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Yet Another First Concrete

On February 25, first concrete was poured for Tianwan NPP Unit 8 constructed with the participation of Rosatom. In China, the Russian nuclear corporation builds four reactors, two at Tianwan and two at Xudabao. We will take this opportunity to cover the latest news from the joint projects in China.

Three out of four reactors are already under construction while preparations are ongoing to build the fourth reactor, Xudabao Unit 4. General contracts for the construction of two reactors at Tianwan and two at Xudabao were signed in March 2019 and June 2019, respectively. Tianwan Unit 7 is expected to be put in operation in 2026, followed by Tianwan Unit 8 and Xudabao Unit 3 in 2027 and Xudabao Unit 4 in 2028. All four reactors will be built to the Russian Generation III+ VVER-1200 design.

"We set up a design supervision team at the Tianwan site. The team will review documents and supervise what the Chinese customer and its subcontractors do," says Valery Kedrov, Director for VVER-based NPP Projects in China at AtomEnergoProekt (part of AtomStroyExport). As set out in the general contracts, Rosatom produces a design of the nuclear islands and supplies key equipment and machinery for two units at Tianwan. At Xudabao, the Russian nuclear

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corporation will deliver the same scope of work and also provide design supervision, installation and commissioning services.

"Russia and China have been working together on the construction of nuclear power plants for many decades. We know and value each other as effective partners, good friends and allies in major strategic projects," says Alexey Bannik, Vice President for Chinese projects at AtomStroyExport.

Construction, production of equipment and installation works are running full tilt. In January 2022, the work started at Tianwan Unit 7 and Xudabao Unit 3 to install core catchers. Their tanks, each weighing 156 tons each, are already in place. The total weight of a core catcher exceeds 800 tons.

Designed by Russian engineers, it is one of the reactor's passive safety systems that prevents radioactive materials from being released into the environment in case of a core meltdown by retaining liquid and solid fragments of the corium and reactor structures. The first ever core catcher was installed at Tianwan NPP Unit 1.

In early January 2022, AtomEnergoMash (Rosatom's power engineering division) began to manufacture pipe sections for the primary coolant loop to be installed at Tianwan Unit 8. Having a total length of 146 meters, the pipes connect systems and equipment that belong to the plant's primary loop, such as the reactor, steam generators and primary coolant pumps. The pipe sections have been tested, machined and plated from inside to prevent corrosion. Primary coolant pipes for Xudabao Unit 3 and Tianwan Unit 7 have already been plated. The next step is to make pipe assemblies.

Last year, AtomEnergoMash began to assemble primary coolant pumps for Tianwan Unit 7. These pumps ensure coolant circulation in the primary circuit at the pressure of about 160 atm and temperature of 300 °C. Each reactor unit is equipped with four primary coolant pumps.

Representatives of the customer, Jiangsu Nuclear Power Corporation (JNPC), visited the plant when the assembly process started. At present, the work is continuing. Assembly of the reactor pressure vessel for Tianwan Unit 7 is also on track.

Construction of VVER-based nuclear power units is far from being the only area of cooperation between Russia and China. Rosatom also takes part in the development of CFR-600, a 600 MW pool-type sodium-cooled fast neutron reactor. Rosatom's power engineering division will supply heat exchanging units (16 evaporators and as many superheaters) for the steam generators of CFR-600. TVEL (Rosatom's nuclear fuel division) will also supply fuel for the first load of CFR-600 and reloads during the next seven years. Deliveries are scheduled to begin in 2023.

Last summer, representatives of China National Nuclear Corporation (CNNC),

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the CFR-600 project owner, visited ZiO Podolsk (part of AtomEnergoMash), which manufactures equipment for CFR-600. They were demonstrated production processes and quality management systems.

