Hydropower in the energy transition and managing extreme hydrological events in China

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There is now overwhelming scientific consensus that a significant part of global climatic anomalies witnessed in recent years is caused by anthropogenic climate change. To help address this and to mitigate some of the most severe impacts of flooding, China plans to continue to add more hydropower capacity by constructing new dams at economically feasible and environmentally acceptable sites. This paper presents the personal reflections of the authors on the progress so far made by China and future steps to be taken.

China made a commitment at the United Nations General Assembly, in September 2021, that it will discontinue building coal-fired power plants outside the country, and accelerate its support for clean energy, both at home and abroad.

During the Earth Day celebrations of 2021, President Xi announced that coal-fired power generation projects will be "strictly controlled" and there would be a "strictly limited" coal consumption during the 14th 5-Year Plan. Thereafter, during the 15th 5-Year Plan of 2026-2030, both of these coal-related targets will be phased down.

During the UN Climate Ambition Summit, in December 2020, China advanced its earlier Nationally Determined Contribution (NDC). It increased its targets for 2030, for its non-fossil fuels component in primary energy consumption, from 20 per cent to 25 per cent, and made a commitment that its total installed capacity for solar and wind energy will exceed 1200 GW.

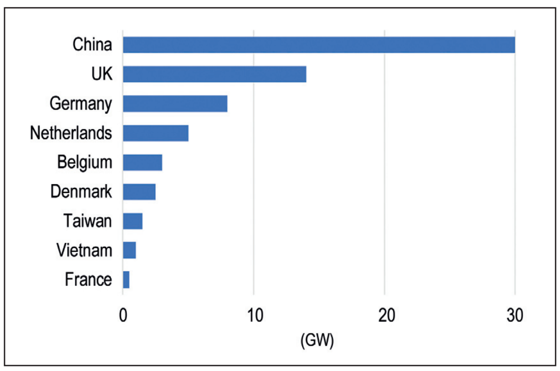

Fig. 1. Offshore wind operational capacity at the end of 2022 [Sparshott et al, 2023[7]].

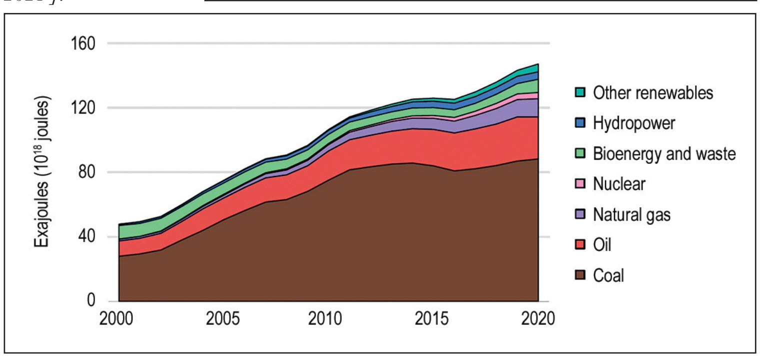

Fig. 2. Total primary energy demand by fuel in China [IEA, 2021[1]].

China has already made remarkable progress in significantly increasing its solar and wind energy generation. Its solar generation capacity has already exceeded 379 GW. This is more than the total generation capacities of the rest of the world . Its offshore and onshore wind generation capacity is more than 310 GW, roughly equal to the generation capacities of the next seven countries combined. Fig. 1 shows installed capacities of offshore wind generation operational capacities for the world's top nine countries or regions, to the end of 2022.

Current indications are China will have around 1270 GW of wind and solar generation by 2025, five years ahead of its 2030 NDC target, which was only announced in December 2020. This is mostly consistent with the Chinese records of not only meeting its planned targets within the stipulated time periods, but also exceeding them.

