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Nuclear Power: Myths vs. Realities

Nuclear power was one of the factors underpinning the post-war success of the Euro-Atlantic region. The world is now in great need of a similar step forward

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The history of nuclear power starts at the end of World War II. The speed and momentum with which the liberated portion of Europe was rebuilt was astounding. Nowadays there is certainly inspiration to be drawn from those models, including from the first words of the Treaty establishing the European Atomic Energy Community:

> *RECOGNISING that nuclear energy represents an essential resource for the development and invigoration of industry and will permit the advancement of the cause of peace, (…) the HIGH CONTRACTING PARTIES establish among themselves a EUROPEAN ATOMIC ENERGY COMMUNITY (EURATOM).*

The fight against the COVID-19 pandemic has coincided with global processes related to demographic changes, technological advancements, climate threats as well as the growing position of China and its rivalry with the weakened and alienated United States. Europe and the United States are no longer bound by a strong alliance. Today's Europe seeks to strike a balance between China and the United States and accepts Russia having a considerable influence over the European energy sector. Emerging economies have growing aspirations, and their rivalry with the most powerful countries is also noticed in Europe. Arguably, the desire to overcome the pandemic may render the upcoming changes turbulent, and key decisions will be made based not only on facts but also on myths. Both facts and myths can be found in the history of nuclear power.

Energy

$E = mc^2$, the iconic equation of nuclear energy, suggests that nuclear reactors make it possible to transform mass into energy and thereby, taking into account the efficiency of thermodynamic cycles, to obtain enough joules of heat from one kilogram of matter to generate more than 8 TWh of electricity – as much as a 1 GW power plant can generate in a year. However, a kilogram of matter will "disappear" from both a nuclear power plant and a coal-fired power station generating the same amount of power. In doing so, however, the coal-fired plant will have to burn several million metric tons of coal delivered by several hundred trains, each with 100 cars filled with 60 metric tons of coal. It is impossible to detect the "disappearance" of this one kilogram of matter after millions of tons of coal are burned in millions of tons of oxygen. A nuclear power plant, in turn, will use about 30 tons

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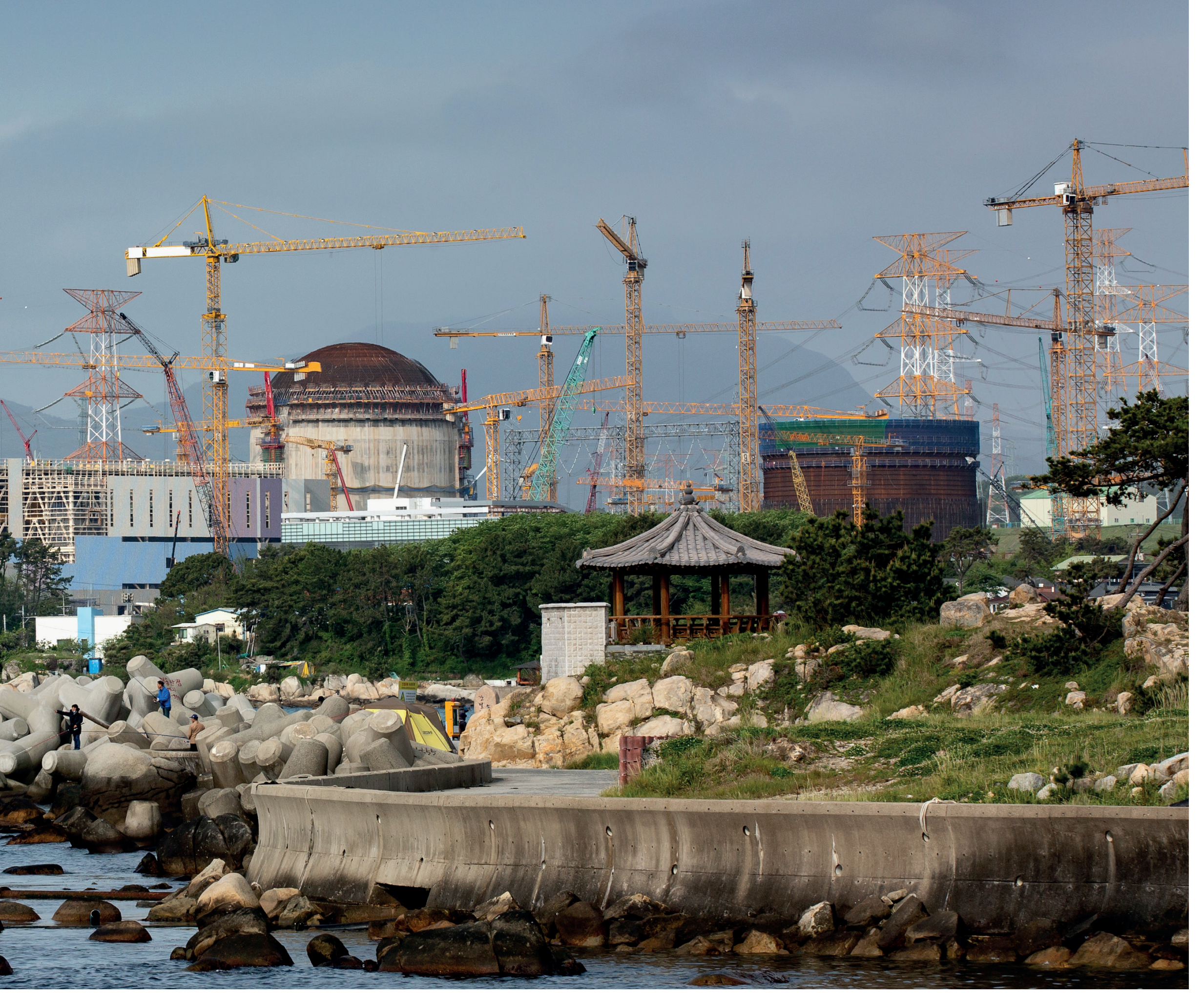
of fuel, a ton of uranium and plutonium nuclei will be split, and one kilogram of matter will "disappear" from that ton, on balance, because the mass of the nucleus before being split is one tenth of a percent greater than the combined masses of the fission products. This amount is measurable but it is insignificantly small and has no impact on the design of reactors.