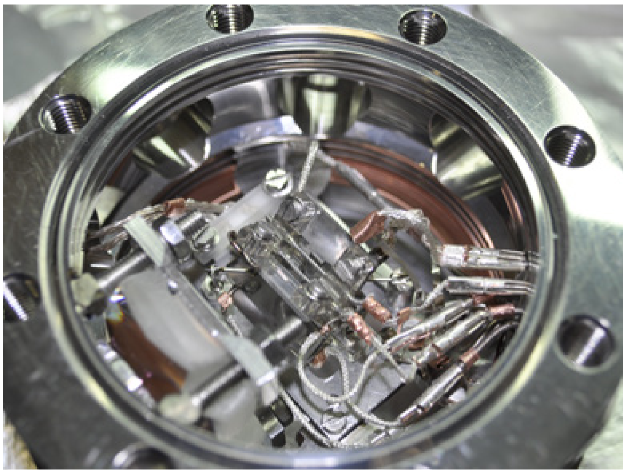
Construction of CFR-600 started in December 2017. It is expected to be launched in 2024. This is the second fast neutron project in which China and Russia cooperate. The first one was CEFR, a 20 MW fast neutron reactor built in 2010 at the Nuclear Power Institute of China with the participation of Rosatom.

Research is another area of cooperation between the countries. Rosatom's Research Institute of Atomic Reactors (RIAR) will conduct in-pile tests and post-irradiation analysis of graphite samples for China's Fangda Carbon New Material Co.

AtomStroyExport (ASE) is Rosatom's engineering division, which is a global leader constructing most of the nuclear power plants abroad and having the world's largest portfolio of nuclear construction contracts. The division is active in Europe, Middle East, North Africa, and Asia Pacific.

AtomEnergoMash (AEM) is Rosatom's power engineering division and one of Russia's largest power machinery producers providing comprehensive solutions in design, manufacture and supply of machinery and equipment for nuclear, thermal, petroleum, shipbuilding and steel-making industries. Its production facilities are located in Russia, the Czech Republic, Hungary and other countries.

Nuclear researchers also collaborate in the social sphere. For instance, Russian and Chinese women working in the nuclear industry took part in a video conference organized during the 3rd Eurasian Women's Forum that was held in Saint Petersburg in October 2021. Among them were female employees of the Jiangsu Nuclear Power Corporation and TVEL's subsidiary Elemash. They spoke about the challenges faced by the women who choose nuclear career, what motivates them to continue their work and what practices exist in the companies to engage women into research and engineering.



Level Up with Ququarts

Russian researchers have developed a two-qudit quantum processor. It is equivalent to a four-qubit quantum computer, a system of four ions that have two potential states each. The development of a quantum processor is the key task supervised by Rosatom within the Quantum Technology roadmap framework.

The Quantum Technology roadmap provides for the development of quantum processors using superconductors, cold atoms and photons. The joint laboratory of the Lebedev Physical Institute of the Russian Academy of Sciences (LPI) and the Russian Quantum Center focuses on the use of ytterbium ions as the most promising technology for a quantum computer.

Each of two ions manipulated by the researchers is a ququart, that is, a qudit for which the number of possible states is four.

A qudit is a qubit that has three or more potential states (or levels). It can be visualized as a multi-story building. **"Transition from one state to another is a change in the ion's electron shell. The wave function of the electron shell changes, too,"** says Ilya Semerikov, a researcher at LPI. It is the qudits that are the key achievement of the laboratory.

A qubit is a minimal piece — or a bit — of information in the quantum universe. A bit, which is a unit of information in an ordinary computer, can only have one of two values (states) that are represented as either 0 or 1, but a qubit can also exist in a superposition of these two states. This means a qubit can simultaneously have the value of 0 and 1 during the computation process.

Physically, a qubit is a system of two states, one being the logical 0 and the other 1.

Each state of a ququart can be represented as either of four potential states of two qubits (00, 01, 10 or 11). **"If we take two ions in the state of 1 and 4, then the equivalent state of a four-qubit system will be 0011, while the ions in the state of 2 and 3 will have an equivalent of 0110,"** Ilya Semerikov explains. Such a computer can run simple algorithms, for instance, those of Deutsch–Jozsa and Grover. The former is used to determine the type of function (either constant or balanced), while the latter performs unstructured search in a database.