Hydropower in China

While the majority of global attention has been focused on China's rapid advances in solar and wind power generation, and justifiably so, hydropower has been the main generator of the country's renewable energy. For example, in 2020, by the end of the 13th 5-Year Plan, hydropower was the main source of renewable electricity generation, at 16 per cent of total national electricity production. It was followed by wind (6 per cent) and solar (4 per cent). China gave hydropower generation significant national priority, especially during the post-2002 period. It was much more than any other country in the world.

Hydropower has accounted for 35 per cent of its total renewable capacity additions between 2000 and 2020 [IEA, 2021[1]]. Two dams, Three Gorges and Xiluodu, significantly increased the country's installed capacities and outputs during this period. From 2000 to 2020, the share of hydropower in China's electricity production has steadily increased, as shown in Fig. 2.

Even with such an intensive plan to construct hydropower dams, China's need to transition rapidly to renewable sources of energy, from fossil fuels, means solar and wind energy will witness exponential growth to 2060, the target date before which the country is expected to reach carbon neutrality. Current indications are that, by 2045, solar energy will become the largest primary source of energy. By 2060, solar energy is likely to meet nearly a quarter of the country's total electricity demand.

Solar and wind power generation capacities of the country have increased very significantly since 2020 and they will continue to do so up to 2060. Together, they are expected to overtake total hydropower generation shortly after 2025. Even then, hydropower generation capacity is expected to increase by some 45 per cent during the 2020-2060 period.

Fig. 3 shows the contributions of different individual sources of energy generation for 2020, and how they are expected to change by 2030 and 2060, the two pledged target dates to reach peak carbon emission and carbon neutrality.

It is worth noting that globally, the western countries were leaders in dam construction and management until about 1980. However, during the period 1980-2000, there were considerable controversies in these countries on the benefits and the costs of large dams, including the nature of beneficiaries and who pays their social and environmental costs. There was extensive media coverage on these issues, some real but others ideological and fictional. They were mostly propounded by single-issue activist environmental and social NGOs. As a direct consequence of such consistent negative media coverages not only were fewer large dams built in the west, but also funding for research and development on dam-related issues mostly declined.

Meanwhile, China began to make heavy investments in the construction, operation and management of large dams, as well as in manufacturing the associated hydraulic machinery. Funding for research and development activities in academia and research institutions increased very significantly during the post-1990 period. This R&D emphasis on dam-related issues continues still today and is likely to continue for at least the next 15 to 20 years. With determined, serious and continuous efforts at improving dam design, construction, operation and management practices, and extensive construction of dams all over the country and also outside, by 2010, China had become a leading country in the world in building large dams economically, efficiently and quickly. Strong and sustained R&D support on dam-related issues has ensured China leap-frogged other countries on dams and hydropower development.

The global impacts of these enhanced Chinese efforts at dam building and financing can be gleaned from the following facts. Prior to 2000, Chinese state-owned enterprises (SOEs) had built only six dams outside the country. By 2020, it is estimated there were some 320 Chinese-built dams in more than 140 countries, with total hydropower generating capacities of around 81 GW [Buckley *et al*., 2022[2]]. The Chinese SOEs are now responsible for some 70 per cent of the global market in dam construction and associated hydraulic machineries. While a majority of these dams have been built in Asia, the Chinese SOEs have also been the major players in Africa and Latin America. They have, however, built a smaller number of large dams in the developed countries of Europe, North America and Oceania.

Construction of dams by the Chinese SOEs has encountered criticisms from several quarters because social and environmental issues were not given adequate consideration. A standard response to these criticisms has been that the SOEs have followed all the environmental and social regulations of the countries concerned. It is true that many developing countries may not have appropriate environmental and social regulations or guidelines, and/or capacities to enforce them properly. However, a better approach would be that at the very least these SOEs should follow similar guidelines as if these dams were built in China.

