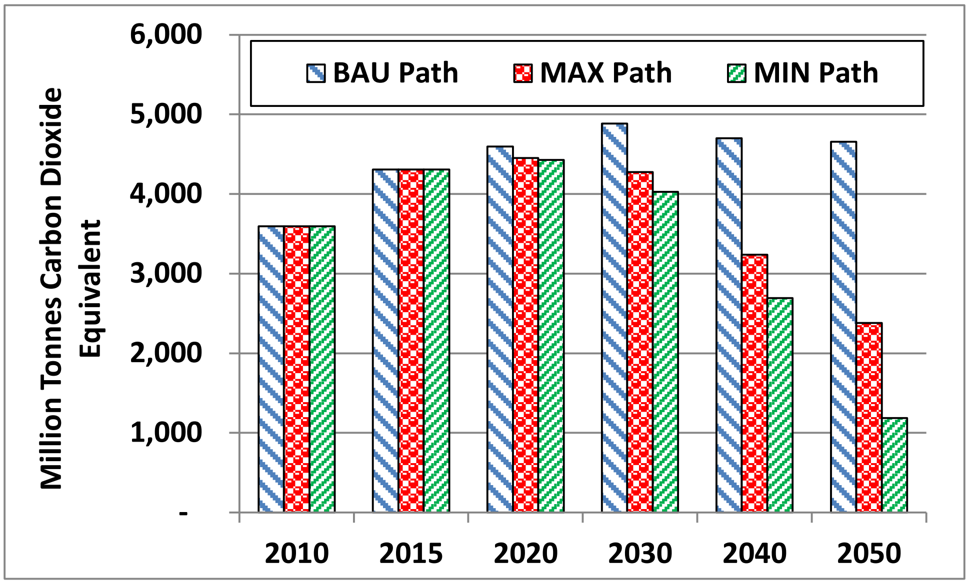


3.3.6 Environment

The environmental component of a broader concept of "energy security" includes comparing the performance of the three scenarios on the basis of emissions of greenhouse gas emissions, local and regional air pollutant production, water pollution, and disposal of nuclear-fuel-cycle related wastes. With respect to these criteria, the three nuclear paths described above yield the following quantitative and qualitative comparisons:

- The MIN path produces nearly 30 percent lower cumulative electricity generation sector (2015-2050) greenhouse gas emissions than the other BAU path, and in particular, as shown in Figure 3-7, produces a small fraction of the year-2050 emissions included in the BAU and MAX paths. Although the overall Chinese societal GHG emissions are the main concern here, and have not been quantified for this paper, the inclusion of additional electrification in the MAX path indicates that China's MAX-path GHG emissions will be considerably lower than in the BAU path, and emissions in the MIN path will be lower still.
- Likewise, though not directly quantified here, non-GHG air pollutant emissions of consequence to local and regional air quality will be less in the MAX path than in the BAU Path, with emissions in the MIN path considerably less in the other two cases, particularly by 2050.

Figure 3-7: Greenhouse Gas Emissions from the Electricity Generation Sector in China Under Three Nuclear Power Development Paths



- Because considerably less coal is used in the MIN and MAX paths than in the BAU path, water pollution from coal mines will be less in those paths. Thermal pollution from coal-fired power plants will also be less, though additional thermal pollution from nuclear power plants, some of which may be on inland sites (on rivers), may occur in the MAX path, relative to the other two paths. Additional water pollution and solid wastes from uranium mining in China and abroad will accrue in the BAU and, especially, MAX paths relative to the MIN path.
- The disposal of nuclear-sector-related waste streams will be much more of an issue in the BAU and, especially, MAX paths relative to the MIN path. Considerable HLW and intermediate and low-level wastes from reprocessing will accrue in the BAU and MAX paths, and China will need to find a final resting place for those materials, as well as for any spent fuel placed in long-term storage/disposal. Finding places to store/dispose of these materials may prove to be foci for political and social problems, as noted below.

3.3.7 Social and Political Criteria, and Military Security

During China's period of rapid economic growth, Chinese decisionmakers have typically given (or at least, exhibited) limited concern to the reaction of local populations in decisions on siting of key energy-sector facilities, relative to decisionmakers in many Western nations. Over the past decade, however, trends have suggested that the role of Chinese civil society in the siting of large and potentially polluting or dangerous facilities has been growing, at least in some ways. Very recent events have arguably suggested that civil society's voice in China may not continue to develop as some in the West might have hoped, though the impact of recent changes in

Chinese governance on the nuclear sector is not yet clear.[82] In general, paths, like the MAX path, that call for large, centralized, secure facilities for handling and managing nuclear materials may galvanize opposition to such facilities on the local and national levels, thus making those paths arguably less secure than paths like the MIN path, where energy needs are supplied by resources that are often tapped by facilities that are more distributed and each smaller and less obtrusive (and polluting) than the other two paths.

Additionally, the nuclear facilities (including enrichment and reprocessing, nuclear power plants, and spent fuel transport) that are part of the BAU and, particularly, the MAX paths will require much more in the way of military security arrangements than the MIN path. These military security requirements increase military costs and enhance the possibility of conflicts between the military security apparatus and a population becoming accustom to greater social and economic freedoms. The impact of required nuclear sector security arrangements will be mirrored, to some extent, by the greater needs to secure supplies of oil and oil transport lanes; the needs to secure oil supplies will be highest in the BAU case.