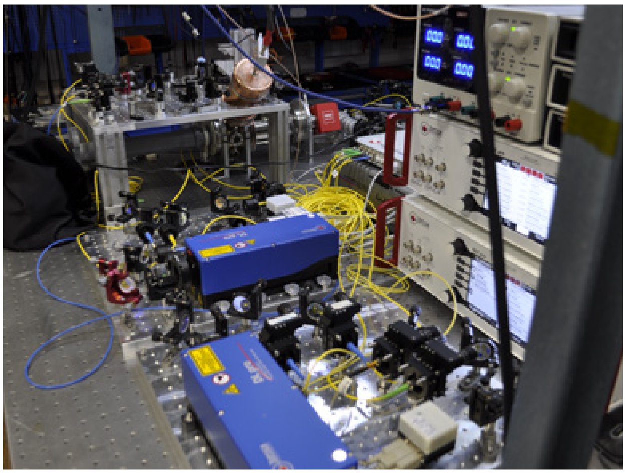
"The ion-based platform yields very promising results, which is quite noteworthy as ions were not considered a priority field of study as short as five years ago. This is our first notional result in quantum computing within the roadmap framework," says Ruslan Yunusov, Head of the Quantum Technology PMO at Rosatom.

What's next

One of the tasks going forward, which is studied by researchers, is to entangle several qubits. Entangling means that the state of an ion changes in dependence to the state of another. For this reason, it is not the number of elements in the system that matters but their possibility of performing together. Russian researchers managed to entangle two ququarts using the Mølmer–Sørensen method developed in the early 2000s. The method is based on the laser-induced excitation of fluctuations in a trapped-ion system. Correlated fluctuations of ions in a trap serve as a kind of a data bus to transfer quantum information between particles.

Another task is to create a cloud-based platform that will give access to the quantum processor prototype. The first remote experiments have started, but interfaces need to be aligned for a full-fledged integration. This work is planned for 2022 and will be done jointly by researchers from Rosatom and the Russian Quantum Center.

The third task is to improve fidelity (probability of correct calculations). This parameter is currently 66% for two-qubit operations and 85% for qudit



operations. **"Taking into account our capabilities and also the fact that this is our first approach to the problem, we have received encouraging results that enable us to proceed to optimizing the quality of operations,"** LPI Director Nikolai Kolachevsky said at a meeting of the Quantum Technology Scientific Council of the Russian Academy of Sciences last December. To compare, the teams of IonQ and Quantinuum, leaders in ion-based quantum computing, are testing processors with 10 to 20-ion qubits in each. Fidelity of their operations has exceeded 98%.

Market context

The quantum computing market is at the nascent stage. It is hardly possible to estimate its size yet as expert estimates differ substantially, ranging from USD 38 million to USD 320 million. It is assumed that the market will reach USD 1–2 billion in the next five years and might grow to as large as USD 450–850 billion within the next 15 to 30 years.

Quantum computing attracts attention from both national governments and private companies. Large investments in quantum technology have formed a clear trend over the last few years. According to the Development of Certain High Technologies white book published by the Higher School of Economics (Russia) in 2022, two thirds of the total investments were made after 2018. In 2021, two 'quantum unicorns' hit the market. The value of American IonQ is estimated at USD 2 billion, while the market cap of UK-based Arqit is USD 1.4 billion.

Meanwhile, Russia lags behind global leaders (US, China and Germany) but puts much financial, administrative and scientific effort in shortening the distance. For instance, Russia accounts for over 4% of research papers globally and ranks eighth by the number of patents issued in the quantum field. In addition, the Russian Quantum Center and the Moscow State University launched two pilot cloud-based services for quantum computing in 2021.

Also in 2021, Rosatom invested over RUB 6 billion in the development of quantum technology and research infrastructure. The money was spent to purchase laboratory equipment and materials. It is planned that a total of over RUB 23 billion from government funds and other sources will be spent on the development of a quantum computer by 2024. The result of these efforts will be a cloud-access multi-purpose quantum computer to be put in operation by the end of 2024.

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Minerals for the Good

Bringing together Rosatom's mining projects in Russia, ARMZ Group plays a crucial role among divisions of the Russian nuclear corporation. The group is engaged in the uranium and gold mining operations, exploration of complex ores, and production of rare metals and rare-earth minerals.