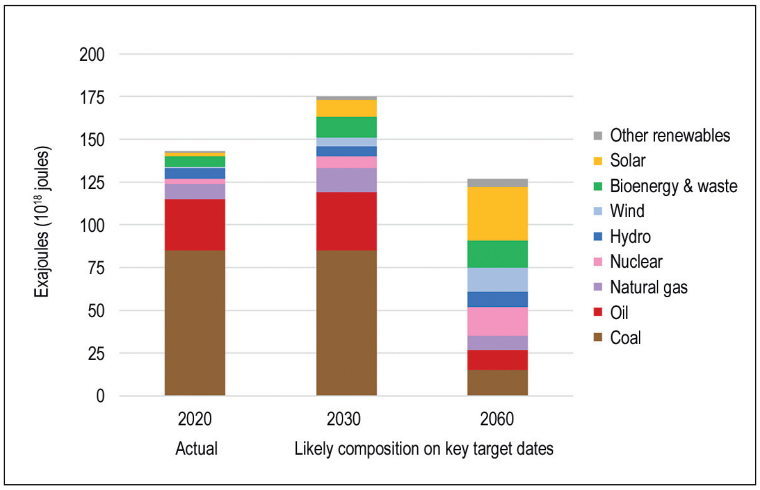

Fig. 3. Primary energy demands in China by fuel. [IEA, 2021[1]].

After the construction of the Three Gorges dam, one of the largest dams and hydropower projects in the world, and the knowledge and experience that were gained during this process, China's 13th 5-Year Plan very specifically targeted construction of hydropower dams in developing countries, specifically in Asia [NDRC, 2016[3]], as an important national economic activity. The Three Gorges Dam Corporation and its more than 20 subsidiaries, including China International Water & Electric Corporation (CWE), have been very active in dams and associated infrastructure construction outside of China. Two other SOEs have also been important players. They are PowerChina, with more than 70 subsidiaries, including Sinohydro Corporation, and China Gezhouba Group Corporation (CGGC) with more than 30 subsidiaries, including China Engineering Corporation, commonly known as Energy China. With strong and continuous national political and financial support, these companies have dominated and changed the global dam-building scene, especially during the post-2010 period.

Pumped storage in China

Pumped storage is going to play an ever-increasing role in the Chinese transition of electricity generation from fossil fuels to renewable sources. Currently, only about 14 per cent of hydro projects, of at least 75 MW capacity, are pumped storage. According to the estimates of the International Renewable Energy Agency (IRENA), 420 GW of pumped storage will be needed by 2050 in China, if its electricity generation and carbon emission targets are to be met.

At present, the three countries having the largest operational pumped-storage capacities are China (50.7 GW), Japan (23.7 GW) and the USA (21.6 GW). No other country has more than 10 GW. This is shown in Fig. 4.

China currently accounts for about 30 per cent of global pumped-storage capacity. This percentage share is approximately equal to the pumped storage capacities of all European countries. The National Energy Authority of China published its mid- and long-term plans for pumped storage in 2021. The targets for PSH

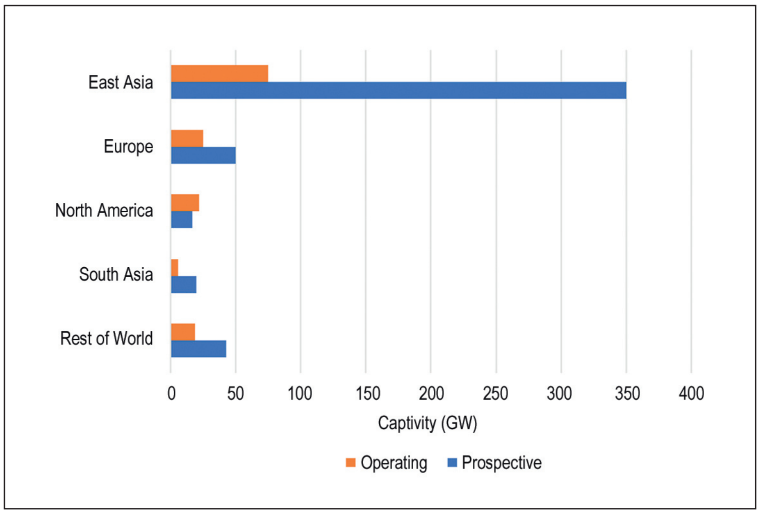

Fig. 4. Pumped storage capacity for selected regions and subregions [Bernardi and Wu ,2023[4]].