[82] See, for example, Chris Buckley and Adam Wu (2018), "Ending Term Limits for China's Xi Is a Big Deal. Here's Why", *The New York Times*, March 10, 2018, available as https://www.nytimes.com/2018/03/10/world/asia/china-xi-jinping-term-limit-explainer.html.

4 Conclusions

4.1 What Alternative Scenarios of China's Nuclear Future Tell Us

As of 2017, China arguably sits at a point of decision, inflection, or possibly both in the evolution of its electricity generation system, its nuclear power future, and possibly its energy sector as a whole. Scenarios of nuclear power development in China, including those presented in this paper and many others, span the range from modest growth to 80-100 GWe by 2050 (from about 34 GWe today) to projecting growth to 300 to 400 or more GWe of nuclear power by 2050, with the beginnings of commercialization of fast reactor technologies. At the same time, transitions are occurring for China's coal-fired power fleet, with plans for future new capacity being rapidly scaled back, and smaller, less-efficient units being taken out of service. The rethinking of plans for expansion of coal-fired power is in part in response to progressively more stringent policies to address local and regional air pollution, but also in response to the two trends, particularly in recent years, of accelerating deployment of wind and solar power, and reduced growth in electricity demand, the latter particularly in comparison to the double-digit growth rates of recent decades.

Developing internally-consistent scenarios of China's electricity sector in general, and the nuclear energy sector within the electricity sector, with the different scenarios designed to serve the same needs for energy services in similar economic futures, provides a means to test policy directions. China could choose a path including rapid deployment of LWRs with spent fuel reprocessing, blending the resulting plutonium into MOx fuel and subsequent use of same in LWRs and, ultimately, in a fleet of fast reactors. Or an explicit or implicit policy (for example, through adjusting levels of power sector subsidies) could damp down the current nuclear build-out after those reactors currently under construction are built, such that additions in the decades after 2025 are modest, while aggressively encouraging energy efficiency and the development of solar and wind power, plus the supply-side changes (transmission systems, smart grids, and electricity storage, for example) that would be needed to maximize renewable energy usability. The estimates of future fuels use, costs, pollutant and waste emissions, and accompanying (typically) qualitative consideration of issues such as the relative political and social security ramifications that result from consideration of different future scenarios provide a way of testing and illustrating for policymakers the different ways of organizing the energy future of a nation.

4.2 Prospects for Meeting China's Future Energy Needs with Limited ***or no*** Increases in Nuclear Capacity and Proliferation-resistant Fuel Cycles

The comparison of the BAU, MAX, and MIN paths for the Chinese nuclear and electricity sectors, considered together with the existing body of China scenarios work described (in part) in section 3.2 of this paper, suggests that it will be possible for China to meet its economic development, GHG and air pollutant emissions reduction, and other goals without an extended and massive build-out of LWR capacity, and without expansions of uranium enrichment or reprocessing capacity beyond those projects now underway. Further, although the MIN case implies that China will not become a major exporter of nuclear power technologies, it also implies that China will continue along its current trend of being perhaps a dominant provider of renewable power systems. Nuclear sector costs in the MIN Path are much lower, both on an aggregate basis and per unit of output, than in the other two paths, largely because of lower uranium, enrichment, and reprocessing costs. Although these costs are only a small part of the overall cost of providing energy services to the Chinese economy, indications from past experience and other studies is that the emphasis on energy efficiency and renewable energy will offer the opportunity for China to effectively address its environmental concerns without significant (if any) additional costs, relative to a reference path. Further, a path with less nuclear power and fewer front-end and back-end nuclear facilities will be arguably easier to deploy in a social and political sense, particularly as expectations for a stronger voice in how its future unfolds continue to grow among the Chinese citizenry.

The MIN scenario provides significant benefits over the other two cases in terms of plutonium production and stocks (transient and otherwise), and thus provides significantly lower risk of the proliferation of nuclear weapons.   For the MIN path to become a reality, policy support for energy efficiency and renewable energy will need to take precedence over policy support for nuclear power. Trends in recent years, including the slow-down in reactor construction and re-thinking of nuclear safety regulations post-Fukushima, ongoing structural change in the Chinese economy away from heavy industry (and much-reduced growth in electricity needs), and exceedance of even the ambitions government targets for renewable energy all point toward the enhanced practicality of a low-nuclear path for the evolution of the Chinese energy sector. Acknowledgement of the benefits of the MIN path (or similar) for China by international political and trading partners, probably including international policies that encourage such a path and embracing energy paths of their own that de-emphasize nuclear power, enrichment, and reprocessing, would likely serve to encourage China to move toward a low-nuclear future.

China arguably is at a point in marketing its nuclear technologies abroad in which its technologies are not particularly competitive—as they are based on older US and other Western designs—and it is facing a worldwide market for nuclear power that even a Russian reactor vendor has reportedly described as weak. If China's domestic market for nuclear power were to follow a trajectory more like the MIN path described above than the BAU or MAX paths, it seems likely that China's nuclear exports would be relatively de-emphasized. Building and maintaining the capabilities to export nuclear technologies, including to countries where nuclear weapons proliferation is a danger (or historical fact, as in Pakistan), will be technically and economically riskier and more difficult without a burgeoning domestic market to fall back on. As such, timely encouragement (including by example) of China by the US and the rest of the international community to focus on non-nuclear technologies for power generation could contribute to influences already in play and induce China to focus its efforts on exporting technologies that do not carry a weapons proliferation threat.