Here, it should be explained that the energy released by nuclear fission is well-described by electrostatic repulsion between the two smaller nuclei that arise from splitting the larger nucleus. The high-speed nuclei are then slowed down inside matter, chiefly through interactions with electrons, and their kinetic energy is transformed into heat. Many important details of nuclear fission are described by quantum physics, which explains why a few kinds of atomic nuclei, such as uranium-235 and plutonium-239, often split into two smaller nuclei after capturing a neutron, and why this process releases two or three neutrons that can sustain a chain reaction of atomic fission. A landmark moment for the energy sector came when it was demonstrated that it is possible to regulate the number of fissions per unit of time, which means controlling the power of the reactor, by slowing down neutrons and capturing them with the help of non-fissionable isotopes (the amount of these present in the reactor core is an adjustable parameter).

The formula $E = mc^2$ could be therefore described as a founding myth that not only placed nuclear power within the "relativistic realm" of mass-energy equivalence and sparked off more myths, but also underscored the enormous density of energy in the reactor fuel.

Safety

Debates on nuclear power always include considerations on the risks posed by spent fuel. As we have noted above, the mass of such fuel is small compared to the amount of the energy generated, but it takes several hundred thousand years for its radiotoxicity to fall to the level of that of uranium ore – a fact that fosters the myth that storing spent fuel poses an insurmountable problem. However, only "fresh" spent fuel poses a threat in and of itself. It must be stored in durable, cooled containers because it produces significant decay heat and is highly chemically active. Nuclear facilities usually store spent fuel in on-site pools at least for the first 10 years. As time passes, radioactive decay becomes less intensive and small enough for well-constructed storage casks. After several hundred years, the spent fuel will no longer contain mobile radioactive isotopes such as cesium-137, which has a half-life of 30 years. After a few thousand years, in turn, there is no risk of mobile radioactive isotopes being released into the environment, and leaks in the casks caused by mistake or by accident will not lead to contamination at a distance of more than a few kilometers. This has been shown by studies of the remains of the natural nuclear reactor at Oklo (Gabon, Central Africa), which spontaneously came into existence two billion years ago in deposits of uranium ore that were



Nuclear power plant in Ulju-gun, South Korea, May 2020

flooded with water. Consequently, what poses a challenge is the construction of safe storage sites that will last several thousand years and in the longer run only offer protection against the intentional use of "old" spent fuel for malicious purposes.

The Three Mile Island, Chernobyl, and Fukushima disasters showed that nuclear power could be dangerous, but the steps taken following those disasters improved its safety. In the disaster that took place at Three Mile Island (in the United States) in 1979, safety procedures failed, the reactor core melted down, but there was no contamination of the environment. After the accident, passive safety systems were introduced and emergency procedures were improved. The disaster that took place in Chernobyl (in the Soviet Union) in 1986, the reactor was destroyed, resulting in numerous casualties and significant environmental contamination. This led to a full-blown revival of the myth about the possibility of a reactor explosion of a magnitude comparable to that of a nuclear bomb. Such a scenario is impossible for many reasons, and this was shown in practice by the disaster in Chernobyl, where an uncontrollable power surge resulted in a chemical explosion that destroyed the reactor core, ruling out any possibility of a nuclear explosion. Analysis of the disaster showed that the reactor design had serious flaws, and emergency procedures permitted the operators to make risky decisions. Currently, reactors with such defects cannot be constructed or used. The disaster that took place at Fukushima (Japan) in 2011 exposed our human helplessness in the face of a major natural disaster. The powerful Indian Ocean tsunami in 2004 had been a wake-up call for such power plants as Fukushima. For several years, attempts were made to convince Japan to better protect power plants against tsunamis. Unfortunately, however, the recommendations were not put into effect at the time.