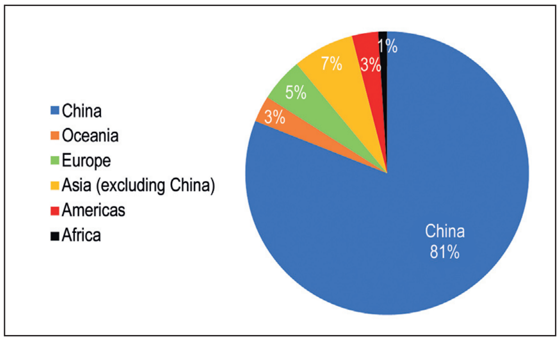

Fig. 5. Prospective global distribution of pumped storage [Bernardi and Wu ,2023[4]].

are at least 62 GW by 2025, 120 GW by 2030 and 305 GW by 2035. Based on the projects under construction at present, the country is likely to have 75 GW of pumped-storage capacity, which means it is likely to exceed the 2025 target by nearly 20 per cent.

Currently, about 16 per cent of China's hydropower is pumped storage. However, this is highly likely to change very substantially in the future as the construction of new conventional hydropower plants start to decline. Concurrently, the construction of new pumped storage is expected to accelerate very significantly in the coming decades. Global Energy Monitor [2023[4]] estimates that pumped storage is likely to account for around 86 per cent of new prospective capacities. They further estimate that China would represent 81 per cent of the prospective pumped-storage capacities of the world, followed by 7 per cent for the rest of Asia, excluding China, and 5 per cent in Europe. The likely prospective global pumped storage development is shown in Fig. 5.

Dam building and employment generation

The Chinese dam-building SOEs have successfully exported the country's expertise all over the world. This has contributed to an important, but implicit, objective of dam building for the country, namely employment generation. Not surprisingly, Chinese-designed and constructed dams have sourced all their hydraulic machinery requirements from Chinese manufacturers. This has further boosted the country's employment generation. The companies are likely to continue playing important roles in dam construction and financing in the developing world for at least the next two decades, and thus continue to boost the employment potential of the country.

China's dominance in hydropower dams and also solar and wind energy and electric vehicles and their batteries, is the result of sustained and strong national policies and financial incentives and support over the long-term. The scientists in the Bell Laboratories, USA, may have first invented practical photovoltaic cells in 1954, and the first solar commercial farm was built near Hesperia, California. However, solar power generation was not a viable large-scale option until after 2000 when China decided it was a national priority and devoted a significant amount of resources over many years to make solar energy commercially viable and cost-competitive with electricity generated from fossil fuels. As a direct result of this policy, China's share of global solar panel production is now 80 per cent.

Similarly, with strong and sustained policy and financial support from the central and provincial governments, China had a 70 per cent share of global wind energy generation growth, compared with 14 per cent for the USA and 7 per cent for Brazil, in 2022.

Strong national policy and financial support have also helped China corner the global electric vehicles market. Nearly 60 per cent of global electric vehicle sales, in 2022, were in China. More than half the electric vehicles on the road in the world at the end of 2022 were in China. The dominance of China is such that only two Chinese companies currently manufacture more than 50 per cent of electric car batteries of the world.

Dam construction by Chinese companies abroad has similarly benefited from strong national policy and financial support, mostly during the post-2005 period. As noted earlier, China now has 70 per cent of the global market for dam construction. Its strong R&D support in this area, and extensive construction and operation of dams, have meant it now has huge knowledge and expertise in this area. Regrettably, since very few people outside the country speak or read Chinese, some recent Chinese advances in dam design and construction are not universally known, as is the case for advances in sensors, robots, digitalization, big data analytics and artificial intelligence for improvement of the operational management of hydroelectric dams. China has nurtured a new group of people who specialize in the intelligent operation of dams. This has already given the country an edge in educating and training new types of specialists for intelligent operation of dams.

