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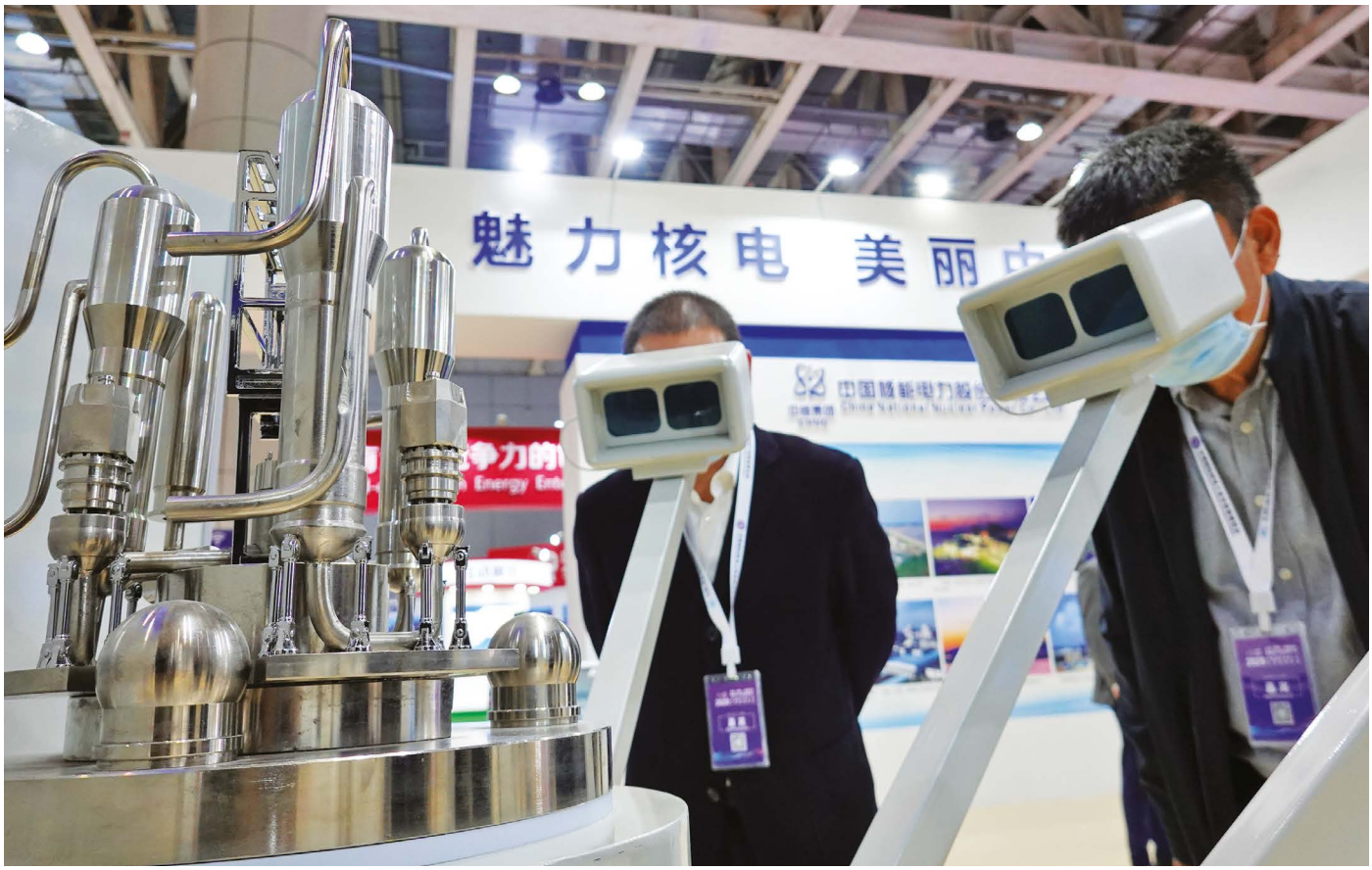

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Visitors to an industry exhibition in 2020 in China view a model nuclear-power reactor through augmented-reality headsets.

Nuclear energy, ten years after Fukushima

Aditi Verma, Ali Ahmad & Francesca Giovannini

Amid the urgent need to decarbonize, the industry that delivers one-tenth of global electricity must consult the public on reactor research, design, regulation, location and waste.

Ten years have passed since a catastrophic earthquake and tsunami damaged the Fukushima Daiichi nuclear power plant in Japan, triggering the worst nuclear accident since the Chernobyl disaster in 1986.

The accident struck at a time of renewed hope and untested optimism surrounding a new wave of nuclear-energy technologies and the part they might play in achieving a low-carbon future. It led to retrenchment, amid fresh concerns over the technological, institutional and cultural vulnerabilities of nuclear infrastructures, and the fallibility of humans in designing, managing and operating such complex systems.

A decade after the disaster, these serious questions linger, even as the climate crisis grows nearer.