There is no doubt that ensuring safety is a task of overriding importance, but we must not mythologize it or let it obscure the assessment of the economic utility of reactors. In the past, numerous attempts were made to implement various technologies, but very few of them made their way into the energy sector. Despite several expensive attempts, high-temperature reactors, sodium-cooled fast reactors, lead-cooled fast reactors, and molten-salt reactors all proved unsuccessful. Modern nuclear power technology allows for the fission of only a few percent of the uranium in the reactor fuel, which is the primary motive driving research into the possibilities of making better use of such fuel. Efforts are being made to design reactors that will be able to reprocess the spent fuel from existing nuclear power plants into a less radiotoxic material. This is why, despite costly failures, attempts to construct novel reactors continue to be made from time to time. Examples include the ongoing construction of a power plant with two high-temperature reactors in China. China and Russia have demonstration sodium-cooled reactors, and the United States has recently decided to build a test reactor using this technology and start preliminary design work on other solutions. France, in turn, which probably has the most experience in designing, building, and maintaining sodium-cooled reactors, has recently dropped plans to implement a similar project. It is likewise worth bearing in mind the importance of developing reactor technologies for special applications, such as the construction of nuclear rocket engines, for example in the past in the program Nuclear Engine for Rocket Vehicle Application (NERVA) in United States and currently in the National Strategy for Space Nuclear Power and Propulsion, or the use of small reactors in extremely remote tundra regions in Siberia, and for the purpose of exploring Mars and the Moon.

The market and costs

Since the Fukushima disaster, the only reactors built for power generation purposes have been large light-water nuclear reactors (pressurized water reactors, or PWRs) with generation units of over 1 GW. One exception is India, which is building 700 MW units with heavy-water reactors, but this project has yet to make its way into the global markets. Only a few PWR projects have attracted investors, and all of these projects are similar. In turn, the power plants being constructed with such reactors vary greatly in terms of the assessment of their economic utility. For years, we have observed delays and rising construction costs in all nuclear power plant projects, but the construction of four plants and the launch of the first Korean APR-1400 reactor in the United Arab Emirates should be treated as successes for nuclear power. The APR-1400 projects in South Korea and all of the projects with Russia's VVER-1200 and China's Hualong One have been similarly successful. In addition, the construction of four US AP1000 reactors and two French EPRs in China was completed quite efficiently. On the other hand, the abandonment of the construction of two AP1000 reactors at the Virgil C. Summer Nuclear Power Station (in the United States) was a business failure that caused losses of up to $10 billion. Other failures include the construction of two AP1000 reactors at the Vogtle Electric Generating Plant in the United States (with costs exceeding $25 billion) and the construction of one French EPR in Finland and another one in France, which were characterized by delays of many years and absurdly high costs. In turn, the two EPRs being constructed jointly by France and China in the United Kingdom may be closer to success than failure.

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Smaller PWRs, with energy units of less than 1 GW, have been driven out of the global market by economies of scale. Such considerations are commonly found for various technologies – for example in the refrigerator market (two small refrigerators are more expensive than one that is twice as large). However, economies of scale have their limitations. In the nuclear power sector, the first of these limitations results from the technological barriers to the production of large and durable vessels for PWRs and, more generally, from the small size of the market of providers of the critical, expensive, and heavy components.

The vessels in which the uranium reactor core is placed are currently so large that they can only be made by several companies in Japan, China, Russia, South Korea, and possibly one in France. The market is shallow and easily influenced, and the prices can be high. In the plans to build several reactors (just like the six reactors being planned in Poland), all the vessels have to be delivered over two or three years, because a typical production line produces a few vessels per year. For this reason, it is almost impossible to optimize the implementation of a small program. If units are built one by one, the last vessel delivered (the sixth vessel in the Polish program) will have to wait even more than a decade to be installed. Alternatively, the power plants could be built concurrently, which is costly in a small program.