On the negative side, a criticism the Chinese companies have faced is that an overwhelming percentage of their construction workers are Chinese, and thus these turnkey construction projects do not contribute much to local employment generation and capacity building. This is a valid issue that needs to be addressed in a satisfactory manner in the future.

The idea of dam construction as an important means for employment generation on a large scale is not new. It originally came from the USA, some 70 years ago during the Great Depression. President Roosevelt, shortly after his election, decided to use the construction of dams to create much-needed employment all over the country. It was an important component of his policy to move unemployed Americans out of poverty rapidly, and make them economically self-sufficient and productive members of society. It became a very effective and successful policy. Under President Roosevelt's leadership, America began a golden age of dam construction. Major dams like Grand Coulee and Hoover were constructed during the 1930s. The Tennessee Valley Authority (TVA) was created in 1934 to provide water and electricity in the economically impoverished Southeast region and to provide flood control. All these activities generated hundreds of thousands of jobs which was one of the principal reasons as to how the USA managed to move out of the Depression.

Two major institutions were responsible for the construction of dams, reservoirs, canals, tunnels, power plants, pumping stations, transmission lines and other associated works in the USA. They were the Bureau of Reclamation and US Army Corps of Engineers. Because of this extensive construction of hydraulic infrastructures both these two institutions amassed a great deal of knowledge in planning, design, construction and operation of all types of hydraulic structures.

While during the 1950s and 1960s American private sector companies built several hydropower dams in various parts of the world. These efforts were not supported as extensively by national policies and financing over a long period, as China has done during the post-2005 period. Lack of strong and continuous political and financial support in the USA after Roosevelt's presidency meant that the golden age of dam construction in the country was basically over by 1955.

Similarly, India started a major dam-building effort with the Bhakra-Nangal project and Hirakud dam during the 1950s and 1960s. Jawaharlal Nehru, the first Prime Minister of India, called Bhakra and Nangal dams 'temples of modern India.' While the Indians gained considerable expertise in the design and construction of such large hydraulic structures, unfortunately, there was no national policy as to how the different expertise obtained during their planning, design and construction could be successfully used for other similar structures which were built later, either in India or South Asia. Unfortunately, India lost a golden opportunity to establish and sustain its dam design and construction expertise because of a lack of any consistent and coherent national policies.

Up to, probably, 1990, India had better knowledge and expertise in planning, design, construction and operation of large dams than China. By 2000 the situation had completely reversed. China overtook India not only in terms of economic and social development but also in activities like the construction and operation of large dams. In retrospect, unlike China, India missed important opportunities for employment generation and also economic development.

Unfortunately, even now, in most countries, policymakers and professionals dealing with dams have not seriously considered employment generation as an important byproduct of the construction of dams. Dam construction, like all other types of major infrastructure developments, not only contributes to employment generation but also helps to advance regional economic and social development.

Importance of hydropower during the era of climate change

Pre-2015, the main reasons for China's breakneck dam construction were electricity generation, reliable supply of water for domestic, industrial and agricultural purposes, and flood control. This changed after 2015 when its policymakers started to realise that because of climate change, heavy floods and extreme droughts are likely to occur more frequently in the future, and their intensities and durations are going to be higher. Thus, intelligent operations of storage reservoirs can significantly reduce their potential impacts. They also could play important roles in enhancing food, energy and environmental securities, contribute to national economic and social development and assist in energy transition from fossil fuels to renewable sources. These are all major benefits.

The Chinese policymakers have also realised that if all these diverse objectives have to be met successfully in the future, existing and future dams alone will not be enough. Their operation and management practices have to be significantly improved to meet future uncertainties the country would face as a result of global warming. This will contribute to more extreme hydrometeorological events which are likely to be more frequent, intense and longer duration. This will further increase management uncertainties. Water infrastructure like hydropower dams and their intelligent operation can significantly reduce management uncertainties of hydrometeorological hazards.