Uranium

ARMZ is a Top-10 uranium producer worldwide, according to the World Nuclear Association. In 2020, the company produced 2,846 tons of uranium, or 6% of that year's global output. The data for 2021 will be disclosed in the annual report of the Russian nuclear corporation. Meanwhile, the yearly press release published by ARMZ says the company outstripped the uranium production target by 5%. All the uranium mined by ARMZ is supplied to Rosatom's nuclear fuel fabrication facilities, covering about 50% of its total demand.

ARMZ Group comprises three uranium mining plants located in Russia. They are Dalur (Kurgan Region), Khiagda (Republic of Buryatia), and the Priargunsky Industrial Mining and Chemical Union (PIMCU, Zabaykalsky Krai).

Dalur and Khiagda mine uranium by in-situ leaching (ISL), which is the most costefficient and sustainable mining process. PIMCU cannot employ the same process due to specific properties of the local ore and uses underground mining methods instead.

The three companies continue carrying out exploration activities, increasing mineral reserves and building new production facilities. As an example from 2021, Khiagda launched uranium production at its Kolichkan deposit, and Dalur completed preparations for the development of Dobrovolnoe deposit. It is assumed that Khiagda will begin to develop at least one more deposit in 2022, while Dalur will start pilot production operations at the Dobrovolnoe deposit. PIMCU continues to build Mine No. 6 to develop Argunskoe and Zherlovoe uranium deposits, which have enough reserves to supply U3O8 production facilities with uranium for 30 years. The mine is expected to be launched in 2026.

Rare metals and rare-earth minerals

ARMZ supervises the Russian industry of rare metals and rare-earth minerals pursuant to the New Materials and Substances Technology roadmap.

Not long ago, Tugansky GOK mining plant was put in operation in the Tomsk Region (Western Siberia). With Rosatom holding a 25% stake in the plant, it produces zirconium, ilmenite, rutile and leucoxene concentrates from the feedstock coming from the Tuganskoye deposit. Its current processing capacity is 575,000 tons of ore sand per annum and can be expanded in the future. The decision regarding capacity expansion will be made in 2023. The zirconium concentrate will be supplied primarily to the Chepetsk Mechanical Plant

(part of Rosatom). The ilmenite concentrate containing titanium will be purchased by VSMPO-Avisma, a Russian manufacturer of titanium sponge. Later, the priority buyer of this material will be a titanium dioxide manufacturing plant, which is being constructed in Seversk by Rosatom's nuclear fuel division TVEL.

Dalur manufactures scandium as a by-product. In 2021, the company produced over 500 kg of scandium oxide and over 200 kg of aluminum scandium alloys. Its target is to bring the output up to one ton of scandium oxide per annum and make a decision of whether to expand the production of alloys.

Thanks to Rosatom's regulatory improvement efforts, it was made possible to begin construction of an extraction plant at the Tomtor deposit. It is the world's third largest deposit of rare-earth minerals, according to the plant co-owner Polymetal. According to initial estimates, reserves of the Tomtor deposit amount to 11.4 million tons of ore, including 0.7 million tons of niobium oxide (2% average grade) and 1.7 million tons of rare-earth mineral oxides (14.5% average grade). The extraction plant for the Tomtor ore will be built in Krasnokamensk; tailings will be stored at PIMCU.

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Gold and complex ores

ARMZ holds a 51% stake in the Lunnoe gold deposit. The rest belongs to Seligdar, a Russian gold manufacturer and project operator. ARMZ also owns Sovinoe and Severnoe deposits. The company plans to confirm Sovinoe reserves in 2024 and carries out exploration activities. As for the Severnoe deposit, its license holder Elkonsky GMK launched pilot production of gold. The reserves of Severnoe are estimated at 36 tons of gold, with an expected output of 1.2 tons of gold per annum.

ARMZ is preparing for the development of Pavlovskoe lead and zinc deposit on the Novaya Zemlya archipelago. Last December, the company published a press release disclosing JORC reserves of the deposit. According to estimates, resources of the Pavlovskoe deposit amount to 55 million tons of zinc ore (3.6% average grade). Reserves are estimated at 19 million tons of ore (3.3% average grade). The deposit is expected to yield 2.6 million tons of ore per annum.

And also...