Many academics have cast nuclear power as an inevitable choice if the planet is to limit global warming[1]. But, given the environmental and social concerns, others are more circumspect, or remain opposed[2]. The Intergovernmental Panel on Climate Change, in its 2018 special report on global warming, acknowledged a possible role for nuclear energy in limiting global temperature rise, but highlighted

the crucial role that public acceptance will have in boosting or derailing investments.

Safety and cost are frequently highlighted as the central challenges for the nuclear industry. New technologies are tackling these issues, but such reactors might not become commercialized until mid-century. That time frame could render them obsolete, as competing technologies such as solar and wind energy (plus storage) become increasingly dominant[3].

In our view, a larger problem looms: the opaque, inward-looking and inequitable ways in which the nuclear sector has long made technology and policy decisions. Hence, two crucial questions concerning the future of nuclear energy need to be asked. First, can and will the sector ever overcome public disapproval? Second, are its benefits worth the risks and costs to people and the environment?

To move forwards, the nuclear industry must confront these questions. This will require a fundamental change in outlook — to a more inclusive, accountable, responsible and forward-looking enterprise.

How we got here

In the 1950s and 1960s, the spread of nuclear energy seemed unstoppable. Policymakers and developers expected that it would become 'too cheap to meter'. But the 1980s and the 1990s witnessed a sharp decline in investment. Growing anti-nuclear sentiment, fuelled by the accidents at Three Mile Island (1979) and Chernobyl, along with rising construction costs and loss of government subsidies, led to a period of stagnation.

Projections by the International Atomic Energy Agency from the 1970s anticipated that nuclear power would account for 430 GW(e) (gigawatts electricity), or nearly 12% of the world's electricity-generating capacity, by 1990, and 740–1,075 GW(e), or about 15% of electricity-generating capacity, by 2000 (ref. 4). In reality, by 1999 it had reached only roughly one-third of that, at 308.6 GW(e) capacity[5]. In the late 1990s, global expectations for a nuclear renaissance had started to revive. By 2010, construction had ticked upwards again.

Then came Fukushima. The accident combined with other economic and political factors to prompt the disbandment of the nuclear-industrial complex in many nations. Four months after the reactor failure, the German parliament voted to phase out nuclear energy altogether by 2022. The Swiss cabinet followed suit, calling for the decommissioning of the country's five nuclear-power reactors. In Japan, out of the 54 reactors operational at the time of the accident, 12 were subsequently permanently closed and 24 remain — at least for now — shuttered[6].

In the United States, a review of the operation of nuclear power plants was conducted after Fukushima by the Nuclear Regulatory Commission. It raised many safety concerns, but the country remains committed to nuclear power. Other nations restarted, or took their first steps towards, nuclear-energy generation.

Today, around 50 nuclear-power reactors are being constructed across 16 countries. China leads, with 16 plants under way, followed by India and South Korea. According to the World Nuclear Industry Status Report (WNISR), as of the end of February 2021, 414 nuclear-power reactors were running in 32 countries, contributing 10.3% of the world's electricity supply (see go.nature.com/3khsxqj). Overall, nuclear energy is ticking along but struggling. The WNISR, for example, depicts an industry largely in stasis.

Meanwhile, many portray nuclear energy as a necessary part of the solution to climate change. Central to this argument is the development of new technologies. Small modular reactors (SMRs), for example, produce less than 300 MW(e) per unit (enough to power 200,000 houses in the United States). Their size reduces the potential for disaster while standardizing design and potentially reducing cost.

In the United States, a handful of water-cooled SMRs are approaching commercial viability. The design by NuScale, in Tigard, Oregon, became the first to receive a final safety evaluation, in 2020; the first plant is planned for Idaho by 2030. Other companies are working on a new generation (Gen IV) of more-efficient, safer reactors — most of which rely on coolants other than water. These are even further from commercialization.

Social engagement

These are interesting developments. But much of the support for nuclear energy focuses almost exclusively on its techno-economic characteristics, downplaying unresolved moral and ethical concerns. Proponents often fail to consider inequalities in how the benefits and risks of nuclear technologies are distributed at the local, regional and global scale. Nor do they consider who is left out of the decision-making processes about what to build, or who will be most affected by problems that arise[7].

Nearly three-quarters of all uranium production globally, for instance, comes from mines that are in or near Indigenous communities, for example in the United States and Australia. These mines, left unremediated after use, have poisoned lands and peoples, and upended traditional ways of life (see go.nature.com/37w5be6). Nuclear waste is similarly mired in equity concerns, given that long-term repositories will probably be sited far from communities that have typically benefited from the production of nuclear electricity. The nuclear industry often presents the problem of waste storage as having known technical solutions. The reality of exactly where it should go, and how, is still highly contentious.

In stark contrast, the 'Green New Deals' proposed in several countries explicitly aspire to wealth redistribution, social fairness and environmental equity. In the United States and other countries where such discussions have emerged, public support for nuclear energy is mixed.