Sensors, digitalization and big data analytics

To reduce the impacts of future hydrometeorological hazards, it will be essential to collect extensive hydrological, meteorological, terrestrial and oceanic data, which have to be complemented with high-resolution pictures and sound, satellite imagery and other related data and information. These millions of data points need to be instantly analysed and actionable results have to be produced. This requires people with specialized knowledge and experience in big data analytics and computers with ever-increasing data-crunching abilities.

Sensors, robots, all types of conventional hydrological and meteorological instruments and satellites, are only some means through which massive amounts of data can be generated. These could be used to make water management more efficient and effective. Nearly 90 per cent of data in the world has been generated during the past two years [Biswas and Tortajada, 2023[5]].

Satellites, sensors, robots and other means for data collection are already producing massive amounts of data for water management of China. These have to be analysed in real-time so that immediate appropriate management decisions can be taken to continually improve water management practices and processes.

Digitalization and hydroinformatics can feed information generated and knowledge obtained from analyses of millions of data points to make water management processes more timely, efficient, cost-effective and relevant. Data-driven management and the formulation of new and innovative models can lead to significantly improved solutions than has been possible previously. New knowledge and insights into complex water management problems can be obtained from massive amounts of data that are currently being collected in China.

Such extensive data management will require that water institutions must train, recruit and retain experienced personnel who can distil and translate important information that could emerge from big data analytics. These findings, in turn, have often to be promptly used to manage the systems efficiently and effectively, especially as uncertainties will further increase in the future.

Some Chinese hydropower institutions are already successfully using all types of new operational models and data-driven management practices, based on massive amounts of data that are being collected and immediately organized. One that is probably in the forefront of all such institutions is Dadu River Hydropower Authority.

Dadu River Hydropower Authority

The Dadu River Hydropower Authority has constructed and will be constructing a cascade of 28 dams in the mountainous region of Sichuan Province. The Dadu river is a tributary of the Yangtze river and has the fifth largest potential in China for developing hydropower, at 34.59 GW. The river has a natural drop of 4175 m. This will be harnessed by the 28 dams, one of which will be Shuangjiangkou dam. When this dam is completed in 2024, it will be the highest dam in the world, at 314 m. This dam alone will save carbon emissions of 7.18×10^6 tons each year. When all these 28 dams are complete, they will collectively generate 115 800 GWh/year. They will also play major roles in managing heavy floods and prolonged droughts in the Basin [Biswas and Tortajada, 2023[6]].

The Authority is now extensively using sensors, robots, high-definition pictures and sound, Internet of Things and mobile internet, to collect, transmit, store and analyse the data instantly. High-definition photographs and sound systems, backed by collected data, enable the Authority to conduct remote scene monitoring. Such technological breakthroughs have allowed it to realistically simulate physical on-site inspections. As of 2021, the Authority had 22 948 risk-sensing points on the back slopes of dams and reservoirs, and also had hundreds of thousands of locations that were being monitored by 350 different types of instruments. The Authority has developed 128 common fault monitoring indexes for turbines, generator rotors and transformers.

The net operational results of this extensive digitalization of all types of data, their analyses and management reforms have been impressive. Between 2014 and 2021, the number of hydropower plants in operation increased from 5 to 9, and total installed capacity more than doubled, from 5.6 to 12 GW. This was achieved with a reduction of employment from 2498 to 2148. In other words, even though the installed capacity more than doubled, the total number of employees was reduced by 14 per cent. The productivity of the workforce increased by 75 per cent. The net result was the Authority's profits increased by 35 per cent. These are impressive results by any standard.