ARMZ Group also comprises VNIPIPromTechnologii and RusBurMash. The first one is an engineering center for all the mining facilities of ARMZ. The other carries out mining and construction operations for ARMZ and third-party customers. The Group also includes ARMZ Mining Machinery, a manufacturer of Li-ion battery-powered mining machines and vehicles.

“We have diversified our business. Further development of ARMZ is associated, first and foremost, with rare-earth minerals and gold mining projects. Needless to say, we are not going to reduce our uranium output,” ARMZ First Deputy CEO Alexey Shemetov says.

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Energy Review 2021

The year 2021 was a shock for the energy industry, particularly for its fossil fuel sector. Here is our analysis of the reasons behind last year's crisis and a brief review of 2021.

The year 2021 started off with a rapid economic upturn driven by the removal of pandemic restrictions. According to the World Bank's Global Economic Prospects report published in January 2022, the global GDP rose 5.5% in 2021. The economic growth spurred the demand for energy resources. The largest global consumers that are short of energy resources — Europe and Asian giants India and China — found themselves competing for supplies.

High demand for gas is partially attributable to the climate agenda and ambitions for replacing dirty coal with cleaner gas. In April 2021, General Secretary of the Chinese Communist Party Xi Jinping said at the Leaders Summit on Climate that coal consumption would be severely restricted in China by 2025 and would begin to decline from 2026. It turned out impossible, though, to meet the announced targets.

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Starting from the second half of the summer 2021, the rising demand for electric power on the back of growing economy and a hotter-than-usual summer made China increase its domestic coal production and import coal from abroad. Demand in India grew, too. What stimulated coal imports to India and China was, among other things, production difficulties due to heavy rains in the both countries and conservation of coal mines in China. As a result, China ended up aggressively buying gas, including LNG.

South America also faced a growing demand for LNG.

And so did Europe, whose economy also stepped on the recovery track after the pandemic. According to Ember, an independent energy think tank, the growth of demand was further spurred by the cold winter of 2020–2021. Low temperatures across Europe sped up the rate of gas withdrawal from storage facilities. Another driver of gas demand was its lower imports from Russia to Europe.

The main problem with Russian gas supplies was that consumers did not want to make long-term contracts because spot prices in the gas market had remained low for long: in September 2019 the Dutch TTF spot price went down to USD 117 per 1,000 cubic meters. More importantly, it was lower than the contract price. But the trend reversed, and the price climbed up on the back of growing demand in China. Almost no country in Europe succeeded in buying LNG due to the 'Asian premium' to the price. The only exception was Spain that purchased it earlier than the others. American LNG, which Europe hoped for, was redirected to China because it was ready to pay more. As a result, the day ahead spot price in December 2021 skyrocketed 595% year-on-year to exceed USD 1,100 per 1,000 cubic meters.

Coal prices changed more modestly. As noted in the Electricity Market Report published by the International Energy Agency (IEA) in January 2022, **"coal prices [in the USA] remained more stable: fuel costs for coal-fired generation increasing by less than 6% in the second half of 2021 compared to the same period in 2020."**

The energy crisis — shortage of energy resources and surging gas prices — caused multiple effects.

First, industrial consumers and power plants in China suffered from deficient energy resources and growing energy prices. Some of them suspended operations because they began making losses, according to the IEA.

"Industrial consumers faced rolling blackouts in several provinces and states of both countries. In China's northeast, the province of Liaoning issued a level two shortage alert on several consecutive days, indicating power shortage equivalent to 10–20% of total demand. Similar shortages were registered in southern Guangdong, China's second-largest province by

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electricity consumption. While supply to residential consumers was prioritized, in certain provinces such as Liaoning, shortages affected residential consumers as well," IEA experts cite examples. The Chinese GDP, which grew 12% over the first three quarters of 2021, marked only an 8% increase at the yearend due to power plant outages and production interruptions.

India faced problems, too. **"Punjab experienced rolling blackouts of up to nine hours at a time due to the shutdown of three power plants from a lack of fuel. The state of Rajasthan was forced to introduce load shedding for industrial and residential consumers even in urban areas like Jaipur and Jodhpur, with some remote areas undergoing up to 12 hours of supply disruption. Bihar experienced power cuts of more than 10 hours per day. Other states such as Gujarat, Tamil Nadu and Karnataka have also been threatened by load shedding due to insufficient generation from thermal power plants,"** the report describes the situation in India.