For this reason, we can see a clash between economies of scale and the depth of the market of reactor buyers, and winning a contract to build 20 or more large reactors is not easy. In recent years, Russia has achieved success in this area with its VVER-1200 reactor, China will most likely succeed with the Hualong One reactor, and it is evident that India's heavy-water reactor has potential. In turn, the order books for the construction of new AP1000, EPR, and APR-1400 reactors have been empty for many years. Russia and China are efficiently handling the construction of large reactors. In Poland, this has given rise to a myth about the availability of well-proven large reactors, including ones for which there is zero demand.

Korea's APR-1400 reactors went out of the market when the country decided to phase out nuclear power several years ago. The phase-out program is spread over many years and provides for the completion of four reactors, but plans to build more reactors have been halted.

It appears that an opportunity to create a large market of buyers of AP1000 and EPR reactors was missed several years ago. The factors behind this situation included business failures and the strategic decisions made years ago by France and the United States. The Fukushima disaster slowed down the development of the nuclear power sector. In 2013, however, China and Russia already showed signs of recovery, and France attempted to win new contracts. In order to consolidate its position, it invited China to take up one-third of the shares in the planned construction of two EPRs at the Hinkley Point C nuclear power station (in the United Kingdom). At the time, China was building two EPRs (which are already in operation), and the new contract in fact gave a green light to the development of the Hualong One reactor, which is modeled on French reactors. France and China are now bound together by joint investments in the UK, which makes it difficult to create a market of EPR buyers because this is not in the interest of China, which has its Hualong One reactor.

The construction of four AP1000 reactors in China was a flagship project in the vision of close collaboration between the United States and China. The reactors are already operational, but a coolant pump failure resulted in one of them being shut for almost the whole of 2019, and there are many signs that these pumps remain a weak point of the AP1000 project. The Americans, just like the French, have sought China's support. In 2013, the conclusion of a deal paving the way for China to become the global supplier for the AP1000 reactors was hailed as a success. Simultaneously, China obtained the right to build clones of the AP1000, dubbed the China Advanced Passive 1000 (abbreviated as CAP1000), and their scaled-up versions named CAP1400. History has shown, however, that construction of an AP1000 reactor using Chinese components has not been launched anywhere in the world, and the Hualong One reactor is supplanting clones of the AP1000 in China's plans.

With the COVID-19 pandemic intensifying the rivalry between China and the United States, it is now evident that the decisions made years ago are making it difficult to create a market of AP1000 buyers because no clones of these reactors are being built in China and the country will not be a global supplier of their components.

Another barrier to the expansion of large reactors is posed by the fact that the size of the buildings designed to accommodate them means that they are erected gradually as the construction of such reactors progresses. This means that many tasks must be carried out one after another, which extends the time needed to complete the project and results in ever-growing delays. The division of the project into parallel paths with small and medium-sized companies participating is likewise rendered more difficult.

These shortcomings might lead us to the conclusion that it is a good idea to build smaller reactors. However, Westinghouse Electric Company's experience with the AP600 and AP1000 projects shows that such solutions are not popular. Westinghouse initially designed the AP600 and completed the licensing process in the United States, but no investor was found for the reactor. The company noticed interest in larger reactors and quickly developed the AP1000, essentially by simply scaling up the AP600, and quickly found buyers for the design. Shortly before the Fukushima disaster, there appeared to be a chance for the construction of up to 50 reactors in China, the United States, India, and the UK. Currently, however, competitors are taking over the foreign market, and the United States will most certainly not launch the construction of a new AP1000 in the wake of the August 2020 decision to sell off the components for the two AP1000s in the abandoned Virgil C. Summer project.

It is doubtful that the world will ever return to smaller reactors such as the AP600. Although Poland's nuclear program might consider replacing the planned six 1200 MW units with 12 smaller units, the idea of building 120 power units of 60 MW each in Poland will always be unreasonable. Economies of scale on this level of power output (20 times smaller) argue strongly in favor of large reactors, and good ideas are needed if mass-produced small reactors are to become competitive. One of these ideas involves building large nuclear units consisting of a dozen or so modules, with each module powered by its own small reactor, but with many systems shared by at least several modules. The most advanced design in this category has been created by the company NuScale Power in the United States. The first 924 MW unit consisting of 12 modules powered by integrated small PWRs is expected to be launched in Idaho in 2030. The US regulator has already approved the placement of these modules within a single building, which was possible because each NuScale reactor has an individual containment vessel. It is evident that this design has a lot of potential, especially thanks to its dry cooling system, which uses only a few percent of the water drawn by the cooling towers. Several years from now, at the latest, we will know if NuScale is just yet another nuclear power myth or a project that will attract investors with billions of dollars at their disposal. Either it will create a true alternative to the Russian and Chinese reactors, or it will join the mythical family of proven large PWRs that no country except for Poland now wants to build. ■

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