Such remarkable progress needed fresh talents, having special expertise in new areas like big data analytics, and also new types of decision managers. More than 300 employees were retrained in digitalization-related work and analyses. The Authority established a big data service company, with new jobs in data analyses which are at the heart of all intelligent operations. The staff of the Authority is continually innovating. This has contributed to new knowledge management practices, including developments of state-of-the-art operational algorithms, as well as continually improving the existing ones and the Authority's operational practices. Extensive use of sensors, robots and artificial intelligence has given the Authority unprecedented new skills for problem-solving and provided it with new and innovative tools to continually improve its operational and management processes and practices.

In addition to all these achievements, the Authority has succeeded in managing extreme hydrological events because of the major technological and management advances it has made. A typical example is how they managed a 1 in 100 year flood in 2020. In early August, the Dadu River Hydrometeorological Centre predicted heavy rain would fall during 12-18 August. Their model indicated that the flood peak downstream of the Gongzui power station could exceed 12 000 m^3/s. Three days before the flood was expected, the Authority released significant quantities of water from the Pubugou reservoir. Thus, when the heavy flood arrived, on 18 August, the reservoir managed to store 500×10^6 m^3 of flood water. As a result, the peak flow from downstream of the Gongzui power station was reduced from an expected 12 600 m^3/s to 7500 m^3/s. This meant, with proper infrastructure and good timely management, a 1 in 100 year catastrophic flood was reduced to an average flood.

Because of global warming and climate change, China expects extreme rainfalls more frequently, which would result in heavy floods. To reduce their impacts, not only more large dams are needed but also, they must be managed with the best management practices available, as the Dadu River Hydropower Authority has shown.

The future

Predicting the success of China's energy transition process, and how successfully it will be able to manage the adverse impacts of heavy floods and prolonged droughts, is difficult. It will depend on many factors, among which are: country's policies on various aspects that would drive the transition processes for the next three decades, and their timely implementation; how successful each of these policies is going to be; geopolitical situations, especially overall relations with both the western and developing countries; the results of China's enormous research and development efforts and their effectiveness and timescales when the breakthroughs may occur; and, whole sets of other issues on which at present there is at best limited visibility. However, even with these limitations, it is possible to make some predictions with considerable certainty.

First, China will start restricting its fossil fuel consumption from the 15th Five-year Plan, starting from 2026. Even during the past decades there have been some interesting developments on China's coal-fired powerplants. Because of the country's extremely rapid economic development over the past two decades, the average age of its coal plants is only 13 years, compared with more than 40 years in the USA and around 35 years in Europe [IEA, 2021[1]]. Operational lifetimes of Chinese coal-fired plants are also much lower, at around 25-35 years, compared with 40-50 years globally. IEA [2021[1]] estimates that around 1850 GW of coal-fired are likely to be operating in 2030, of which 950 GW is expected to be in China.

Since China's coal-fired plants are younger in age, and their lifespan is shorter than the rest of the world, the Chinese plants tend to be more efficient compared with their global counterparts, including for carbon emissions. In addition, most of the new ones that are being constructed are likely to be decommissioned by 2055, well before the deadline of 2060 when China has pledged to be carbon neutral.

Second, China will continue to spend significant resources on research and development to maintain its pre-eminence in the areas of solar and wind energy generation, construction and operation of hydropower dams, electric vehicles as well as their batteries and high-speed trains. These mean the country is likely to retain its edge, compared with the rest of the world, in all these areas.

Energy transition from fossil fuels to renewable sources will be a long-term process, and will cost the country trillions of dollars. Based on the authors' personal discussions with high-level Chinese policymakers, we are convinced that the country will continue with its determined attempts to allocate very substantial resources on a long-term basis, to selected areas where it may be able to carve out globally dominant roles. These could include many emerging areas like carbon capture and storage, hydrogen energy, and so on. Given the current geopolitical tensions with western nations, China is likely to make determined attempts to develop new and innovative cost-effective technologies in as many aspects of energy transition process as possible.

There will be intense competition between the countries for dominance in specific areas. However, China is likely to have an edge because of the enormous resources it has access to, and, for the most part, is likely to support R&D activities for a much longer period compared with its competitors.