The nuclear sector has consistently failed to engage meaningfully with the public over such

The Zaporizhzhia nuclear power plant in Ukraine, the largest in Europe.

DMYTRO SMOLYENKO/BARCRAFT MEDIA VIA GETTY IMAGES

concerns. This failure can be traced back to the 1960s and 1970s. Psychological studies of risk at that time described the public as affective, irrational and neglectful of probability in its assessments of risk, and called on the nuclear industry either to accept and design for the public's perceptions of risk or to educate the public[8].

Industry chose the latter path, typically attempting to engage the public only at the final stages of plant regulation and focusing on educating the public with the industry's own view of risk. This is a straightforward, quantitative equation that multiplies the probability of disaster and consequence. It often avoids or ignores the public perspective. For example, many people are willing to accept risks that are voluntary or familiar — such as flying, smoking or driving a car — against risks that are unfamiliar and over which they have little control. For involuntary risky activities, most individuals tend to de-emphasize probability and require higher levels of safety and protection for their comfort.

The industry's mode of engagement with the public has led to an antagonistic expert–public divide. Fukushima, for example, left an undeniable mark on the public psyche. But the nuclear industry consistently plays down the disaster by focusing on the fact that it did not cause any direct casualties. Although no human deaths resulted directly from the accident, disruptions to livelihoods, social ties and irreversible damage to ecosystems have been significant. An estimated 165,000 people were displaced, and, a decade later, some 43,000 residents are unable to return to their home towns[9]. Industry risk assessments capture the economic impacts of such issues, but usually fail to capture the harder-to-quantify collateral damage to people's lives and the environment.

From uranium mining to waste management, genuine citizen engagement, which aims to listen, not convince, is needed.

Different paths

The problems of unequal environmental and social burdens are not, of course, unique to the nuclear industry. The mining of lithium for renewable technologies and the recycling of electronics, for example, also raise these issues. But other industries have been better at engaging the public. Shifts to human-centred design have long been under way in other fields of engineering[10]. Developers of solar panels, for example, have focused on what the end user really needs. Such discussions have resulted in semi-transparent panels that farmers can grow crops beneath, opening up a new field of 'agrivoltaics'.

The nuclear industry faces a particular barrier to democratizing its technologies. Large nuclear reactors are not suited to the community-driven ownership models evolving for some renewable energies. There are signs of more-creative thinking, though. For example, the US National Reactor Innovation Center, launched in 2019, has been investigating how local communities that might host advanced reactors perceive risks.

Newer generations of designers — including some start-ups funded by the US Department of Energy's Office of Nuclear Energy — have been asking what kinds of reactor the public might endorse. This questioning, keeping the Fukushima accident in mind, has led designers to think more creatively and qualitatively about safety and risk[11]. Some designers claim they have invented reactors that cannot experience core meltdowns or release large amounts of radioactivity.

"Newer generations of designers have been asking what kinds of reactor the public might endorse."

We are not calling for the public to become co-designers of nuclear reactors. But lay perceptions of risk, accounted for early in the design process, should inform choices concerning reactor safety systems, emergency planning procedures, and the role of human agency and improvisation in a complex system. And, of course, the public must have its say in decisions of where and how to site new reactors, if at all.

Inclusive future

The historical lack of meaningful engagement with the public has also led to 'regulatory capture': this is the co-opting of governance groups to advance the interests of the nuclear industry. It is a common misconception that this is prevalent only in developing countries with weak institutions. Not so. It is present in most places to a greater or lesser degree.

For example, the capture of the then Japanese Nuclear Industry Safety Authority by the nuclear industry is widely regarded as an institutional cause of the Fukushima accident[12]. Even in the United Arab Emirates (UAE), which is often portrayed by the nuclear industry as a textbook model, the private entity that developed the UAE's strategic plan for commercial nuclear energy advises the country's nuclear regulator: a clear conflict of interest.

A few countries with established nuclear industries, such as the United States, China and Russia, are positioning themselves as global suppliers of nuclear technologies. The push to install nuclear programmes in countries with frail governance — including Nigeria, Vietnam and Saudi Arabia — should be treated with caution. We do not dispute these countries' right to develop nuclear energy but rather whether they are ready to do so. Those championing the development of nuclear energy in these countries should offer support in the form of institution building, rather than simple contracts for technology sales. Unfortunately, regulatory empowerment receives scant attention and resources.

In many cases around the world, the decision to establish nuclear programmes is taken by a small circle of the political elite without any real needs assessment, understanding of how nuclear energy fits within the broader national energy policy, or regard for the public's view of the technology and its risks. Companies have tended to view new buyer countries as having little input or interest in the technology design and development process. As such, the inclusion of nuclear energy has seemed contrived, spurred by the industry's desire for profit and market dominance, rather than being an organic component of a collective response to a societal problem such as climate change.

If nuclear energy is to have a meaningful role in deep decarbonization, perspectives that up to now have been excluded from the design, development and policymaking process must have a seat at the table.

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