Second, electricity generation costs spiked in Europe. According to Ember, the cost of electricity in the European Union, which also includes carbon rates and variable expenses, reached an average of EUR 255/MWh in December 2021 on the back of growing gas prices, displaying a sevenfold growth year-on-year. The generation cost was also affected by carbon prices — they went up from EUR 33 per ton of emissions as at January 1, 2021 to EUR 89 per ton as at December 8, 2021.

Third, the USA and Europe began to replace natural gas with coal to decrease generation costs. **"In 2021 the relative increase in gas prices versus coal led to a reversal in coal's decline, many markets experiencing fuel switching and consequently higher emissions. We estimate that US coal-fired generation grew by 19% and Europe's by 11% compared with 2020, while US gas-fired generation fell by 3% and Europe's grew mildly (up 4%),"** the IEA writes in its report. It should be mentioned that coal generation increased not only in the European Union, but in the UK as well.

And, finally, the fourth effect is not that evident as the other three but no less interesting: renewable sources replace gas and not coal as it used to be, at least in the European Union. This is a central point of the European Electricity Review published by Ember in February 2022: **"Historically, Europe's growing renewables replaced coal power, the most emissions-intensive fuel. However, as a result of soaring gas prices in the second half of 2021, new renewables replaced fossil gas instead. The interruption to the EU's coal phase-out slowed emission reductions."** In 2011–2019, the renewable power output increased by 42 TWh while the coal power output decreased by 34 TWh over the same period, the review says. However, another 44 TWh of renewable output added in the last two years replaced 23 TWh of gas power and as little as 7 TWh of coal power.

If analyzed by country, though, this trend will look different because national approaches to their energy mixes are also different. The Netherlands and Spain, for example, did increase their renewable power output by 17 TWh (up 24%) and cut gas power by 15 TWh (down 18%). In France, renewables and coal replaced retired nuclear capacity and gas. Sweden added renewable capacity instead of nuclear power. In Germany, power output from all sources decreased, while Poland demonstrated growth in the output across the energy mix, with coal power displaying the

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largest increase (8 TWh). And, finally, Ireland replaced gas and renewable power with coal.

According to Ember, the second half of 2021 faced **"one of the largest energy price shocks since the OPEC oil embargo of 1973."** We wrote about the similarities of the two crises in our Newsletter from November 2021. American economist Daniel Yergin wrote in his book The Prize: The Epic Quest for Oil, Money and Power, which was published back in 1991: **"A far-reaching clash between anxieties about energy security and economic well-being on the one side, and fears about the environment on the other, seems all but inevitable. One point of convergence of the two themes is energy conservation. Another may be greater utilization of natural gas"** (a quote from the Third Environmental Wave section). It is remarkable how accurate his forecast was and continues to be, this time in a new energy market reality.

Both the IEA and Ember assumed in their forecasts of future energy prices that they would go down in 2022 onwards. It is evident, however, that the prices of oil, gas and coal hit historic highs, and no one knows when they will go down.

In turn, we would not miss a chance to remind that the key advantages of nuclear power are a small share of fuel in the generation costs and a relatively low fuel consumption. Roughly speaking, a 1 GW power reactor needs as little as 20 tons of fuel, or 200 tons of U3O8 per annum. Nuclear energy looks like a safe haven amidst the shocks that hit the fossil fuel sector.

Here is another quote from Daniel Yergin's book: **"However, until such time as there are new technological breakthroughs, perhaps in solar and renewable energies, industrial society has only three primary clusters of alternatives on which to rely for its new power needs: oil, gas, and coal; nuclear power; and conservation in the form of technological improvements and greater efficiency in the use of energy."** If we read the latest IEA recommendations for Europe, we will see that this forecast of the American economist also becomes a reality. This is why Daniel Yergin's book telling one of the most breathtaking stories from the 20th century politics and economy produces an unexpected impression that crises in the fossil fuel market occurred in the past, occur now and are likely to occur in the future. Those crises do good neither to consumers nor to producers, but they eventually come to an end, sooner or later.

The nuclear industry, however, has never faced any shortage of supply yet. We hope it never does.

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