Third, while the transition to solar and wind energy will reduce China's carbon emissions, this will not help the country to deal effectively with extreme hydrological events, like prolonged droughts, high floods or intense typhoons. Hydropower and dams can provide the country with both clean energy and means to deal with such extreme events. In addition, the dams constructed will concurrently provide the country with a reliable source of water for domestic, industrial and agricultural purposes.

Finally, pumped-storage schemes will provide the country with a base load whenever needed. In contrast, solar and wind generation can only generate electricity when the wind is blowing and the sun is shining. Thus, hydropower and dams have several additional advantages over solar and wind energy.

Fourth, science and technology behind weather forecasting have improved very significantly during the post-1970 period. Computing capacities have gone up exponentially, and the costs of computing have come down remarkably. Advances in both computing capacities and numerical modelling techniques have been very significant during the past two to three decades, as well as the data that are available to validate and fine-tune the models. As a result, the five day rainfall forecasts are now as accurate as the two day forecasts were some 15 years ago.

With a reliable five-day forecast for heavy rainfall in a region, it is now possible to forecast the timings and magnitudes of serious floods that may impact specific locations. Using this information, water from reservoirs can be released in anticipation of the high flood flows that would be forthcoming from heavy rainfall. This will create space for the storage of excess flood water in the reservoirs. Hence, river flows downstream can be controlled so that the heavy floods upstream of the dam could be reduced to a 'normal' flood downstream. This is exactly what the Dadu River Hydropower Authority did to manage its 2022 flood, as mentioned earlier.

As computer capacities increase and significantly more data are obtained from satellites, balloons, aircraft, ground hydrometeorological stations and ocean buoys, the predictions of numerical models will become progressively more accurate. It is now estimated that 90 per cent of data available in the world have been collected during the past two years. For example, consider the data centre of the European Centre for Medium-Range Weather Forecasts (ECMRWF), in Bologna, Italy. It receives more than 800 million data observations each day, which it analyses. This would not have been possible even a decade ago. Good and accurate models have high demand for reliable data. The amount of data available will increase very substantially in the future.

There have also been some new and exciting developments on the horizon. To formulate a reliable numerical model, analysts must have a good understanding of the physical processes that determine the weather. Unfortunately, the atmosphere is a chaotic system which is still not well understood by scientists.

In contrast, machine learning, a form of artificial intelligence, analyses billions and billions of data points and searches for patterns from historical datasets. Huawei, a Chinese company, has formulated an artificial intelligence (AI) system, called Pangu-Weather. Based on 39 years of data, this system can make seven-day meteorological forecasts which are as reliable as can be obtained from numerical models. However, Pangu-Weather can make forecasts that are thousands of times faster than made by ECMRWF.

Based on the current developments and trends, it should be possible to forecast future extreme rainfall and flood events weeks in advance, rather than days as at present. This would give managers of hydropower dams more time to manage the heavy floods effectively.

While there has been good progress in flood forecasting, commensurate progress in drought forecasting is still at its infancy. Currently, we simply do not have enough knowledge to predict the onsets and ends of droughts and their severity. It may require another two decades before reasonably reliable forecasts of droughts can be made.

Transition to a zero-carbon world will be a difficult and complex process. To achieve this goal, it will be essential to have many scientific breakthroughs over the next two decades. No one can predict when these breakthroughs may occur, or how effective they could be. Thus, progress during the next two to three decades is not certain. The world, including China, will continue to face these risks and uncertainties for some time to come.

However, in terms of becoming carbon neutral before 2060, China has made several major commitments, over short, medium and long terms. In many cases, it has outlined the pathways by which these targets are likely to be

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met. All the current indications are that the country will meet most of its short-term objectives well before the target dates. For the long-term commitments, success of China, and also for other countries of the world, will depend on several major scientific and technological breakthroughs which are likely to occur after 2030. Until then, our crystal balls for forecasting the future will remain cloudy. There are reasons to be cautiously optimistic but no one can predict when such breakthroughs will occur. ◊

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